Welding in the World (2018) 62:249–257
https://doi.org/10.1007/s40194-017-0533-y

RESEARCH PAPER

Induction heating in a wire additive manufacturing approach

Jean-Yves Hascoët[1] · Jérôme Parrot[1] · Pascal Mognol[2] · Etienne Willmann[3]

Received: 20 June 2017 / Accepted: 23 November 2017 / Published online: 6 December 2017

Abstract
In additive manufacturing (AM), three-dimensional objects are built layer by layer by joining each layer to the previous one. For metal parts, there are three main methods: powder bed, powder deposition, and wire deposition. This latter makes optimal use of the material in contrast to other processes, which makes it very interesting industrially. Indeed, with powder, the ratio between powder used and powder melted is not equal to one, in opposition of the use of wire. In order to ensure the proper melting of the metal, several methods already exist, including the use of lasers or electric arc. This paper presents a novel approach of wire deposition using inductive energy for additive manufacturing applications. This approach does not make use of a storage of the molten material. Instead, the tip of a metal wire is melted by an induction heating system. Inductive energy is also used to obtain an optimal thermal gradient between the tip of the wire and the substrate or previous layer. A numerical model has been developed and validated experimentally. It shows that the induction heating system is able to melt the tip of the wire and heat the substrate to create suitable deposition.

Keywords Wire · Manufacturing · Simulating · Induction · Heating · Process parameters

1 Introduction

There exists a variety of techniques, in additive manufacturing (AM), that build three-dimensional objects layer by layer by joining each layer to the previous one. It is also known as solid freeform fabrication (SFF), and it has evolved from early rapid prototyping manufacturing techniques. AM techniques are becoming very popular [1], because they are flexible, easily automated, and capable of producing functional and complex objects of different materials, polymers being the most common ones. The use of AM for directly manufacturing metallic parts is very interesting, especially for objects with complex shapes and small production volumes. For these reasons, it is principally used in the medical, aeronautical [2], and die manufacturing industries [3].

AM techniques for producing metallic parts can be separated into two groups [4, 5]: (a) those which—in a first step—metal powder is put into a container before melting it locally to create the first layer of the part, and—in a second step—again covers powder and locally melting for the second layer, until the part is finished. And (b) those which directly deposit the metal corresponding to this cross-section (Direct Electron Deposition, DED) and, if necessary, use auxiliary support structures. Selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM) are some examples of techniques included in the first group [6]. Functional graded materials (FGM) are also studied. This technique can couple two—or more—materials during the deposition process to create better mechanical characteristics and/or bio-compatibility of the part [7, 8].

This article is part of the collection Welding, Additive Manufacturing and Associated NDT

✉ Jean-Yves Hascoët
jean-yves.hascoet@ec-nantes.fr

Jérôme Parrot
jerome.parrot@ec-nantes.fr

Pascal Mognol
pascal.mognol@ens-rennes.fr

Etienne Willmann
etienne.willmann@eder.fr

1 Ecole Centrale Nantes, Institut de Recherche en Génie Civil et Mécanique (Gem) – UMR 6183, CNRS, 1 Rue de la Noë, 44321 Nantes, France

2 Institut de Recherche en Génie Civil et Mécanique (Gem), École Normale Supérieure de Rennes, Campus de Ker Lann, 35170 Bruz, France

3 EDER, Pa de Monteno, 56190 Trinité Surzur, France

There are several technologies included in the second group which differ in the way the metal is fed and melted. A sub-classification can be made: those using metal powder—laser metal deposition (LMD)—and those using wire—wire additive manufacturing (WAM). Laser systems are the most used among several commercial solutions such as direct metal deposition (DMD), laser-engineered net shaping (LENS), and direct light fabrication (DLF). These techniques use a specific deposition head that provides the metallic powder, a shielding gas and a laser beam to melt the metal. The high-energy laser is located at the centre of the deposition head. The laser is focused on a point of the substrate to create a molten pool. The metallic powder is carried by the shielding gas stream through the feeding nozzle and is delivered to the molten pool. In this technique, the metal powder melts and then solidifies as the deposition head moves away from that point. These systems have been able to produce fully dense metallurgical parts from materials such as steels, alloy steels, nickel super alloys, or titanium alloys. Some variation of this setup combines a subtractive process (CNC process) and the additive process [9, 10].

Several attempts have been made to adapt arc-welding systems for AM. These systems use an electric arc as the energy source to produce the metallurgical bond between the filler metal—a wire—and the substrate [11, 12]. The electric arc is established between an electrode and the substrate inside a shielding gas. Metal deposition has been achieved using gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) torches. In GMAW-AM process, the added material is a metallic wire which is also used as a consumable electrode. It melts the wire tip and forms the pool on the substrate. Variations of the wire tip are using short circuit energy, instead of an arc, to produce metal melting without splashing. In GTAM-AM process, the arc feeling and the metal feeding are controlled independently. The arc is formed between the substrate and a non-consumable tungsten electrode inside the shielding gas. The wire tip is melted as it is introduced in the pool by an independent wire feeding system. PAW-AM systems are similar to GTAW-AM, but they obtain a higher energy concentration by using a constricted plasma arc to induce melting. This allows one to work at a higher deposition speed or with higher melting temperature alloys [13].

