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The influence of the workpiece illumination proportion in annular laser beam wire deposition process

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Abstract

The paper provides a description of an annular laser beam based direct wire deposition head, which can be used to perform controllable, simultaneous, and symmetrical heating of both the workpiece surface and the axially fed wire. In order to characterize the proportion of energy delivered to the workpiece and fed wire, respectively, a new process parameter, referred to as the workpiece illumination proportion, has been introduced, which is defined as the percentage of the annular laser beam power incident on the workpiece surface. The influence of this newly defined illumination parameter on the process outcome was characterized, based on single-layer deposition experiments using a 0.6 mm diameter nickel wire which was fed onto a stainless steel workpiece. The results show that the geometry of the deposited layer is influenced, as well as by the conventional process parameters, also by the newly introduced workpiece illumination parameter, which also affects the process stability and its robustness.

Keywords: Annular laser beam; wire deposition; process parameters

1. Introduction

Laser direct wire deposition (LDWD) is an additive manufacturing process, in which a metal layer is deposited on a workpiece surface by feeding a metal wire-end into the melt pool, generated on the workpiece surface by a laser beam. The LDWD process has a variety of applications such as surface coating, 3D printing, and repair of damaged parts of complex shapes, and exhibits 100% efficiency in the utilization of the added material, high deposition rates [1], and a low price of the metal wire compared to metal powders. At the same time, it shows high sensitivity to the process parameters [2]. In conventional LDWD, the laser beam is aimed in a direction perpendicular to the workpiece surface in order to create a melt pool into which the wire is fed laterally at a certain angle. Besides the common LDWD process parameters (laser power P, wire feeding velocity v_f, scanning velocity v_s), the deposited layer geometry and process stability are also influenced also by the wire feeding direction, the wire feeding angle, and the location of the wire-end in the melt pool (i.e. the centre, trailing or leading edge of the melt pool) [3]. As a best solution for the lateral wire feeding LDWD, front wire feeding at an angle of approximately 45° was proposed [4], with the wire end at the leading edge of the melt pool. In other positions the wire-end causes shadowing of the laser beam, resulting in disturbances in the melt pool formation [3]. To avoid laser beam shadowing and to make the process direction independent, two new approaches to axial wire feeding were proposed. The first utilizes three single laser beams symmetrically positioned around the wire [5]. whereas the second uses an annular laser beam [6]. However, axial wire feeding which is perpendicular to the workpiece also has a disadvantage, since improper process parameters can cause plunging of the wire-end and collisions with the melt pool bottom. The latter can result in bending of the wire, especially in the case of wires with smaller diameters. The design with axial wire feeding ensures a direction-independent process which is very favorable in the manufacturing of 3D free surface structures. Additionally, application of an annular laser beam provides continuous and symmetrical heating of the

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wire-end over its circumference and simultaneous heating of the workpiece surface, the proportion of which can be controlled in order to achieve a proper and stable melt pool. The achieved symmetry has a potential benefit in multilayer deposition due to the less-demanding programming of the path direction, whereas the simultaneous heating of the workpiece and the wire enables higher wire feeding velocity and stabilization of the LDWD process at lower laser power.

In this work, an annular laser beam based direct wire deposition process is investigated. The research is focused on an analysis of the influence of the workpiece illumination proportion (WIP) on the process stability and its outcome. In order to characterize the energy input into the workpiece and wire, a new process parameter i.e. workpiece illumination proportion (WIP) is proposed, which is equal to the percentage of the annular laser beam power incident on the workpiece surface. For this purpose, in the next section the experimental setup for annular laser beam LDWD and the performed experiments are described, showing the laser beam power and WIP influence on the geometry of the deposited single layer and the deposition process stability. The results show that WIP is a very influential parameter with appropriate annular laser beam caustic, and that it is possible to achieve controllable symmetrical heating of the workpiece surface and axially fed wire on its circumference simultaneously.

2. Experimental

2.1. Experimental setup

The experimental setup for LDWD is schematically presented in Fig. 1a.

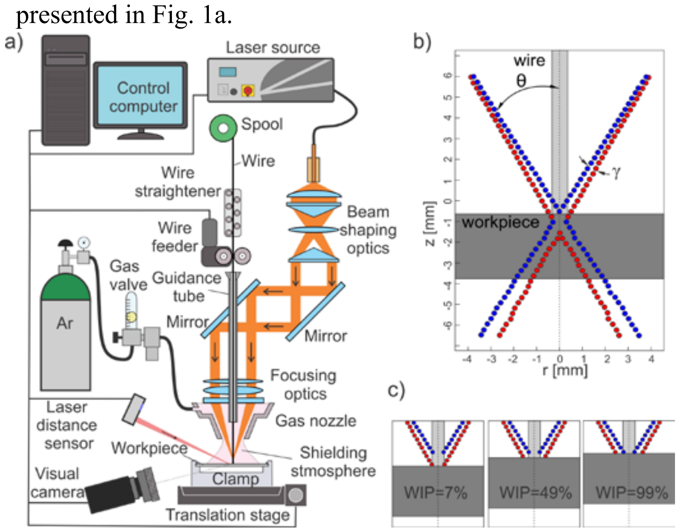

Fig. 1. a) Schematics of the experimental setup for annular laser beam LDWD, b) annular laser beam caustic, c) workpiece position at different WIP values.

