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Annular laser beam based direct metal deposition

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- Invited Paper -

Abstract

The paper provides a description of a direct annular laser beam based metal deposition head, which makes use of axial material feeding and variation of the laser beam intensity distribution (LBID) on the surface of the workpiece. The application and advantages of the developed head are presented by processes of direct metal droplet, metal wire and powder deposition. Due to the achieved process symmetry, the stability and robustness of the processes are increased. This is the most clearly seen in the case of metal droplet deposition, which is an inherently unstable process. In the case of wire deposition, a precise pre-set of the proportion of energy input into the workpiece surface is enabled, which has been shown to be an important parameter affecting the stability and process outcome. In the case of laser powder deposition, the benefits of the developed head are reflected in achieved powder catchment efficiency greater than 80 \% and in the head's ability to influence the deposited layer properties by adjusting the LBID.

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1. Introduction

Direct metal deposition is an additive manufacturing technology which can be used to repair and to rebuild high-value damaged parts, to apply functional coatings, and to manufacture complex 3D, free-form components [1]. It involves the continuous supply of a metallic material in the form of a wire or powder and the delivery of a localised high density energy source. The energy source is used to heat and melt the workpiece surface and supplied metal material. Due to the many advantages which arise from such a highly-controlled and localised heat input, a laser beam is most frequently used as the high density energy source, so that laser direct metal deposition (LDMD) has been accepted as a promising additive manufacturing technology [2].

In LDMD the geometrical, metallurgical and mechanical properties of the deposited layer and the manufactured part are influenced by the complex laser beam – fed material - workpiece interactions. These are, in addition to the process parameters, governed by the geometrical relations of the laser beam and of the fed wire or powder stream. Apart from the laser beam caustics and the geometry of the fed wire or powder stream, the geometrical relations are primarily defined by the design of the deposition head which is used to supply the metal material into the melt pool created by the laser beam. Such a head consists of laser beam guiding and focusing optics, and a metal wire or powder delivery nozzle, and forms one of components of LDMD systems which has the greatest influence on the process. Depending on the application, in the case of commercially available LDMD systems, a head with an axial Gaussian laser beam and a single nozzle from one side (Fig. 1a) is usually used to deliver the metal material into the melt pool [3]. The main advantage of a single side nozzle is its simple geometry and design. However, the related deposition process is asymmetrical with respect to the laser beam and therefore dependent on the deposition direction. In order to ensure process symmetry and a free shape, in the case of direction independent metal pow-
Fig. 1. Deposition head—material feeding nozzle concepts: (a) Lateral with an axial beam; (b) Coaxial with an axial beam; (c) Axial with three laser beams; (d) Axial with an annular laser beam.

der deposition, a coaxial nozzle with multiple jets or a continuous annular stream is applied (Fig. 1b). A common property of a deposition head with a side or coaxial nozzle is that the Gaussian or Tophat laser beam is usually delivered along the axis of the head. Application of side or coaxially fed powder can cause overheating at the centre and laser beam power attenuation and insufficient heating at the edge of the deposited layer. This, together with higher powder density and higher cooling rates at the edge compared to the centre can lead to deep, non-uniform and even asymmetrical dilution with a weak bond at the edge of the deposited layer [4]. Additionally, side and coaxial powder feeding are accompanied by relatively low powder catchment efficiency. In order to increase powder catchment efficiency, and to deposit layers having the desired properties, the laser beam intensity and powder density distribution need to be adjusted properly so as to achieve a uniform heat input over the width of deposited layer. In order to avoid the previously mentioned drawbacks of heads which make use of an axial laser beam and a side or coaxial material delivery, recently a novel design with material supply along the head’s axis and the coaxial delivery of multiple beams (Fig. 1c) [5], or with an annular laser beam, has been developed (Fig. 1d) [6,7]. In addition to axial feeding of the material, the latter enables variation of the laser beam intensity distribution (LBID) from a Ring shape to a Gaussian like shape [8]. This brings additional advantages which are due to the possibility of adjusting the LBID towards a particular application optimum.

In the following text the newly developed annular laser beam head is described, and its application to various processes of direct material deposition, including metal droplet, metal wire and powder deposition, all of which can be performed with minor modifications of the head. In addition to the achievement of a general increase in process stability, the observed and particular potential advantages of such an annular laser beam application are presented and discussed.

