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Full Length Article

Finite Element mesh coarsening for effective distortion prediction in Wire Arc Additive Manufacturing

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ABSTRACT

WAAM (Wire Arc Additive Manufacturing) is a metal AM (Additive Manufacturing) technology that allows high deposition rates and the manufacturability of very large components, compared to other AM technologies. Distortions and residual stresses affecting the manufactured parts represent the main drawbacks of this AM technique. FE (Finite Element) modeling could represent an effective tool to tackle such issues, since it can be used to optimize process parameters, deposition paths and to test alternative mitigation strategies. Nevertheless, specific modeling strategies are needed to reduce the computational cost of the process simulation, such as reducing the number of elements used in discretizing the model. This paper presents an alternative technique to reduce the number of elements required to discretize the substrates of WAAM workpieces. The proposed technique is based on dividing the substrate in several zones, separately discretized and then connected by means of a double sided contact algorithm. This strategy allows to achieve a significant reduction of the number of elements required, without affecting their quality parameters. The geometry and dimension of the mesh zones are identified through a dedicated algorithm that allows to achieve an accurate temperature prediction with the minimum element number. The effectiveness of the proposed technique was tested by means of both numerical and experimental validation tests.

1. Introduction

Among metal AM (Additive Manufacturing) processes, WAAM (Wire Arc Additive Manufacturing) appears to be one of the most interesting in terms of achievable material deposition rates and maximum part size [1]. WAAM is a DED (Direct Energy Deposition) technology, i.e., a metal AM technique in which the component layers are created by selective deposition of molten metal. In WAAM, the added metal is deposited using arc welding techniques such as GMAW (Gas Metal Arc Welding), GTAW (Gas Tungsten Arc Welding) or PAW (Plasma Arc Welding) [2].

The components manufactured by WAAM are prone to residual stresses and distortion issues [3]. It should be pointed out that such criticalities affect all metal AM technologies, since they are caused by the non-uniform temperature field in the part during the manufacturing process. Simulations provide an effective tool to investigate the main leverages to mitigate or compensate such issues, allowing to test process improvement in a cost and time effective way. The effectiveness of process simulation has been proven in several works: Denlinger and Michaleris [4] used FE modeling to develop a distortions compensation strategy tailored for AM of large parts and to investigate the effect of stress relaxation on part displacements and residual stresses [5]. Salonitis et al. [6] studied the interaction of direct laser deposition AM and post-process milling to determine the actual residual stresses after the finishing process. The simulation of AM processes is usually carried out in analogy to the techniques used in multi-pass welding simulations: basically, a transient thermo-mechanical FE analysis is carried out, simulating the heat transfer to the workpiece by means of an heat source model [7]. The material deposition is taken into account by including specific algorithms that activate the bead elements according to the deposition process [8].

Despite the accuracy and effectiveness achievable by FE process modeling, a significant drawback of such technique is the high computational cost associated with the large model size and the

Abbreviations: WAAM, Wire Arc Additive Manufacturing; AM, Additive Manufacturing; FE, Finite Element; DED, Direct Energy Deposition; GMAW, Gas Metal Arc Welding; GTAW, Gas Tungsten Arc Welding; PAW, Plasma Arc Welding; DOF, Degree of Freedom.

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high number of simulation steps required. Since AM simulations are performed via transient analyses, two main paths could be followed to improve the simulation time efficiency: reducing the number of simulation steps and reducing FE model DOFs (Degrees Of Freedom). The most effective approach to reduce the number of simulation steps was presented by Ding et al. ([9,10]) that proposed to treat both the heat transfer and the mechanical domains as steady state problems in a reference frame moving according to the deposition path. This strategy requires a single simulation step to be performed for each component layer, resulting in a significant reduction of computation time. However, this approach returns accurate results only on large components, since the steady state approximation introduces significant errors for reduced part size [11]. Therefore, for an effective reduction of simulation time in arbitrary part size, it is crucial to develop techniques focusing on the reduction of FE model DOFs. This paper deals with this aspect, aiming at improving AM simulation efficiency.