The setup consists of a laser source, an annular laser beam cladding head [7], a wire feeding system, a workpiece positioning table, a shielding gas nozzle and a workpiece positioning table, a shielding gas nozzle and a process monitoring system. A 2.5 kW diode continuous laser was used as a source of the Gaussian laser beam. In the annular laser beam cladding head, the Gaussian laser beam is shaped into an annular laser beam, which is than guided by reflective mirrors coaxially to the wire guiding tube, and focused on the workpiece.

The geometry of the resulting focused annular laser beam can be described as a hollow cone with the thin wedge-shaped wall (Fig. 1b). The related wedge angle of the wall is $\gamma = 2.5°$ and the half-angle convergence of the beam is $\theta = 30°$.

The metal wire is axially fed into the annular laser beam focus using the wire feeding system consisting of a wire straightener, the wire feeder servo drive and a wire guiding tube for precise lateral positioning of wire end. The workpiece is moved relative to the annular beam cladding head by means of a horizontal translation stage.

2.2. Workpiece illumination proportion

In order to characterize the energy input into the workpiece and wire, a new process parameter i.e. workpiece illumination proportion (WIP) is proposed. To be able to determine the workpiece illumination proportion (WIP), the laser beam caustic was measured over the range from 6 mm above to 6 mm below the laser beam focus. Using the measured caustic, the proportion of power incident onto the workpiece surface, i.e. WIP, can be calculated from an integration of the laser beam intensity distribution profile. Different values of WIP can be achieved by changing the workpiece position relative to the laser focus as shown in Fig. 1c. Based on its definition, the WIP has a value between 0 and 100, where 0 means that all the laser power P was in the wire and 100 % denotes that all the laser power P was in the workpiece.

2.3. Experimental procedure

In the LDWD experiments, a 99.6% pure nickel wire (Nickel 200) with a diameter of 0.6 mm was deposited on a 3.0 mm thick AISI 304 stainless steel workpiece. Single layer deposition experiments were performed using a constant wire feeding velocity $v_f = 13$ mm/s and a scanning velocity $v_s = 5$ mm/s. and a power P in the range between 900 W and 2500 W, with 100 W steps. In order to investigate the influence of WIP on the process, three different WIP values, WIP = 7%, 49%, and 99%, were selected at which the experiments were performed.
For visualization of the deposition process a CMOS visual camera was used. Photos of the cross-sections taken by an optical microscope were used in order to characterize the process outcome by the deposited layer parameters, including width w, height h and maximum penetration depth h_p.

3. Results and discussion

In order for a LDWD process to be successful and stable, a molten bond between the melt pool on the workpiece surface and the melted wire-end needs to be established and maintained continuously from the start to the end of the process. The WIP value determines the proportion of the laser beam power delivered to the workpiece and wire respectively, and thus influences the shape of the molten bond and the process stability related to it. In Fig. 2 images of the typical melt bonds established at P= 1700 W and WIP = 7, 49 and 99 % are shown. It can be seen that at WIP = 7% (see Fig. 2a), most of the energy is absorbed by the wire which results in a thin molten bond between the melt pool and the wire end that can easily break due to the excessively high energy input at the selected wire feeding velocity v_f. At WIP = 49% (see Fig. 2b), the molten bond is well formed and more stable as in the previous case since nearly half of the energy is delivered into the workpiece. At WIP = 99% (see Fig. 2c) most of the energy is delivered to the workpiece, the molten bond is well formed. Based on brightness of image, the melt temperature is lower due to stronger heat conduction into the workpiece.

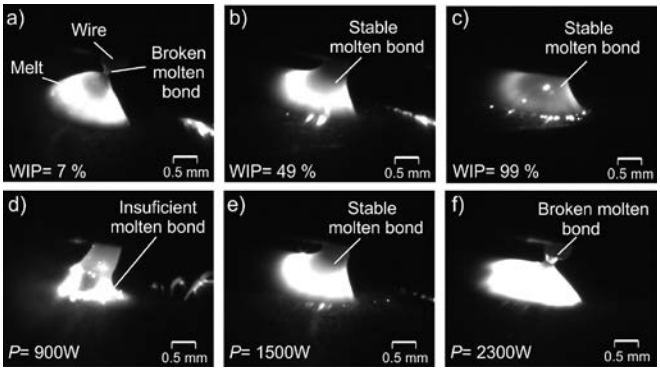

Fig. 2. Images of typical molten bonds taken during the LDWD process at different values of WIP and P = 1700W. The bright regions correspond to an incandescent melt. a) WPI = 7%; b) WIP = 49%; c) WIP = 99%, and at WIP = 49%. d) failed molten bond at P = 900W, e), stable molten bond at P = 1500W, f) thin molten bond just before it broke at P = 2300W.