2. The annular laser beam direct metal deposition head

The scheme of the novel annular laser beam (ALB) direct metal deposition head is presented in Fig. 2a. It consists of a laser beam shaping unit, a guiding mirror, a laser beam focusing unit, a material feeding unit, an axial material delivery nozzle, and a coaxial shielding gas nozzle. In the laser beam shaping unit, a collimated beam is shaped into an ALB. By means of the mirror the ALB is then guided coaxially to the axis of the material delivery tube into the focusing unit, so that it is focused onto the workpiece surface. The laser beam shaping unit, which consists of two axicons and a lens in between them can be used to shape various ALB caustics by varying the position of the lens. An example of an ALB caustic measured by the IR camera on a thin metal foil, with the related LBIDs vs. the laser beam focal plane $l_{FW}$, is shown in Fig. 2b. In Fig. 2b $\theta$ denotes the convergence and $\gamma$ the wedge angle of the caustic, which are defined based on the detection of the $1/e^2$ intensity boundaries of the LBID IR images at different workpiece standoff positions $l_{fw}$. It can be seen that, by varying the position $l_{FW}$, the LBID and the related laser beam diameter $d_0$ can be changed. In general, by varying the positions $l_{FW}$ and the position of the lens between the axicons, various LBIDs can be generated, from Ring to Gaussian-like, at various diameters $d_0$. This property, together with the presented design of the head, makes the ALB direct metal deposition head applicable for various applications. This is because, by replacing the material feed-
ing unit (Fig. 2c) and making some minor adjustments to the head, a metal material in the form of a wire or powder can be applied, and the ALB direct metal deposition head can be used either for deposition of droplets generated from a metal wire, or for direct deposition i.e. laser cladding of metal wire or powder, as presented in the following.

3. Droplet deposition

In metal droplet based manufacturing a molten droplet is deposited on the workpiece surface to form a bond with the surface [9]. The unique properties of metal droplet deposition, including a minimal heat load on the workpiece and discrete material deposition, can be employed in various applications such as joining [10], surface cladding, and additive manufacturing [11], especially when temperature-sensitive materials and components, e.g. ceramic substrates, thin layers or foils, are involved. Apart from conventional liquid jetting and electric arc based droplet deposition, laser based droplet deposition provides benefits due to the well-defined spatial and temporal energy input, including a low heat load of the surroundings, individual droplet size, and deposition timing control, and the ability to employ materials with a high melting point [12]. However, as described in the following, for the drop-on-demand and continuous droplet generation and deposition process to be stable, the axially symmetrical energy input which can be achieved by the annular laser beam focused onto the axially fed wire, as well as precise synchronization between the laser power and wire feeding velocity, are of great importance [13].

3.1. Experimental

In laser droplet deposition experiments, a Nd:YAG pulsed laser with a wavelength of 1064 nm was used as the energy source. The laser emits pulses with a time-dependent profile of power in the range from 0.5 to 8 kW and a duration from 0.3 to 20 ms. As a fed material in drop-on-demand deposition (DoD-D) and continuous droplet deposition (CD-D) a Ni wire of 0.6 and 0.25 mm diameter was used. The wire feeding unit shown in Fig. 2c consisted of a wire spool, a wire straightener, and a DC motor feeder, which was capable of 20 µm displacement resolution, a max. 30 m/s² acceleration, and a max. velocity of 0.35 m/s.

DoD-D consists of two phases: 1) formation of a pendant droplet, and 2) pendant droplet detachment from the solid wire-end, and deposition. The corresponding time course of the laser pulse power \( P \) and the wire feeding velocity \( v_w \) are presented schematically in Fig. 3a. In order to form an initial, small-diameter pendant droplet, the wire-end is melted by the first part of the laser pulse, delivering the energy \( E_1 \). Then, to increase the pendant droplet diameter to a pre-set value, the second part of the laser pulse delivers the energy \( E_2 \) to melt an additional length of the wire, which is synchronously fed downwards at a feeding velocity of \( v_w \). In order to detach the formed pendant droplet, the wire is fed further downwards to position the droplet neck at the proper distance in relation to the laser beam focus, which has been shown to be a highly influential parameter [13]. The laser pulse with energy \( E_3 \) is then used to force detachment by inducing Rayleigh-Plateau instability of the molten column of wire above the droplet, as illustrated in the example of the IR image sequence in Fig. 4. Using a 0.6 mm diameter Ni wire, droplets with diameters \( d_d \) ranging from 0.85 to 1.25 mm can be generated, with a resolution of 50 µm and a standard deviation of 15 µm [13]. Besides the droplet-based joining applications presented in [10], in Fig. 5a various examples of different 2D patterns manufactured on a room-temperature Ti workpiece of 0.4 mm thickness are shown. They were produced in Ar protective atmosphere using a DoD-D at a standoff distance of 1 mm to demonstrate droplet diameter \( d_d \) flexibility, repeatability, and accuracy of deposition. Additionally, in Fig. 5b an example DoD-D of a simple 3D structure i.e. pyramid is shown.

