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Finite element modelling of Wire-Arc-Additive-Manufacturing process

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Abstract

Wire-Arc-Additive-Manufacturing (WAAM) is an Additive-Manufacturing (AM) process, allowing to produce metal components layer by layer by means of Gas-Metal-Arc-Welding (GMAW) technology. The advantages of this technology are the capability to create large parts with a higher deposition rate with respect to other AM technologies. Despite these great benefits, WAAM components are affected by severe distortions and residual stresses issues. Finite element process simulation provides an efficient way to study mitigation strategies for such issues. In this paper, a WAAM modelling strategy is proposed based on a novel heat source model that takes into account the actual power distribution between filler and base materials. In order to prove the effectiveness of proposed modelling, an experimental validation is provided by comparing the measured distortions of a WAAM tests-case with the simulated ones, highlighting the accuracy of proposed model.

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Keywords: Welding; Finite element method (FEM); Additive manufacturing;

1. Introduction

Additive Manufacturing (AM) processes, for the production of metal components, represent one of the most relevant innovations in the manufacturing sector. Indeed, such technologies provide several benefits such as the possibility of manufacturing parts with complex geometries and a significant reduction of material waste with respect to machining processes. Among metal AM processes, Wire-Arc-Additive-Manufacturing (WAAM) is one of the most efficient in terms of deposition rate (2÷10 [kg/h]) [1] and allows to manufacture large components, up to several meters [2]. In this process, the part is created stacking subsequent layers by means of an arc welding process, generally Gas-Metal-Arc-Welding (GMAW).

Despite WAAM advantages, components manufactured with such technology are prone to residual stresses and distortions issues [3] affecting the subsequent machining operations [4]. The cause of such phenomena is the non-uniform temperature field experienced by the component during the deposition process, strictly connected to the deposition path [5]. Process simulation is a powerful tool to tackle such issues, allowing to test the effect of different deposition patterns on residual stresses field, optimizing the process[6]. Furthermore, post-process machining operations can be simulated, assessing their effects on AM parts distortions and residual stresses([7],[8]).

From a simulation perspective, WAAM process is very similar to multi-pass welding process. The heat and mass transfer between the arc and the workpiece is governed by the molten pool, characterized by complex physical phenomena. Despite some works focus on molten pool and arc dynamics simulation [9], it is not possible to apply such complex techniques at component scale level, due to the unacceptable computational time requirements. Therefore, the process is usually simulated by means of coupled thermo-mechanical Finite-Element (FE) analyses. Basically, the heat transfer from the arc to the molten pool is simulated using a heat source model, which prescribes a heat generation per unit volume in the molten pool region. Material deposition is taken into account by means of specific elements activation algorithms [10]. Many researchers focused on improving simulation accuracy and efficiency: J.Ding et al. [11] developed a steady state approach tailored for the simulation of large parts

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manufacturing; Bai et al. [12] proposed an infra-red imaging procedure to calibrate model input parameter; Michaleris [13] compared material deposition modelling techniques and proposed an algorithm to improve its accuracy and efficiency.

In most of literature works dealing with AM simulation, the heat source model proposed by Goldak et al. [14] is used. In this model the heat input is delivered over a moving double ellipsoid region according to a Gaussian distribution. Despite such strategy permits to correctly model the shape of the weld pool, it does not take into account the correct heat distribution between filler and base material. This is responsible for inaccuracies in part distortions estimation.

In this paper, the WAAM process is simulated using a novel definition of the heat source, based on a modified Goldak model, in order to have a more realistic heat flow distribution in the filler material. In the following sections, Goldak model is discussed highlighting its criticalities. Proposed simulation technique and heat source model are then presented. Finally the measured distortion of a test case component, manufactured by means of WAAM process, are compared with FE results obtained with the proposed and the Goldak heat source models.

Nomenclature

$a_{f,r}$	Ellipsoid x semi axis (front or rear)
b	Ellipsoid y semi axis
c	Ellipsoid z semi axis (front)
C_p^{eq}	Equivalent heat capacity
d_{el}	Bead finite elements length in feed direction
$f_{f,r}$	Ellipsoid distribution factor (front and rear)
h_l	Bead model height
h_{lat}	Latent heat of fusion
i	Welding current
l	Filler metal heat source length in feed direction
$P(T)$	Generic material property
P_{act}	Material property in active state
P_{quiet}	Material property in quiet state
$\dot{q}_v$	Goldak power density function
$\dot{q}_b$	Base material power density function
$\dot{q}_w$	Filler material power density function
q_w	Energy density transmitted to filler metal segment
q_{eq}	Equivalent power density function
$\dot{Q}_b$	Thermal power transmitted to the base material
$\dot{Q}_w$	Thermal power transmitted to the filler material
T	Temperature
T_{sol}	Solid temperature
T_{liq}	Liquid temperature
V	Welding voltage
v_f	Feed speed
V_{el}	Bead finite elements length in feed direction
$\dot{V}$	Material volume flow rate
w_l	Bead model width
η	Heat source efficiency
ρ	Material mass density
τ	Filler metal model heating time

2. Double ellipsoid heat source model

The Goldak model prescribes a Gaussian distributed heat generation per unit volume defined in a moving frame of reference, shown in Figure 1: *x* axis is oriented in the feed direction, *z* axis in the arc aiming direction and *y* is defined according to the right hand rule.

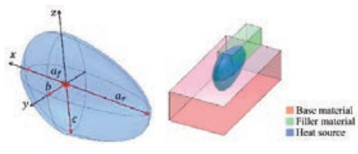

Figure 1: Goldak double ellipsoid model

Basically two different power distribution functions are defined for positive and negative x semi axes, allowing to model asymmetries in heat distribution over the molten pool. Eq. 1 shows the power density distribution functions:

$$\dot{q}_v = \frac{6\sqrt{3}\dot{Q}f_{f,r}}{\pi\sqrt{\pi}a_{f,r}bc}\exp\left[-3\left(\frac{x^2}{a_{f,r}^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}\right)\right] \quad (1)$$

Coefficients $a_{f,r}$, b and c are the semi axes of two ellipsoids centered in the origin of the frame of reference, as shown in Figure 1. The double subscript for the parameter a means that different values are used depending on x sign (a_f if positive and a_r if negative) leading to two different functions. Ellipsoid surface represent the space region where the power density falls to 5% of its peak value. Usually the value of ellipsoids semi axes is set according to molten pool dimension [15]. The terms $f_{f,r}$ are the distribution factors, having different values for the frontward and backward ellipsoids, provided that the following condition is fulfilled [14]:

$$f_f + f_r = 2 \quad (2)$$

$\dot{Q}$ is the heat input per unit time and it is computed as the product of welding current, welding voltage and arc efficiency, as described by eq. (3):

$$\dot{Q} = \eta i V \quad (3)$$

Integrating the two power density functions in spatial coordinates returns the total energy input per unit time generated by the heat source. According to Goldak this integration returns the following result [14]: