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Directed Energy Deposition of stainless steel wire with laser beam: evaluation of geometry and affection depth

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Abstract

This paper is aimed at investigating the process of Directed Energy Deposition of steel wire to the purpose of maintenance and repair: this technology is receiving increasing interest in the frame of Additive Manufacturing and has been investigated for different metals and different substrates. An experimental plan has been designed here to investigate the dependence of the geometry on the governing factors in single-track deposition and quantify the depth of the affection in the substrate in terms of geometrical dilution and variation of the micro-hardness.

Keywords: Directed energy deposition; Additive manufacturing; laser.

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1. Introduction

Many industrial fields are increasingly considering Additive Manufacturing (AM), since many advantages are offered [1], including the customization of the part, its topological optimization and a reduction of waste, in comparison to conventional technologies. Namely, it has been widely reported that powder-bed techniques, such as Selective Laser Melting [2, 3] or Electron Beam Melting [3], allow to manufacture complex components at high degree of accuracy. Nevertheless, both are not suitable to the purpose of maintenance and repairing.

To address this application, the process of Directed Energy Deposition (DED) of metal can be considered [4, 5]: a melting pool is formed over a surface using an energy source such as laser, electron beam, plasma or arc gun [6, 7]; then, powder or wire are delivered to create a deposited metal. Namely, higher accuracy is benefited in case of powder; indeed, this is process is among the most common in the literature related to AM [6, 8, 9]. Nevertheless, a considerable amount of powder is lost if not catched by the melting pool, due to the contamination by the surrounding area. With this respect, cleaner working environment, reduction of waste and higher process stability are achieved in case of wire, although precision and surface quality are severely affected, mainly because the coaxial addition of wire and energy source is challenging; therefore, side feeding must be arranged in general. A remarkable attempt has been made in the literature to combine the advantages of wire and coaxial powder feeding [10], although a proper set-up of the system is thought to be complex and expensive.

As regarding the energy source in wire feeding, electron or laser beams allow the best accuracy, thanks to tight focusing; in particular, since the laser can be used at atmospheric pressure, the need for vacuum is prevented and a shorter lead time is benefited; nevertheless, an inert atmosphere is mandatory.

Many research papers in the literature already addressed laser-based DED of different metal alloys [4, 11], but austenitic stainless steel appears as a very common choice, given the wide diffusion of this alloy in many industrial applications, thanks to its mechanical resistance. For instance, the microstructure and the resulting mechanical properties have been discussed in configuration of multiple-layer [12, 13]: although an optimum condition of processing is suggested in these works, limited stress has been given to the correlation among the governing factors; consequently, additional research is required to quantify in which measure the solution yields an affection to the base substrate.

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In this frame, the paper is aimed at further developing the existing knowledge about DED of steel wire: namely, an experimental plan has been designed to investigate the dependence of the geometry on the governing factors in single-track deposition and eventually assess the affection in terms of geometrical dilution and variation of the micro-hardness.

2. Experimental procedure

A deposition line, including a solid-state disc laser source and a commercial wire gun to supply the material has been arranged [11, 9]; in addition, a device supplying argon at a constant flow rate of 20 L/min at atmospheric pressure to prevent the oxidation, has been employed, as a carryover of a patented device for welding [14]. The wire gun is integral with the laser head and they are moved by a gantry system with dedicated controller, the wire forming a 50° angle with respect to the direction of beam propagation (Fig. 1).

Stainless steel of different chemical composition has been used for the 1.2 mm diameter wire (Table 1) and the 10 mm thick plate (Table 2); the need for a different composition, in agreement with the expected behavior of steel under thermal loading [15], is driven by the attempt of reducing hot and cold cracking upon processing.

Table 1. Nominal chemical composition (wt. %) of wire.

Cr	Al	Si	S	Zr	Fe
12÷14	3÷5	1.3	< 0.2	< 0.1	Balanced

Table 2. Nominal chemical composition (wt. %) of the substrate.

Cr	Ni	Mn	Fe
17÷20	7÷9	2	Balanced

Many factors are involved in laser-based DED of wire, with different importance over the responses. Based on both the literature and past experience [11, 5], laser power and speed are crucial because they control the heat input to the material; in addition, among the factors of main concern is the speed ratio *k* of the wire speed to the laser speed, affecting the amount of delivered mass per unit length over the substrate.

To the purpose of investigating the main governing factors, the laser speed and the speed ratio have been changed, for given laser power of 1.6 kW and given defocused spot diameter of 1.5 mm. It is worth noting that two benefits are achieved by defocusing: firstly, a larger spot is produced to better cover the wire; secondly, the tendency to pore formation is reduced thanks to a decreased areal optical intensity [16].

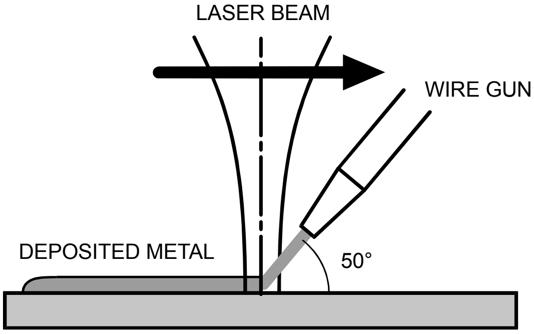


Fig. 1. Positioning of the wire gun over the substrate.

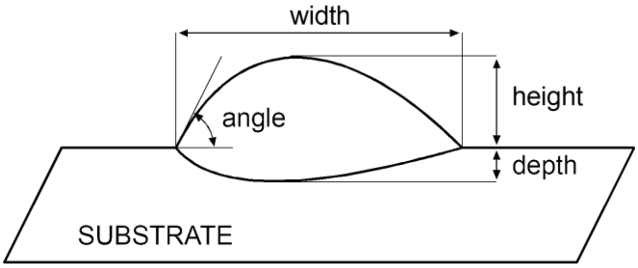


Fig. 2. Scheme of the geometrical responses in the cross-section.

Table 3. Experimental plan.

Processing condition	*k*	Laser speed [mm·min^{-1}]
A	4	100
B		150
C		200
D	5	100
E		150
F		200
G	6	100
H		150
I		200

A 2-factor, 3-level complete experimental plan has been arranged, resulting in 9 testing conditions (Table 3). These have been investigated via visual inspections and optical microscopy to measure the geometrical responses (Fig. 2).

In addition, the geometrical dilution has been considered as an index for the affection of the substrate with respect to the reported metal: to a first approximation [26], this can be even given as the ratio of the depth to the total transverse size of the reported metal (i.e., height plus depth).

Eventually, the Vickers micro-hardness has been measured to assess the depth of the affection in the substrate: namely, an indenting load of 0.2 kg has been used for a dwell period of 10 s; a step of 135 mm has been allowed between consecutive indentations, in compliance with the referred ISO standard [16] for metallic materials.

3. Results and discussion

At first, the visual aspects and the macrographs have been considered (Table 4); only condition G was ineffective. No macro-cracks neither macro-pores resulted in the reported metal, therefore shielding is deemed to be effective and the selection of the composition of the base metals proved to be successful to control possible imperfections.

3.1. Geometry

The geometrical responses have been measured (Table 5) and plotted versus the processing factors. Namely, as regarding the width of the deposited metal (Fig. 3): this decreases with increasing laser speed, since the size of the welding pool is reduced, and with increasing speed factor, since the laser energy is used mainly to melt the wire instead than creating the melting pool. The same reasons apply to explain the trend for depth (Fig. 4).

Table 4. Visual aspects and macrographs for each processing condition.

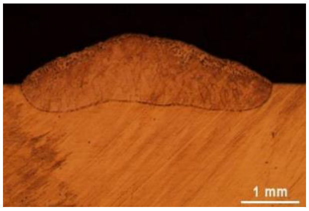
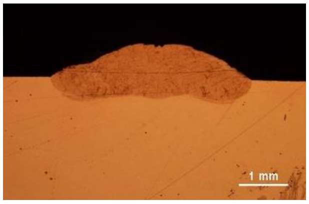
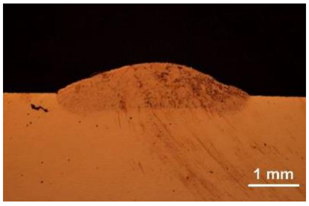
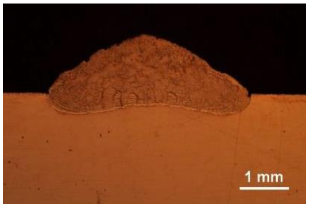
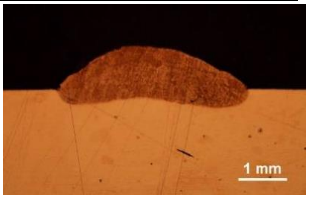
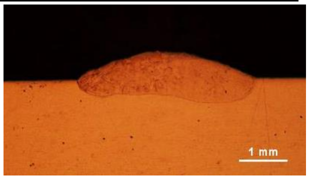
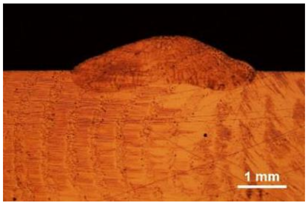
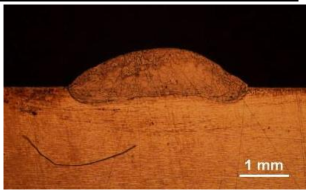
	Visual aspect	Macrograph
A		
B		
C		
D		
E		
F		
G		Excluded from further investigation due to irregular deposition
H		
I		

Table 5. Geometrical responses.

	Width [mm]	Depth [mm]	Height [mm]	Dilution [%]
A	4.32	0.45	0.67	40
B	4.11	0.43	0.56	43
C	3.73	0.33	0.49	40
D	4.10	0.41	0.88	32
E	3.88	0.41	0.66	38
F	3.62	0.30	0.52	37
G	Excluded from further investigation due to irregular deposition			
H	3.77	0.37	0.73	34
I	3.58	0.26	0.69	27

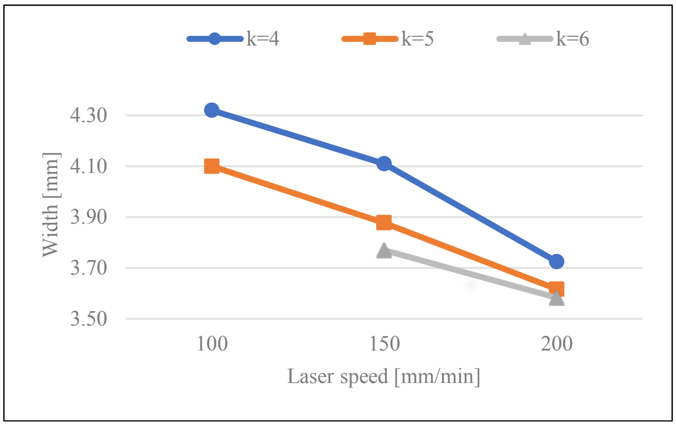


Fig. 3. Width of the deposition versus laser speed and speed factor.

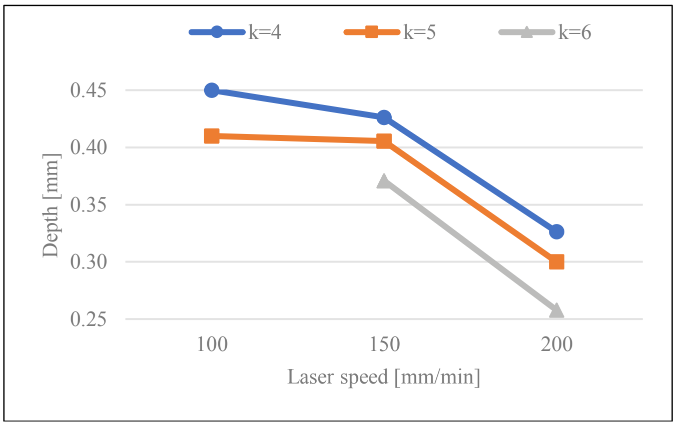


Fig. 4. Depth of the deposition versus laser speed and speed factor.