This paper presents a novel technique to melt the wire tip of alloys stainless steels by using an induction heating system. The essential difference with respect to those described above resides in the energy source. Some studies have been done with induction heating in a drop production system in AM [14]. In this technique, the tip of metal wire is melted by an induction heating system when it is introduced in a nozzle, where the metal emerges at the bottom by a continuous drop formation. The technique proposed here does not use any nozzle or crucible, by opposition to the work made by [15], and the metal is melting and linked to the substrate only by the action of the inductor system. The new view for melting metal in additive manufacturing that is proposed here forces us to create a numerical model of this technique to ensure the validation and the potential of this new approach for additive manufacturing. The numerical model has been created using the Multiphysics Software COMSOL, with AC/DC module which adds possibilities for magnetic fields studies. This method of deposition offers an important advantage over the previous ones: it is possible to be more energetically efficient, because it could be adjusted to consume only the energy necessary to melt the wire tip and preheating the substrate to ensure a proper bond at any times. In addition, the device makes use of simpler tools, because one does not keep a reservoir of molten material during the process, which could induce some splashing.

2 The proposed approach

2.1 System description

The proposed technique is essentially composed of an induction heating power supply with a maximum power of 6 kW with a dedicated water-cooling system, a 3-axis machine to assure the displacement of the deposition head and a wire feeding system for the metal deposition (Fig. 1a). At the tip of the deposition head, the inductor coil is used to melt the wire and the substrate at the same time. The open-loop geometry serves to further the heating of the substrate, thanks to the small distance between the two of them, with a possibility for the melted material created by the coil to be evacuated (Fig. 1b). A gas shield—Argon—is also present to prevent the oxidation of the melted metal during the deposition.

The procedure for producing the layer consists of the following steps: (1) the coil is used to ensure preheating of the substrate in order to start the deposition on a substrate with a temperature close to the melting. (2) When the temperature of the substrate is reached, the wire is introduced in the coil to be melted with the substrate. (3) The wire feeding speed (WFs) and travel speed (Ts) are set and the deposition can start. During the creation of the layer, a stationary operating point is established. This stage is the subject of this paper.

The main problem in additive manufacturing is to assure a mechanical bond between the new layer and the previous one. In order to assure this association of material, a microscopic bond between the substrate and the layer deposited is essential. To create a bond without any mechanical issues—porosity, cracks for example—the deposited material and the pre-deposited one should have a similar microstructure. Indeed, if the microstructure evolution is too different, there is a high

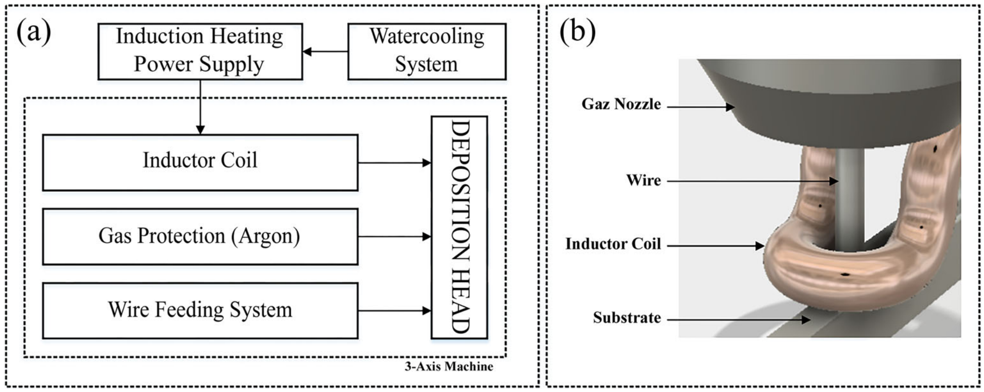

Fig. 1 Global description (**a**) and details (**b**) of the deposition head

risk of cracks at the interface, which will cause a loss of mechanical behaviours. The first step is to make this bond correctly.

The approach used in this study is to have the interface between each layer at the melting temperature during the deposition process. With this high temperature, each layer has the same metallurgical phase, and at the microscopic scale, the bond is made, without difficulty. However, during the deposition, the thermal diffusion between the first deposition—on a substrate—and after—on a previous layer—could be different, which requires an adaptation of the inductive power in order to guarantee the deposition temperature.

The purpose of the simulation and the experiments is to validate the mechanical association between layers. A numerical model is created in a first step to determinate the geometry and characteristics needed by the process to ensure a good deposition, and link between each layer and the experimental validation is made in order to adjust the numerical model to the real properties of the approach and to endorse the model and the approach (Fig. 2).

2.2 Numerical model

The objective of the model is to show the possibility of deposition using induction heating. The thermal aspect of the deposition is the main objective. All the analysis is made with stainless steel 316 L as material (wire or substrate) with thermal emissivity of 0.8 and a melting point of 1450 °C. The thermal losses—radiation, convection, and conduction—in the substrate and the wire are included in the numerical model which used a two-step algorithm (Fig. 3).

