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Title

Heat accumulation prevention in Wire-Arc-Additive-Manufacturing using air jet impingement

Authors

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Keywords

Wire-Arc-Additive-Manufacturing, Jet impingement, Finite Element Method

Abstract

WAAM (Wire-Arc-Additive-Manufacturing) is an additive manufacturing process which uses arc welding to create metal components, enabling to manufacture large parts at a high deposition rate. One of the most relevant open issues of the process is the heat accumulation, caused by the large amount of heat transmitted to the workpiece which cannot be effectively transmitted to the environment. This phenomenon results in a progressive increase of the workpiece average temperature with detrimental consequences on the workpiece quality, e.g. non-homogeneous material properties, structural collapse. This paper proposes to tackle this issue by introducing a workpiece cooling system based on impinging air jets. The effectiveness of the proposed system is preliminary investigated by applying a validated numerical model of the jet impingement heat transfer to a thermal finite element model of the WAAM process. The results highlight that the jet impingement technique can be regarded as a promising approach to prevent the occurrence of heat accumulation.

1. Introduction

WAAM (Wire Arc Additive Manufacturing) is an additive manufacturing process to produce [1,2] or repair [3] large metal components at a high deposition rate. In WAAM, the high amount of energy transmitted to the workpiece causes the detrimental heat accumulation phenomenon: during metal deposition, the heat is mainly transmitted from the molten pool to the substrate by conduction, therefore as the number of layers increases the conductive heat flux decreases [4] causing an increase of both molten pool size and interpass temperature. This phenomenon has several detrimental effects, such as non-homogeneous material along the building direction [5,6], modification of the metal transfer mechanism [7], possible workpiece structural collapse [8].

The most common technique to prevent heat accumulation is the introduction of idle times to cool the workpiece down [9], with the drawback of a reduced productivity. A different approach is to increase the heat sink effect of the substrate by using water cooled fixtures [10,11]. The drawback of this approach is that the heat of the molten pool is still dissipated through conduction, not ensuring a constant cooling rate during the process. A further strategy is to increase the convective heat flux to the environment, as proposed by Sasahara et al. [12,13], who performed WAAM operations immersing the workpiece in a water-cooled tank. Despite its effectiveness, the approach is complicated to be applied on existing machine tools, which is a standpoint of WAAM technology [14].

This paper presents an alternative approach to prevent the heat accumulation: increasing the convective heat transfer using air jet impingement cooling, a consolidated technique in different manufacturing processes [15,16]. It is proposed to convey an air jet, cooled by means of a vortex

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tube [17], on the deposed surface by means of a hose attached to the deposition head, achieving the following advantages: i) local cooling effect, preventing heat accumulation ii) easy integration on existing machines. This paper assesses the effectiveness of the proposed technique by integrating a validated jet impingement model in a FE (Finite Element) thermal model of the WAAM process. A WAAM operation is simulated with and without jet impingement, comparing the calculated temperature field.

2. Jet impingement modelling

Figure 1a presents an archetype of the proposed cooling system: a coolant hose is attached to the welding torch, thus moving synchronously with it.