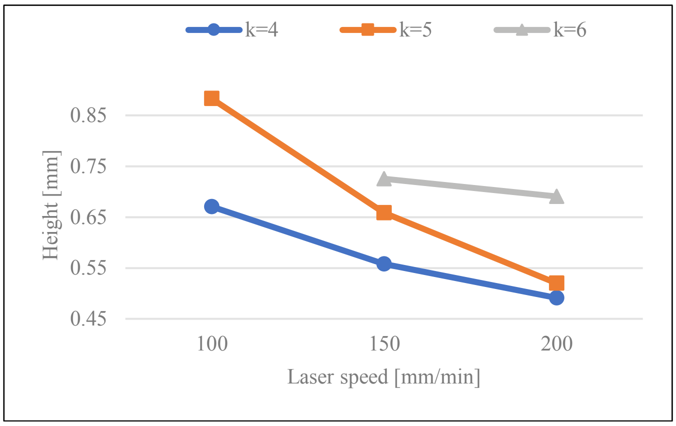


Fig. 5. Height of the deposition versus laser speed and speed factor.

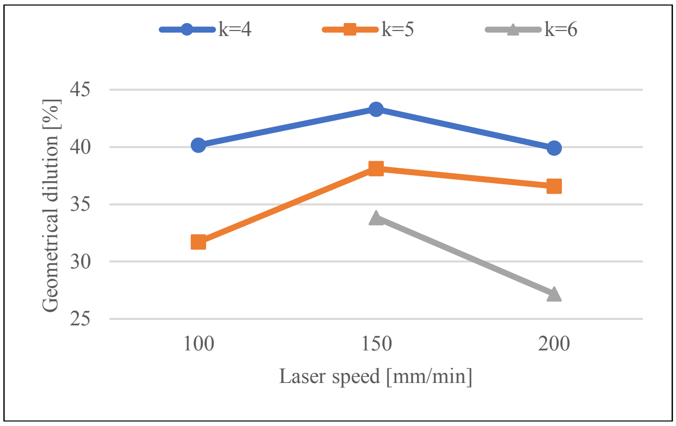


Fig. 6. Geometrical dilution versus laser speed and speed factor.

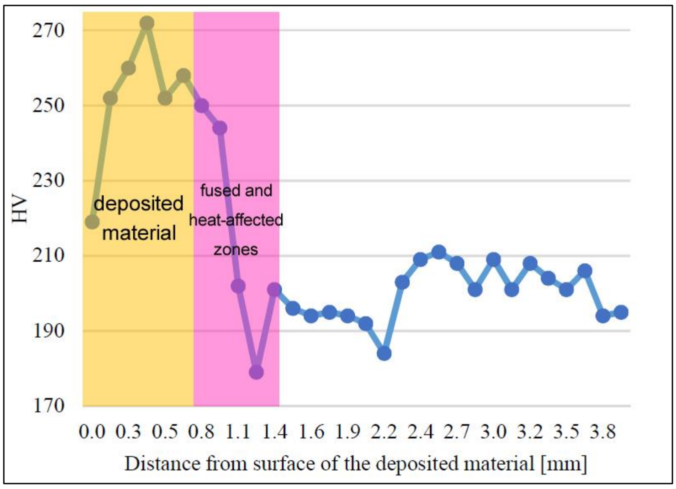


Fig. 7. Vickers micro-hardness trend in condition I.

Conversely, increasing the speed factor yields an increase in the resulting height (Fig. 5), provided that a melting pool is created for the adhesion of the wire to the substrate, whereas increasing the laser speed results in less wire per unit length.

As regarding the dilution (Fig. 6), a combined effect on its trend is determined by depth and height, because of its definition. It is worth noting that under proper conditions of processing, dilution can be limited below 30%.

3.2. Depth of the heat-affected zone

To further investigate the depth of the thermal affection, Vickers micro-hardness testing has been performed. The results in condition I, resulting in the lowest dilution, are presented. Namely, based on the trend of hardness along an indentation path starting from the top surface of the reported metal (Fig. 7), and considering the position of the reference plan of the surface of the substrate, the reference value of the base material is found at 1.5 mm depth from the original surface, although a value within a 10% difference is already found at 0.4 mm depth from the surface.

4. Conclusions

Although mechanical testing is required for a definite validation of the process, convincing grounds are given to shift laser-based Directed Energy Deposition of wire over real steel components, since the depth of the thermal affection with respect to the original surface plan is limited below 0.6 mm on average. Moreover, based on the trends of the responses, an optimum condition may be selected, based on the application, to maximize the height or the width of the reported metal, to the purpose of fabrication or surface cladding, respectively.

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