The results on the temperature field (T(x,y,z)) shown are in steady state. They are obtained by following a few steps: (1) a frequency study is made at the beginning to model the electromagnetic field (HPV(x,y,z)) created by the circulation of current in the coil of the inductor system. This magnetic field is also used—in the same step—to obtain the current density in the different components—wire and substrate (Fig. 4a). It is this density of current which is used for the second step. (2) A stationary thermal study is made using the first step's results (Fig. 4b). The current density obtained is reused to be assimilated as a heating source in the study. A movement of the substrate and the wire is made virtually—to simulate the evolution of the deposition rate—by associated an extremity of the wire—respectively of the substrate—with an ambient temperature and add a movement of this temperature field at the speed of the wire feeding—respectively at the travel speed. So, the results shown are in Eulerian point of view.

Three parameters are temperature-dependent: the electrical conductivity, $\gamma(T)$; the thermal conductivity, $\lambda(T)$; and the specific density, $\rho_c(T)$.

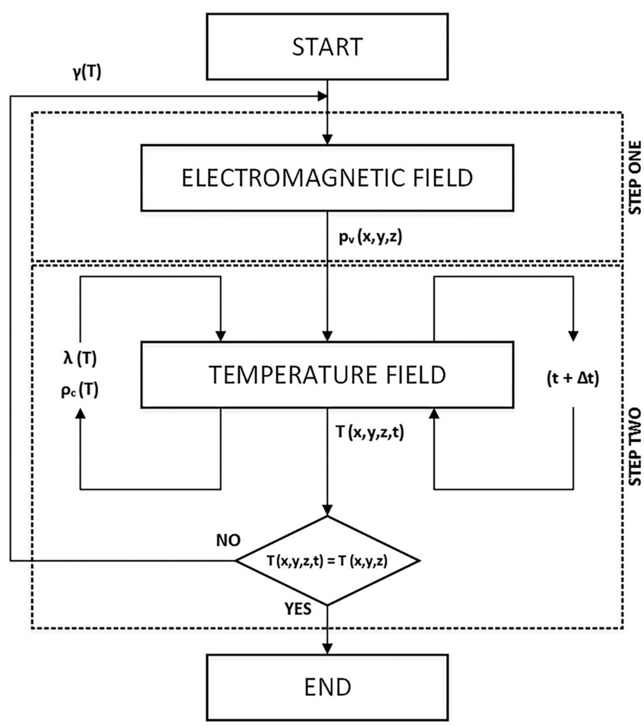

Fig. 2 Validation steps proposed

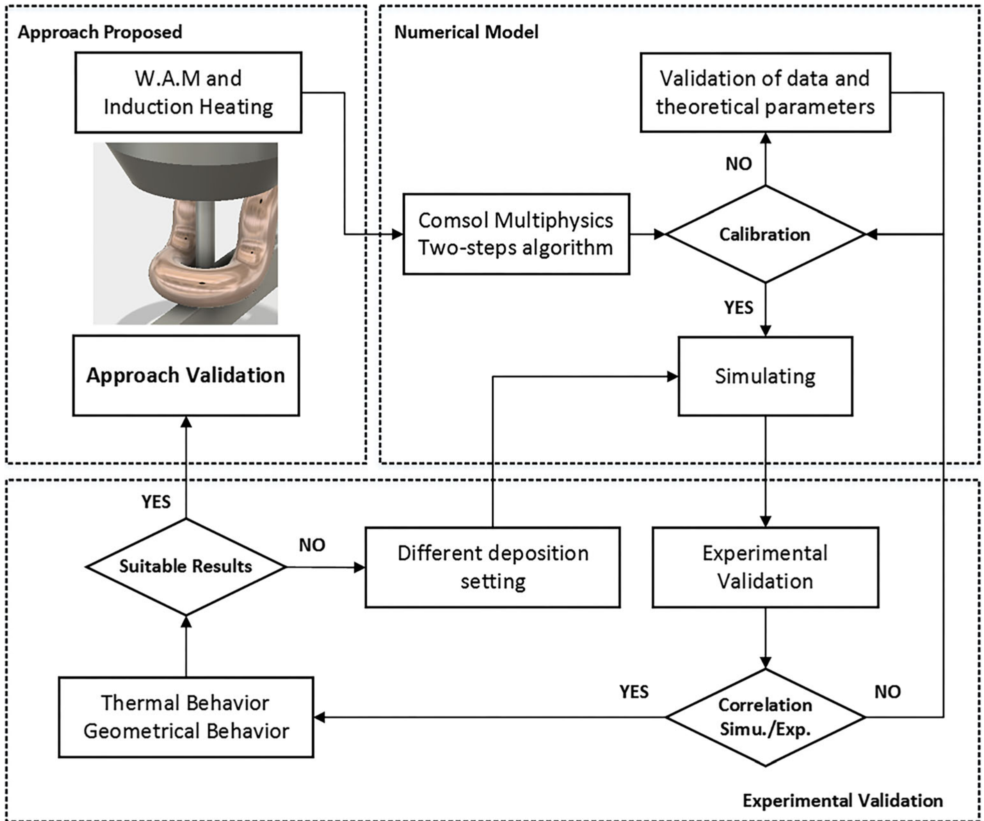

Fig. 3 Algorithm for calculation of coupled electromagnetic and temperature field