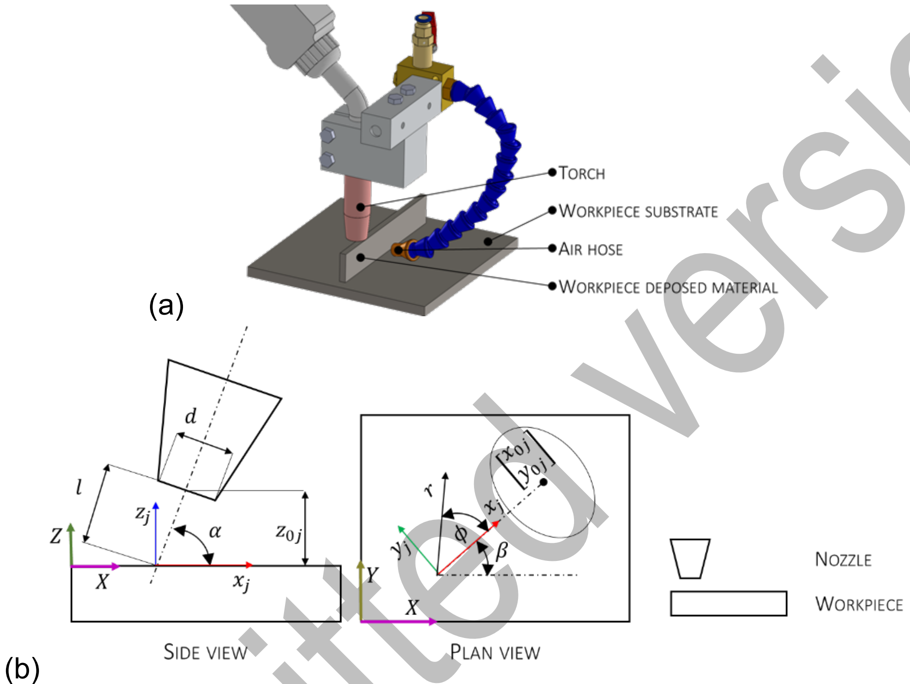

Figure 1: Archetype of the proposed cooling system (a); Geometric parameters of the jet impingement model (b).

Since this paper aims at assessing the jet impingement effectiveness by numerical simulations, a suitable convection boundary condition of the cooling mechanism is defined to be integrated in the FE model of the WAAM process. Convective heat transfer is modelled by Newton's law:

$$\dot{q} = h(T_s - T_\infty) \quad \text{Eq. 1}$$

Where $\dot{q}$ is the heat flux per unit surface, T_s is the local surface temperature, T_∞ is fluid reference temperature and h is the transfer coefficient. Both h and T_s depend on the specific heat transfer condition. In this paper, these values are calculated using semi empirical literature correlations: the Goldstein and Franchett [20] one for the heat transfer coefficient and the Hollworth and Wilson one [21] for the fluid reference temperatures. Eq. 2 summarizes the quantities involved in the correlations, while Figure 1 (b) highlights the main geometric parameters:

$$\begin{cases} Nu = Nu(Re, l/d, \alpha, r/d, \phi) \\ T_\infty = T_w = T_w(T_a, T_{0j}, r, d) \end{cases} \quad \text{Eq. 2}$$

The heat transfer coefficient is given in its dimensionless form (Nusselt number Nu) as a function of: Re, the jet outflow Reynolds number; r and ϕ, which define the position of the surface points where

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Nu is evaluated, in the coordinate system x_j, y_j, z_j, defined as shown in Figure 1b; d, the nozzle diameter; l, the distance between the nozzle and the target surface; α, the inclination of the nozzle axis with respect to the target surface normal. The second relation of Eq. 2 returns the fluid reference temperature as the adiabatic wall temperature (T_w), i.e. the local wall temperature of the impinging jet in adiabatic condition. According to the authors of [21], this enables to consider jets with non-ambient outflow temperature. T_w is given as a function of: r; d; the ambient temperature T_a; the jet outflow total temperature T_{0j}.
The presented correlations were implemented in the commercial FE code LS-DYNA (the solver used for WAAM simulation), as a user defined boundary convection (*BOUNDARY_CONVECTION [22]). The jet motion was considered by introducing time dependency of the x_j, y_j, z_j coordinates according to Eq. 3:

$$\begin{cases} x_j = X - \{x_{0j}(t) + |Z - z_{0j}(t)|\, cotan(\alpha)\, cos(\beta)\} \\ y_j = Y - \{x_{0j}(t) + |Z - z_{0j}(t)|\, cotan(\alpha)\, sin(\beta)\} \\ z_j = Z - z_{0j}(t) \end{cases} \quad \text{Eq. 3}$$

Where X, Y and Z are the global coordinates; $x_{0j}(t)$, $y_{0j}(t)$, $z_{0j}(t)$ are the coordinates of the nozzle center (Figure 1b); α and β are defined in Figure 1b.
The presented model was validated by cooling in jet impingement conditions using an Exair vortex tube a 250x250x8mm square steel (S235JR) plate for 900 seconds; the transient temperature field of the target surface was measured using a Flir EB-40 IR (Infrared) camera, as shown in Figure 2a. FE simulation of the plate cooling was performed using the presented jet impingement model (as Figure 2b) and the IR and FE temperature profiles along the comparison line were analyzed. The results for the final time frame are reported in Figure 2c.