Sequential metal droplet deposition, as required by certain applications, can be achieved by repeated DoD-D with implemented control, based on the initial temperature of the wire-end. Alternatively, continuous droplet deposition (CD-D) can be used, where periodic laser pulses of frequency \( f_p \) and duration \( \tau \) are applied with a constant wire feeding velocity of \( v_w \) (see Fig. 3b). In CD-D, the mechanism of the pendant droplet detachment and the corresponding detached

Fig. 4. Example of selected IR images of the droplet detachment phase, with induced Rayleigh-Plateau instability at \( t = 0.75 \) ms.

Fig. 5. Examples of deposited droplets: (a) Various 2D patterns with different \( d_d \) (b) A 3D structure, (c) Column and a porous wall structure.
droplet diameter \( d_d \) depend on the laser pulse frequency \( f_p \), as shown in Fig. 6. The presented results were obtained for the case of a 0.25 mm diameter Ni wire, with a feeding velocity of \( v_w = 0.06 \) m/s, a pulse duration of \( \tau = 0.8 \) ms, and using an average laser power of 120 W. At a low frequency \( f_p = 50 \) Hz, the detachment of the smallest droplets occurs due to Rayleigh-Plateau instability, whereas at higher frequencies \( f_p \) the detachment of larger droplets is triggered by resonant oscillation of the pendant droplet's eigenmodes with polar wavenumbers \( n = 1, 2, \) and \( 3 \), as has been proved theoretically in [13]. At high frequencies of \( f_p > 250 \) Hz, spontaneous detachment of the largest droplets is caused by gravity alone. As can be seen in Fig. 6, the most stable detached droplet diameter \( d_d \) is caused by the \( n = 1 \) eigenmode and by spontaneous detachment at the laser pulse frequencies \( f_p = 130 \) and 300 Hz, respectively. The corresponding mean droplet diameters \( d_d \) with standard deviation intervals were (1.18 ± 0.01) and (2.97 ± 0.02) mm, and the mean detachment frequencies were (3.79 ± 0.06) and (0.254 ± 0.006) Hz. An example of a column and a porous structure produced by CD-D of 1.18 mm diameter droplets using a 0.25 mm diameter Ni wire and a laser pulse frequency of \( f_p = 140 \) Hz is shown in Fig. 5c.

4. Wire direct deposition

In laser direct metal deposition a material in the form of a wire or a powder can be used. In comparison with the use of a powder, one of the main advantages of laser direct wire deposition (LDWD) are the 100% efficiency of the wire material, the high deposition rates, and the lower prices of metal wire [2]. On the other hand, the stability of the direct powder deposition process is fairly robust, whereas in the case of wire deposition the energy input into the workpiece surface and the wire has to be very well defined and synchronized with the wire \( v_w \) and workpiece \( v_{wp} \) feeding parameters. Thus, in general, process stability depends on many parameters, including the wire initial position and the inherent process parameters: laser beam power \( P \), wire \( v_w \) and workpiece \( v_{wp} \) feeding velocity, which define the input energy.

One of the advantages of annular laser beam direct wire deposition is that the workpiece illumination proportion (WIP) and the related energy input into the workpiece and wire surface can be influenced by variation of the annular beam caustic and the position of the workpiece surface \( h_{\text{ad}} \) with respect to the ALB, as shown in Fig. 7a. A WIP value of 100% means that all the laser beam energy is introduced into the workpiece surface. In the following text some results concerning the influence of WIP on the stability of the annular laser beam wire deposition process and its outcome are presented.