3 Results

3.1 Current density

At the end of the first step of the simulation's calculation—frequency analysis—the current density is obtained. This gives knowledge which surfaces—of the wire and substrate—are the most affected by the magnetic field, which allows for an optimisation of the coil's geometry to have a better distribution of the magnetic field and therefore, of the current density. The results here are shown with a coil geometry that is optimised for a coil with a circular section, and which can be fabricated for experimental validation (Fig. 5a). The focus is on the current density J (A/m^2) because of the link between the temperature field w (W/m^3), in the substrate or/and in the layer, as Joule's law demonstrated [16]:

$$w = \rho J^2 \quad (1)$$

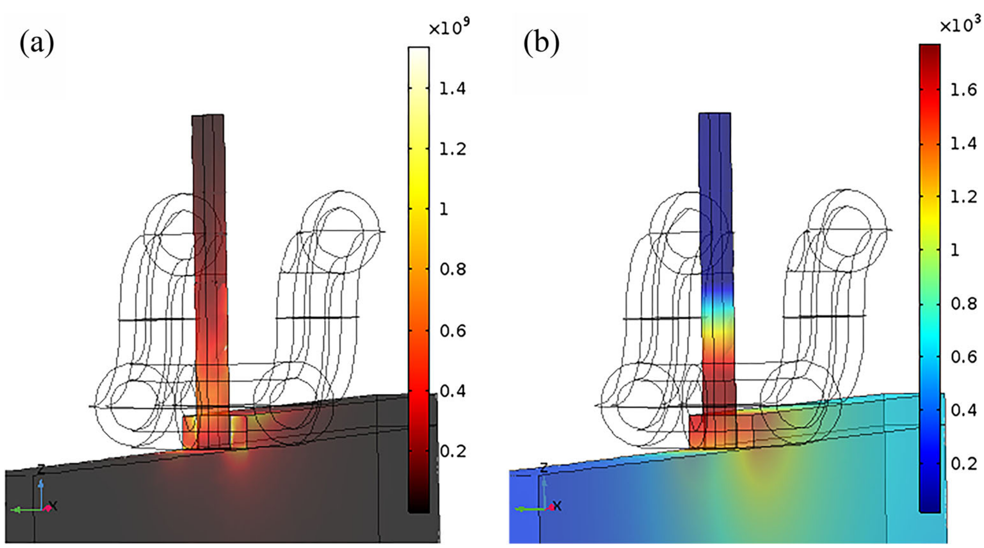

Fig. 4 **a** Distribution of current density (A/m^2). **b** Thermal distribution (°C) during the deposition

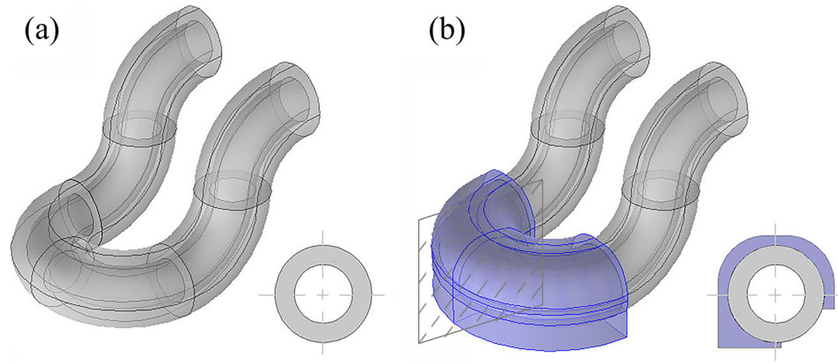

Fig. 5 Coil geometry without (**a**) and with (**b**) magnetic shield

with ρ the electrical resistivity of the material (Ω.m). The temperature field is highly dependent on the density of current. As a consequence, the higher temperature field will be located where the current density is at its maximum.

The coil geometry impacts the density of current but it is not the only parameter to take into account—in the magnetic field. The distance between the coil and the part—wire or substrate—should be very small to obtain a better current density efficiency (Fig. 6) and as a consequence a better heating efficiency (Fig. 7). The higher this distance, the more magnetic losses are present. The augmentation of these losses reduces exponentially the current density in the part and by implication, the maximal temperature reachable:

$$T = T_0 e^{-\beta . z} \quad (2)$$

with T_0 the maximal temperature for a coil distance with the substrate and z close to 0 mm.

By definition, the magnetic field is all around the coil's open loop. There is also a magnetic loss in regions further away from the wire and the substrate. To minimise this loss and to have as a consequence, a better efficiency, a magnetic shield is added on the coil geometry (Fig. 5b). The thermal evolution increases by 50% when a magnetic shield is added (Fig. 8). With this system, it becomes possible to move the coil slightly away from the substrate or/and to increase the speed of the deposition, for a given power.