Besides the WIP, the laser power P exhibits strong influence on the established metal bond and the related stability of the DLDW process. In Fig. 2 d, e and f images of the molten bonds at WIP = 49% and the selected laser beam powers P = 900, 1500 and 2300 W are presented. In the case of the laser power P = 900 W, the bond broke after its initial creation due to the insufficient energy input. was not able to continuously sustain the molten bond (see Fig. 2d). In such a case, the formation of the deposited layer is interrupted. By increasing the laser power to P = 1500W, the energy input became high enough to continuously melt the fed wire and to form a melt pool on the workpiece. In this case the bond between the wire end and the melt pool is stable (Fig. 2e). At laser power P values that exceed the maximum power (e.g. P = 2300 W), the energy input is so high that the wire feeding is not fast enough to maintain a stable bond between the molten wire end and the melt pool. In this case, the bond gets thinner (see Fig. 2f) until it breaks due to surface tension forces which interrupt the process. After the bond breaks, the laser light, reflected from the workpiece surface, melts the wire end, and forms a metal droplet.

At the selected WIP the interval of stable DLDW, i.e. the process window, with regarding to the laser power P, is therefore limited by the minimum and maximum laser power P. Based on single layer deposition experiments, laser power P intervals of stability were determined in steps of 100 W for all three selected WIP values, as shown in Fig. 3. From this figure it can be seen the interval of stability is displaced towards higher values with increasing WIP, which will be explained below.

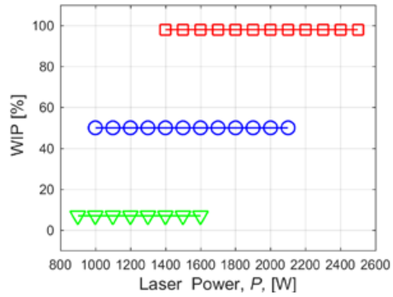

Fig. 3. Process windows for three selected values of WIP.

In addition to process stability, the WIP and laser beam power P influence the geometry of the deposited layer, including the layer's height h, width w and maximum penetration depth h_p, the dependence of h, w and h_p vs. P at the given WIP with selected characteristic examples of the deposited layer cross sections is shown in Fig 4. It can be seen that, as the laser power P is increased, so too does the layer width w and the maximum penetration depth h_p, almost linearly, whereas the layer height h decreases. The observed relations are qualitatively independent of the value of the WIP. From the photos of cross sections presented in Fig. 4, it can be seen that the shape of the deposited layer clad changes as the laser power P is increased, from a more unsymmetrical shape with large wetting angles at lower laser power P, to a symmetrical shape with smaller wetting angles at high laser power P.

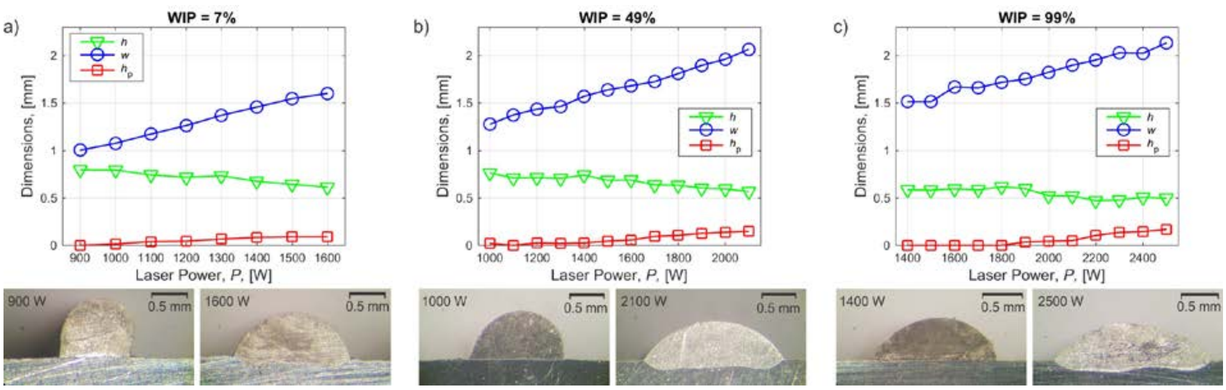

Fig. 4. Deposited layer height h, width w, and maximum penetration depth h_p at different values of WIP. a) WIP = 7%, b) WIP = 49%, c) WIP = 99%. Below the diagrams, photos of the layer cross sections at lowest and highest power P for each corresponding WIP value are presented.