In an AM simulation model, the number of elements (i.e., the number of DOFs), is constrained by the maximum mesh size required by the molten pool. Indeed, since metal deposition involves a local heating of the workpiece, to achieve an accurate description of the temperature field, a minimum number of elements per molten pool radius must be used. This aspect was already shown in the simulation of similar processes, such as welding [12], and laser forming [13]. Such requirement leads to a constraint for the elements size of both filler material and substrate. In particular, all the FE elements representing the deposited material should meet the maximum size criterion, because during the simulation they will experience a melting transformation. Nevertheless, one should consider that this requirement needs to be met locally, where the molten pool induces relevant temperature gradients. It is worth noting that, as the simulation progresses, the deposition head and consequently the molten pool move along the substrate. This leads to filler regions represented by a number of elements, originally defined in accordance with the maximum size criterion, that would result excessive, considering the reduction of temperature gradients over those areas. In addition, the substrate elements size shall be defined in accordance to the one of the filler (to ensure mesh connectivity) even though the substrate will not experience any phase change.

Considering these aspects, the techniques to reduce the model DOFs pursue two main strategies: i) reducing the number of elements of the filler metal far from the molten pool and ii) reducing the number of elements of the substrate. In the first group, an adaptive re-meshing of the deposited material elements is performed. Denlinger et al. [14] presented a re-meshing technique in which a mesh coarsening is performed after the deposition of every layer, extracting solution variables on the coarsened grid by means of an interpolation algorithm. In AM simulation, the most common technique to reduce the elements of the substrate is mesh-biasing [15], in which the substrate mesh size is increased proportionally to the distance from the filler elements. This technique is adopted in most AM FE simulations, but it shows a significant drawback: an excessive increase in mesh size could affect elements geometry, leading to the generation of elements with excessive aspect ratios [16]. This can lead to severe issues in the mechanical analysis, introducing errors in estimating the base material bending [17].

This paper presents a new method to reduce the number of elements required for the substrate discretization. Unlike the traditional mesh biasing technique, the proposed approach increases the elements size without affecting the elements quality. This is achieved by splitting the substrate geometry in multiple sections that are discretized individually with different mesh size. The model of the complete substrate is then created by connecting the different sections with a double sided contact algorithm. The details of the proposed technique will be discussed in Section 2. In Section 3 a numerical validation is presented: a simple bead on plate simulation is carried out using the proposed mesh coarsening technique and the results in terms of temperature distribution are compared with a reference model. In Section 4 both the mesh biasing and the proposed technique are applied to an experimental case study, comparing the actual and simulated distortions. This validation allowed to prove the accuracy of the proposed modeling technique, in terms of distortions prediction, which, together with the reduced computational time, paves the way to the adoption of suitable optimization approaches [18], to mitigate such criticality.

2. Proposed method

The residual stresses and distortions of AM parts are related to the non-uniform temperature distribution in the workpiece. For this reason, thermo-mechanical coupled FE models are used to model such effects in AM operations.

Since the outcome of the heat transfer analysis (transient temperature distribution of the workpiece) is used as input load for the mechanical analysis, correctly capturing the temperature gradients in this phase is mandatory to ensure an accurate prediction of the workpiece mechanical response. Hence, the FE mesh pattern and size must be consistent with temperature gradients experienced by the workpiece, conflicting with the need of reducing the simulation time, usually achieved by reducing the number of elements.

The proposed method allows to reduce the number of FE elements used to discretize the workpiece, without introducing significant errors in estimating the temperature field. The base concept is to replace the mesh biasing technique with a mesh zoning approach, which consists in defining different zones of the workpiece substrate to be separately discretized and then connected in order to achieve a continuous body behavior. Hence, the workpiece is discretized with a discontinuous mesh, achieving a significant reduction of the elements number without compromising their aspect ratios and the results. The key points of proposed technique are:

1. Mesh zones joining.
2. Mesh zones definition.

2.1. Mesh zones joining

Varying the mesh size throughout the substrate geometry is a common practice to reduce the number of elements used for the discretization. This is usually performed with the mesh biasing technique, i.e., the element dimension is progressively increased in a specific direction to reduce the number of elements. This leads to a non-uniform mesh size, increasing with the distance from the filler material. An example of a biased mesh is shown in Fig. 1b.

Despite the straightforward implementation of such technique in the commercial FE pre-processors, it has a significant drawback: as the distance from the substrate increases, the element geometry experiences significant distortions, leading to high aspect ratio values, as exemplified in Fig. 1b. It is worth highlighting that this issue gets particularly relevant in hexahedral elements, while tetrahedrons better suite a biased mesh pattern without relevantly affecting the elements aspect ratio. On the other hand, hexahedrons are the most common type of elements used in both AM and welding simulation since they allow to achieve a high accuracy in the mechanical analysis with first order shape functions, unlike tetrahedron elements. For this reason, the proposed mesh coarsening technique will be discussed referring to hexahedral elements, but the application to tetrahedral elements is feasible and straightforward.