In conclusion, the increase of the magnetic heating in the part is directly coupled to the current density. At a fixed inductive power, the increase of coil inductor distance leads to a considerable reduction in the density of currents within the part. Thereby, to increase the heating, there are at least three possibilities: reducing the coil inductor distance with the part, adding a magnetic shield to the coil without changing the coil distance, or a coupling of these two solutions: reducing the distance and adding a magnetic field to the coil. These optimisations allow for an energetic gain in the part, which will be allowed to increase the deposition parameters (Ts and Wfs) without any changes to the coil geometry or/and inductive power.

3.2 Interface's thermal behaviour

The AM main objective is to deposit a material layer by layer. To ensure that a link should exist between the layer, this link is made by the thermal behaviour at the layers' interface. Depending on the inductive power, coil distance, and magnetic shield, this thermal behaviour changes—for fixed Ts and Wfs. To consider two layers with a definitive bond, it is necessary to have a similar thermal history. With adaptation of the

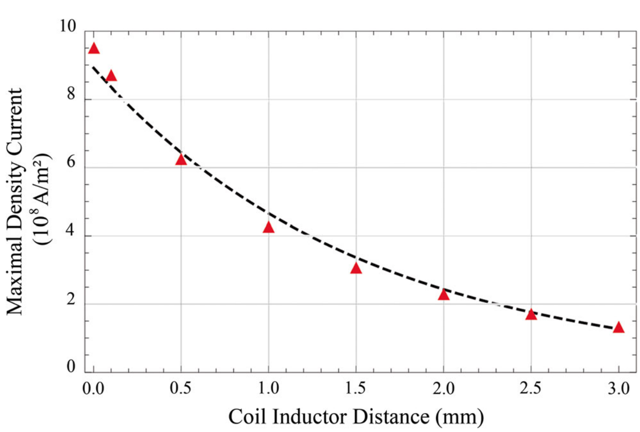

Fig. 6 Current density evolution of the substrate in function of the coil distance for 4.5 kW of power

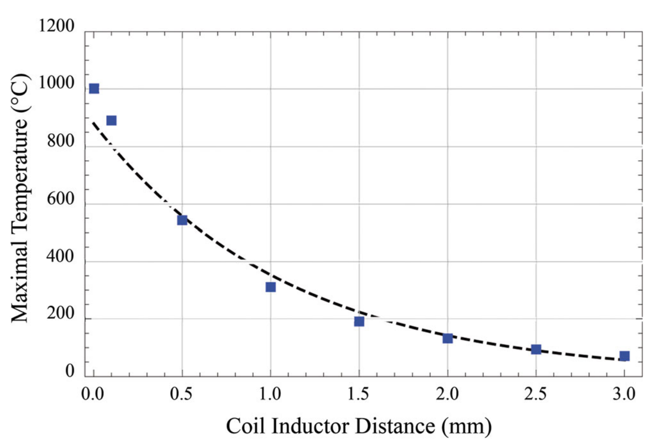

Fig. 7 Thermal evolution of the substrate in function of the coil distance for 4.5 kW of power

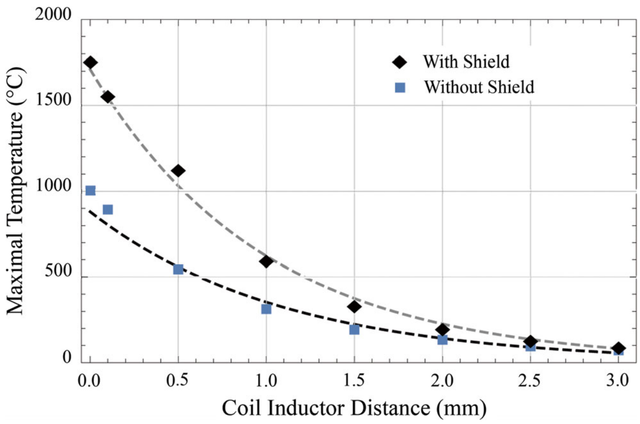

Fig. 8 Thermal evolution of the substrate in function of the coil distance with and without the magnetic shield

coil distance, inductive power, and magnetic field, we are able to concentrate the heat at the lower deposition position—close to the interface—and create a common thermal history between the substrate and the melting metal.

This common thermal history needs to be local. If the surface with a temperature close to the melting point is bigger than that of the layer, there is a risk of layer collapse. This would modify the magnetic behaviour of the field with the layer and substrate due to the change of geometry and as a consequence the heat. The objective of the simulation is to determine suitable deposition parameters. The second step after the simulation is to carry out experimental validation. With this intention, the inductive power is fixed at 4.5 kW, the coil optimisation—magnetic shield—is not used and the coil is positioned at 0.5 mm from the substrate.

At the deposition interface, the principal parameter influencing the temperature is the travel speed—with the inductive power fixed. However, the mechanical link, and the common microstructure between the deposited metal and the substrate are only possible if—close to the wire's tip—the temperature is a little lower than the melting point. As a reminder, these studies are made for stainless steel deposition, which has a melting point close to 1450 °C.