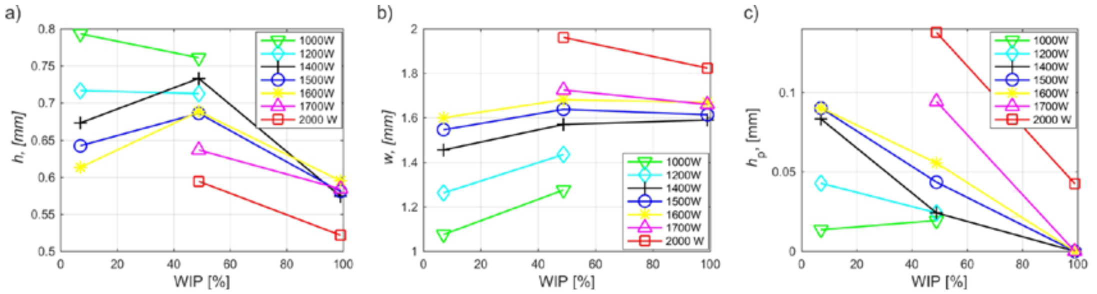

Fig. 5. Influence of the WIP at different values of the constant laser power P on a) the deposited layer height h, b) width w, and c) maximum penetration depth h_p

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An important result of this study is the characterization of influence of the WIP on the DLDW process. Contrary to the observed qualitative independence of the geometrical characteristics of the clad layer on the WIP, the latter's highly nonlinear quantitative influence on the geometrical properties of the deposited layer was observed, as shown in Fig 5. It can be seen from this figure that the height h of the deposited layer can either increase or decrease when the WIP is changed from a low value to the mid value, i.e. from 7 to 49 % (Fig. 5a). In the case of lower power P, the layer height h decreases since insufficient energy is provided with increasing WIP to achieve good wetting so the layer stays high. If the power P is sufficiently high to form a large melt pool at WIP = 7% and 49%, the layer height increases with increasing WIP, as can be seen in the cases with P = 1400-1600 W. If the WIP is increased to 99 %, this results in the decreasing of height h; lower values of h can be observed in the case of increased laser power P. The deposited layer width w was found to increase with WIP in the case of lower values of the WIP (Fig. 5b). This is because a melt pool of smaller width is formed at WIP = 7 % compared to 49 %. Towards the highest value of WIP = 99%, the width slightly decreases. It can be assumed that the decrease in layer width could be due to the larger laser beam diameter (1.0 mm compared to 1.4 mm) at WIP = 99% not enough intensity is provided to achieve the size of the melt pool and melt temperature similar to the cases with lower WIP. Another possible reason for the observed decrease of the layer width is the hitting of the unmelted wire into the bottom of the melt pool, and thus a reduction in the wire feeding velocity. The deposited layer's maximum penetration depth h_p was found to decrease with increasing WIP (Fig. 5c). This is because the annular laser beam spot diameter increases with increasing WIP, so that the laser beam intensity decreases. Also, at lower WIP values, the smaller part of the total energy is used for melting of the wire, whereas the larger part of the energy is conducted into the workpiece, thus creating a narrower but deeper melt pool.

Besides the deposited layer geometry, the WIP also influences the laser power P interval of the LDWD process stability, as can be seen in Fig. 3. This is because the laser beam power interval is shifted towards higher values with increasing WIP. With increasing WIP, less laser power is absorbed by the wire and more is energy is transferred by heat conduction into the workpiece volume. With regarding to the robustness of the process, it was found that at low WIP values it was very difficult to find a balance between the introduction of sufficient laser power P to successfully form the melt pool through heat conduction, and not so much laser power P that the bond between the wire end and the melt breaks due to Rayleigh-Plateau instability [8]. This makes the process very sensitive to its parameters, especially at higher laser power P, when the molten bond between the wire-end and the melt breaks easily. On the other hand, at higher WIP, it is easier to establish a stable melt pool which regulates the melting of the wire and the formation of a molten bond. The length of the laser power interval which ensures a stable LDWD process increases with increasing WIP, and the LDWD process becomes more robust.

4. Conclusions

The LDWD process using an annular laser beam and an axially fed wire are presented. Besides the increased process symmetry the annular laser beam enables a well-defined energy input into the workpiece and the wire surface. For this purpose a new parameter referred to as WIP (the workpiece illumination proportion) was introduced. It was shown that the deposited single-layer geometry displays similar dependence on the laser beam power to conventional side fed wire deposition. However, the WIP was shown to influence the deposited layer geometry and the laser power process window, as well as process stability and robustness. Further investigation is needed in order to determine the influence of wire feeding and scanning velocity on the annular laser beam LDWD process.

Acknowledgements

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