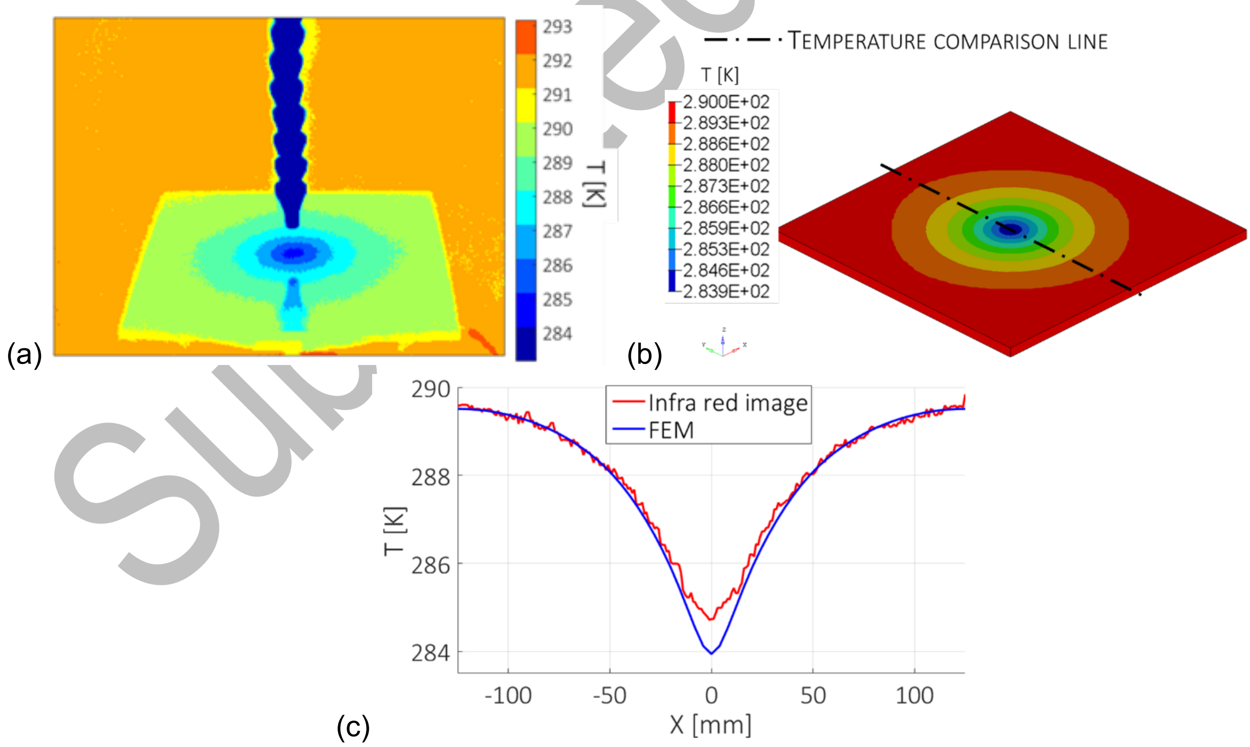

Figure 2: IR image taken during the jet impingement model validation (a); FE model used in the validation (b); comparison of numerical and IR temperature profiles (900 s) (c).