For such a thermal condition, a Ts to more than 120 mm/min (Fig. 9c, f, i) is not suitable. Indeed, at this speed, the interface temperature is close to 1300 °C, which is too low, in comparison with the melting point. Conversely, a minimum Ts of 60 mm/min (Fig. 9a, d, g) leads to a temperature that is extremely close to the melting point of the material. With a

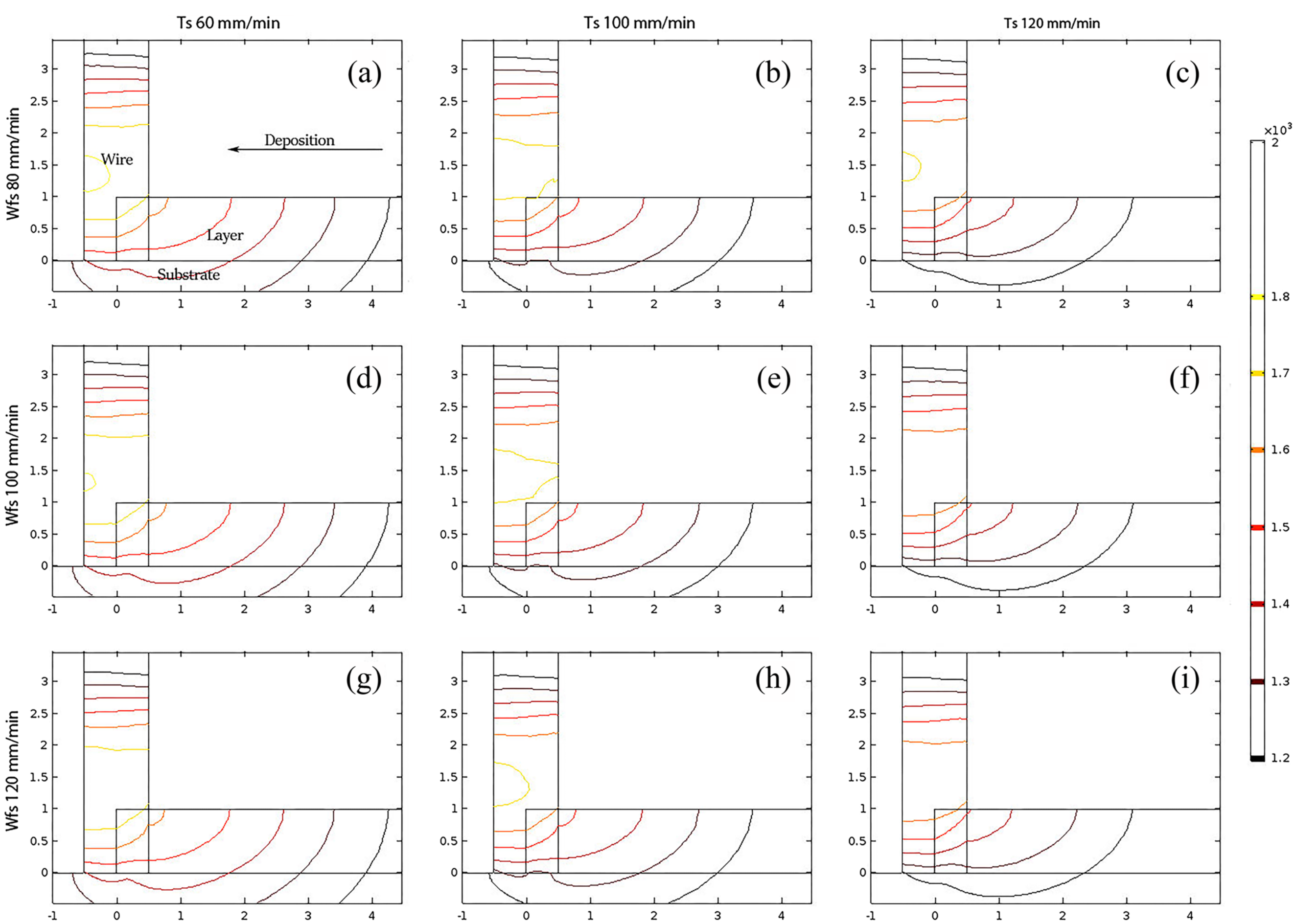

Fig. 9 Thermal iso-values (°C) during the deposition for different travel speed and wire feeding speed for 4.5 kW of inductive power

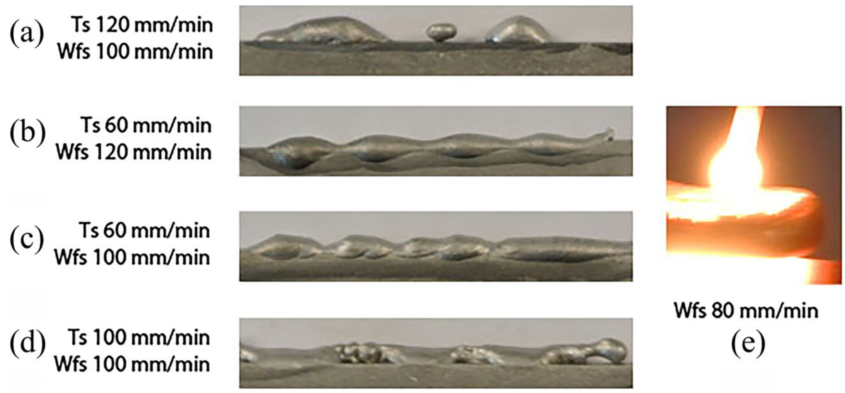

Fig. 10 Experimental results for different Ts and Wfs

temperature too close to the melting point, the risk of collapse of the substrate is higher. Finally, an intermediate Ts (around 100 mm/min) allows an interface temperature between 1300 and 1400 °C, which is lower than the melting point and thus limits the possible collapse of the substrate (Fig. 9b, e, h).

In terms of Wfs, the simulation results show a very small movement of the thermal iso-values in the direction of the wire tip when the speed decreases. Otherwise, an increase in Wfs reduces the interface temperature and increases the risk of a non-regular link/or no link between the deposited metal and the substrate.

3.3 Experimental validation

In order to validate the numerical model, an experimental validation was made, with the same inductive power and coil position. As predicted, in the numerical simulation, if the travel speed is around 120 mm/min, the heating of the substrate is insufficient to create a permanent link between the melted wire and the substrate. The melting metal is deposited in a discontinuous manner (Fig. 10a). However, if the travel speed is close to 60 mm/min, the heat in the substrate is too high and the deposition is not viable. With a Wfs at 120 mm/min, the substrate collapses under the effect of an important energy added by the wire melted (Fig. 10b). Indeed, with a low travel speed, the substrate temperature is close to the melting point, and the addition of the melted wire creates a more heat. Such heating causes an over-penetration of the layer into the substrate. For the same Ts and a Wfs at 100 mm/min, the deposition is not constant (Fig. 10c). This results in an excessive heat supply in the wire which induces too fast a melting of the wire for this travel speed, which may lead to the creation of deposit pads. At intermediate travel speed, i.e., 100 mm/min, the deposition is not completely linked to the substrate, which indicates a lack of heating during the deposition (Fig. 10d). But this travel speed does not lead to deposit pads, which indicates that the adequate travel speed is close to 100 mm/min.

Concerning the wire feeding speed, the experimental results show inability to melt the wire if Wfs is higher than 120 mm/min, for a travel speed of at least 100 mm/min. Conversely, a Wfs lower than 90 mm/min creates too much heat in the wire and causes inability to deposit the melting wire (Fig. 10e). The melting metal stays on top of the coil inductor under the effects of Lorenz's forces.

These experimental results, together with the simulation, confirm the necessity to have a temperature at the layer—substrate interface close to 1350 °C, and a maximal temperature not exceeding 1800 °C throughout the wire—in order to limit the influence of the Lorentz forces and to ensure the proper melting of the wire.

The result shown in Fig. 11 confirms the link between the layer and the substrate. For this result, the Ts is fixed at 90 mm/min and the Wfs is set at 110 mm/min. Some aspects are notable: the layer geometry is very regular and homogeneous. These geometrical aspects could represent a positive

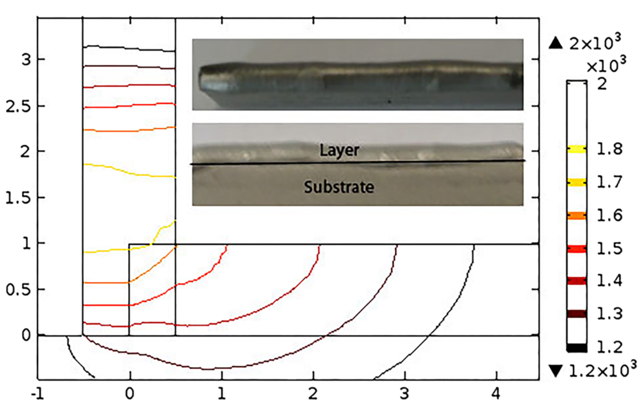

Fig. 11 Thermal iso-values (°C) and corresponding result at Ts 90 mm/min, Wfs 110 mm/min, 4.5 kW of inductive power

Fig. 12 Multi-layer deposition (3 layers)

effect of the magnetic field on the melting material before its natural cooling. The numerical model (Fig. 11) corresponding to the experimental results allowed us to gain knowledge of the thermal characteristics—for this simulation—corresponding to process parameters that lead to a good deposition. For a change of power induction, travel speed, or wire feeding speed—for example—a thermal evolution close to the results introduced here needs to be found.

The numerical model is developed at first for one layer deposition, but AM is a creation of complex parts, which means there is more than one layer. Multiplayer deposition had been made (Fig. 12) and shown interesting results in terms of geometrical aspect.

However, during the experimentation, some aspects are not taken into account. For example, the magnetic field behaviour between the simulation and the experimentation could differ around the wire (affected by the flowing gas). Also, the geometry of the coil could be slightly different between the experiments and the numerical model. This numerical model of the studied process is a first approach, and it will need to be further developed in order to gain a better accuracy on the real thermal behaviour during the deposition process. For example, the numerical model could include phase changes of the material and use a coil geometry closer to the real one and include multi-layer deposition aspects.