Table 1 summarizes the test conditions used in the validation experiment:

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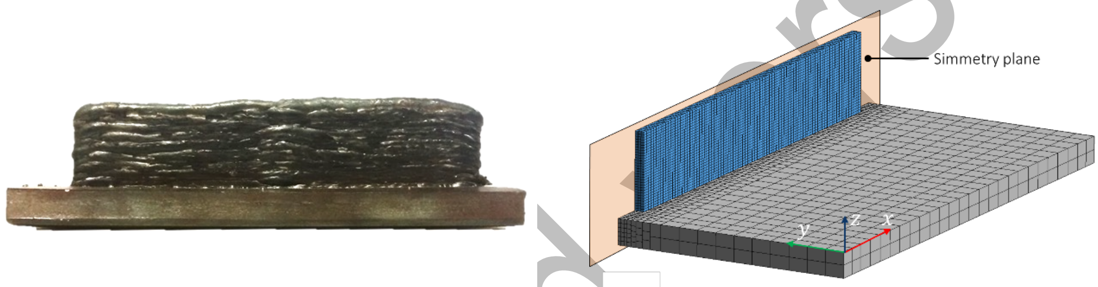
Table 1: Test conditions used in the validation experiment

Re	T_{0j}	T_a	l/d	d	α
31200	265.3 K	294.5 K	4	6 mm	90°

Both Re and T_{0j} were preliminary measured using a pitot tube and a thermocouple respectively. The ambient temperature was monitored during the experiment using a k-type thermocouple.
Figure 2c highlights that the presented jet impingement model predicts the temperature profile with a maximum error of about 1 K. This jet impingement model has, hence, been considered accurate enough to be included in the WAAM simulation with the aim of assessing jet impingement effect.

3. Numerical assessment of jet impingement effectiveness in WAAM

The effectiveness of the jet impingement cooling in preventing the heat accumulation was tested by simulating the manufacturing of a 15 layers wall, i.e. a series of vertically stacked straight layers. Figure 3a shows an example of WAAM wall.



(a) (b)

Figure 3: Example of a wall produced by WAAM process (a); FE element model used for the numerical test (b).

Wall manufacturing was simulated both in standard process conditions and applying the jet impingement cooling. The FE model used is shown in Figure 3b: 15 layers 6 mm wide and 1.6 mm thick, made of ER70S-6 steel, are deposed on a 150x150x8 mm plate, made of S235JR structural steel. The symmetry of the model was exploited modelling only half of it. The effect of jet impingement was evaluated on the exterior surface of the wall, considering a moving nozzle. The jet is activated at the beginning of the 5th layer deposition, with nozzle axis positioned at $z = 0$, since in the starting layers there is no need of additional cooling. The conditions reported in Table 1 were used in the simulation. Due to the symmetry condition, the simulation considered the effect of two symmetric impinging jet.
The WAAM process was simulated using the techniques (heat source model, material model, elements activation strategy) presented and validated in [18,19]. The WAAM operation was simulated using the following parameters [19]: heat input 1480 W, travelling speed 300 mm/min. Both free convection and radiation to environment were included as boundary conditions (room temperature 294.5 K). Convective coefficients and emissivity were set according to [19], jet impingement effect was included by replacing the free convection on the wall exterior surface with the impingement boundary condition (after 5th layer).
Figure 4 presents the results of the numerical comparison: Figure 4a compares the temperature distributions of the two models in terms of contour evaluated at a simulation time of 140 s and 350 s i.e. during the deposition 4th and 10th layer; Figure 4b compares the two models in terms of temperatures time histories of two nodes located at different distances from the substrate.