One principal difficulty with this approach is the magnetic behaviour of the substrate and the wire during the deposition. When the metal reaches the melting point, the microstructure is changing depending of the initial composition with—principally—a ferrite creation, when iron base material is used. This change could make a non-magnetic metal magnetic, and by consequence change its magnetic behaviour. A different behaviour will make the heating process changing depending of the ferrite percent create after the first deposition. In order to limit this effect, an austenite material could be used. This metal does not have ferrite creation after reach the melting point according to Schaeffler diagram [17].

4 Conclusion

In this paper, a novel technique to melt the metal is proposed—via simulations and with a first experimental validation—using an inductive power source. In this technique, the wire is melted by the magnetic field created by the inductive coil. To induce the melting, a first optimisation on the coil has been made. For the creation of parts using this technique, a definitive link between the melted wire and the substrate must exist. This bond is also made by induction heating. The magnetic field—which melts the wire—is also used to heat the substrate on its surface to create a common thermal history between the melting metal (wire) and the substrate. This common thermal history refers to a melting point. When this melting point is reached, the bond between layers is created. The proposed technique is easily adaptable depending on the material used, by adapting the power induction and potentially the coil size. However, this technique makes it difficult to deposit layers side by side due to the coil's geometry.

The present paper deals with magnetic fields created by an inductive source in a wire additive manufacturing context. The manufacturing apparatus is already being designed, and the first experimental tests give interesting results for this novel technique.

Acknowledgements Support from an industrial collaborative project with Eder company.

References

1. Warton J, Dwivedi R, Kovacevic R (2014) 'Additive manufacturing of metallic alloys' *Robot*. Fabr Archit Art Des 2014:147–161
2. R. Liu, Z. Wang, T. Sparks, F. Liou, and J. Newkirk (2017) '13 – Aerospace applications of laser additive manufacturing,' in *Laser* Additive Manufacturing pp. 351–371
3. Choi J, Chang Y (2005) Characteristics of laser aided direct metal/material deposition process for tool steel. Int J Mach Tools Manuf 45(4–5):597–607. https://doi.org/10.1016/j.ijmachtools.2004.08.014
4. I. Gibson, D. W. Rosen, and B. Stucker (2010) Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. Springer US. DOI: https://doi.org/10.1007/978-1-4419-1120-9
5. Gu DD, Meiners W, Wissenbach K, Poprawe R (2012) Laser additive manufacturing of metallic components: materials, processes and mechanisms. Int Mater Rev 57(3):133–164. https://doi.org/10.1179/1743280411Y.0000000014
6. Ruan J, Sparks TE, Fan Z, Stroble JK, Panackal A, Liou F (2006) A review of layer based manufacturing processes for metals. Solid Free Fabr Symp:233–245
7. Muller P, Mognol P, Hascoet J-Y (2013) Modeling and control of a direct laser powder deposition process for Functionally Graded Materials (FGM) parts manufacturing. J Mater Process Technol 213(5):685–692. https://doi.org/10.1016/j.jmatprotec.2012.11.020
8. Kerbrat O, Mognol P, Hascoët JY (2011) A new DFM approach to combine machining and additive manufacturing. Comput Ind 62(7):684–692. https://doi.org/10.1016/j.compind.2011.04.003
9. Rivette M, Hascoët J-Y, Mognol P (2007) A graph-based methodology for hybrid rapid design. Proc Inst Mech Eng Part B J Eng Manuf 221(4):685–697. https://doi.org/10.1243/09544054JEM666
10. J. Kerninon, P. Mognol, J.-Y. Hascoet, and C. Legonidec (2008) 'Effect of path strategies on metallic parts manufactured by additive process,' Solid Free Fabr Symp, pp. 352–361
11. P. Almeida and S. Williams (2010) Innovative process model of Ti – 6Al – 4V additive layer manufacturing using cold metal transfer (CMT). Texas Austin, Austin, TX, no. pp. 25–36
12. Clark D, Bache MR, Whittaker MT (2008) Shaped metal deposition of a nickel alloy for aero engine applications. J Mater Process Technol 203(1–3):439–448. https://doi.org/10.1016/j.jmatprotec.2007.10.051
13. Martina F, Mehnen J, Williams SW, Colegrove P, Wang F (2012) Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti –6Al – 4V. J Mater Process Technol 212(6):1377–1386. https://doi.org/10.1016/j.jmatprotec.2012.02.002

14. Vega EJ, Cabezas MG, Muñoz-Sánchez BN, Montanero JM, Gañán-Calvo AM (Oct. 2013) A novel technique to produce metallic microdrops for additive manufacturing. Int J Adv Manuf Technol 70(5–8):1395–1402
15. Du J, Wei Z, Wang X, Fang X, Zhao G (2016) A novel high-efficiency methodology for metal additive manufacturing. Appl Phys A Mater Sci Process 122(11):1–10
16. Rudnev V, Loveless D, Cook RL, Black M (2003) Handbook of Induction Heating. Marcel Dekker, New York, p 796
17. Metal Handbook (1993) Vol. 6, 10 edn, 4th printing. ASM International, Materials Park