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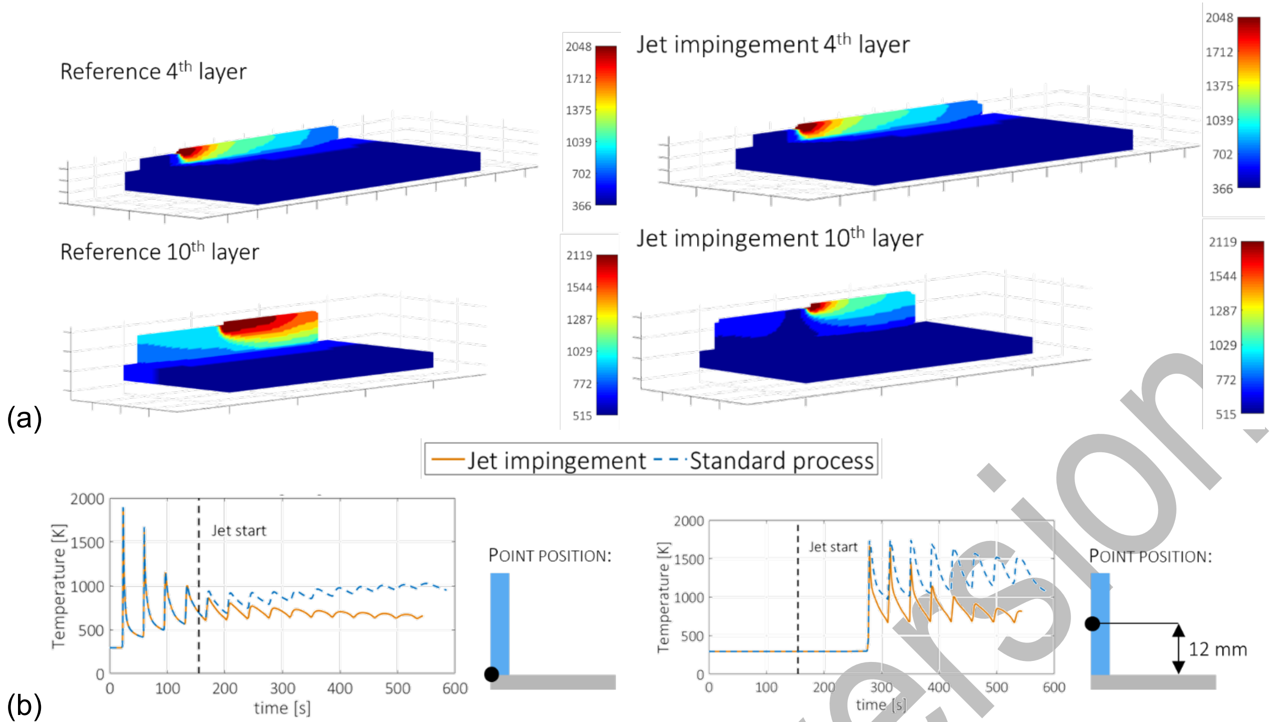

Figure 4: Comparison of temperature field (K) of reference and jet impingement simulations: contour plot during the deposition of 4th and 10th layers (a); temperature time histories of two nodes at different distances from the base plate.

In Figure 4a highlights that the reference configuration results in a significant increase of the molten pool size (elements above 1673 K) from the 4th to the 10th layer condition, while the simulation including jet impingement results in a constant molten pool size. At the 10th layer, the application of jet impingement allows to reduce the volume of the elements above the solidus temperature of about 87%. The time histories presented in Figure 4b highlights a similar trend. Both simulations show a cyclic temperature pattern, related to the passage of the welding torch. In the standard configuration, the minimum temperature per each cycle increases progressively during the simulation due to the heat accumulation. On the opposite, using jet impingement, the minimum temperature value is almost constant.

In summary, simulations highlight that the jet impingement cooling could be an effective technique to prevent heat accumulation.

4. Conclusions

This paper proposes to apply the jet impingement cooling technique to prevent the heat accumulation phenomenon during WAAM operations. The goal is to increase the convective heat transfer between the workpiece and the environment using impinging air jets. The effectiveness of the proposed cooling system is assessed using a numerical procedure: a numerical model of the jet impingement cooling is developed, validated and integrated in a FE simulation of the WAAM process. The manufacturing operation of a test case is simulated both with and without jet impingement. The comparison of the two simulations results highlights that jet impingement: i) prevents an excessive increase of the molten pool size ii) keeps the average temperature per cycle almost constant during the whole process. The presented results, hence, highlight that jet impingement cooling could be an effective approach to prevent heat accumulation, which should be further investigated in more complex configurations and using an experimental implementation of the proposed cooling system.

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