4.1. Experimental

In the performed annular LDWD experiments, a 99.6 % pure Ni wire of 0.6 mm diameter was deposited on a 3.0 mm thick AISI 304 stainless steel workpiece. A CW diode laser, with a wavelength range of 900-1100 nm, was used as the energy source. The experiments involving single layer deposition were performed using a constant wire \( v_w = 13 \) mm/s and workpiece feeding velocity \( v_{wp} = 5 \) mm/s, and a laser beam power \( P \) in the range between 900 W and 2500 W, with steps of 100 W. In order to investigate the influence of WIP on the process, three different values of WIP, i.e. 7 %, 49 %, and 99 %, were selected. The process stability was analysed based on process visualisation using a CMOS visual camera. The related process outcome was characterised based on the geometrical characteristics of the deposited layer, i.e. its width \( w \), height \( h \), and maximum penetration depth \( h_{\text{ad}} \), all of which were extracted from photos of the deposited layer cross-sections taken by an optical microscope.

If the LDWD process is to be stable, a continuous molten bond has to be established, at the start, between the melt pool on the workpiece surface and the fed wire, and then maintained without breaking throughout the process. Photos of characteristic examples of a continuous and broken molten bond are shown in Fig. 7b and 7c. Based on this criterion, at a wire feeding velocity of \( v_w = 13 \) mm/s and a scanning velocity of \( v_{wp} = 5 \) mm/s, a stability diagram corresponding to the annular LDWD process in the space of the laser beam power \( P \) and WIP was defined, as is shown in Fig. 8, where markers denote the stable process windows. It can be seen that the WIP strongly influences the laser beam power \( P \) stability.

![Fig. 6. Influence of the laser pulse frequency \( f_p \) on the generated droplet diameter \( d_d \) (blue dots).](image)

![Fig. 7. (a) Definition of WIP, (b) Continuous and , (c) Broken molten bond.](image)

![Fig. 8. Stable process windows vs. \( P \) at values of WIP = 7, 49, and 99 %.](image)
Fig. 9. (a) Deposited wire cross sections and (b) cross section width $w$, height $h$ and maximal penetration depth $h_{\text{md}}$ vs. WIP at laser power $P = 1.5$ kW.

windows. At higher WIPs process stability is achieved at a higher laser beam power $P$, whereas the window width is narrower at lower WIPs and is nonlinearly dependent on the WIP. In addition to process stability the WIP also influences the process outcome. In Fig. 9 examples of photos of the deposited wire cross section at a laser beam power of $P = 1.5$ kW and WIPs of 7, 49, and 99 %, with the related values of the deposited layer's width $w$, height $h$, and maximum penetration depth $h_{\text{md}}$ are shown. Closer examination of the photos of the cross-sections shown in Fig. 9a reveals that, at the lowest WIPs, the largest dilution area and wetting angle $\alpha$ are observed, which decrease as the WIP is increased. Based on the graphs shown in Fig. 9b, although not yet statistically confirmed, the nonlinear dependence of $h$, a linear increase in $w$, and a linear decrease in $h_{\text{md}}$ with increasing WIPs, from 0 towards 100 %, could be assumed. As presented in [14], the observed relations do not qualitatively change with variation of the annular laser beam power $P$.

5. Powder deposition

One advantage of laser powder deposition is the diversity of available powder materials, including pure metals, alloys, super alloys, ceramics and composites, which are not available in the form of a wire. In laser beam powder direct deposition the key problem is how to deliver a proper heat input by means of which, taking into account the laser beam-powder-workpiece interactions, the process will run in a stable manner, and the related deposited layer or built-up part of the desired geometrical, metallurgical and mechanical properties will be produced. In comparison with the use of a wire, the stability of laser powder deposition is more robust. However, in the case of powder, as well as process stability and the mechanical properties of the manufactured part, the powder catchment efficiency $\eta_p$ is an important process characteristic. All of these characteristics, in addition to the inherent process parameters including the laser beam power $P$, the powder mass flow $\Phi_m$, and the workpiece feeding velocity $v_f$, can be influenced by the design of the head, which defines the powder supply and the related laser beam / powder / workpiece interactions, and the laser beam intensity distribution itself. The latter has been shown to be very important in many applications [15], including SLM [16].

5.1. Experimental

In the laser metal powder deposition experiments a CW diode laser with a wavelength range of 900-1100 nm was used. Using SS316L powder with a particle size spanning from 53 to 125 $\mu$m, the deposition was performed on a SS304 workpiece with the dimensions (60 x 25 x 10) mm. Several experiments were performed using four different LBIDs, i.e. Ring, Tophat(-), Tophat(+) and a Gaussian like, with a 4$\sigma$-diameter 3.0 mm, shown in Fig. 10. In order to monitor the process a CMOS visual camera was used. The related process outcome was characterized by the geometrical properties of the deposited layer and the powder catchment efficiency $\eta_p$.

In Fig. 11a examples of the deposited layer's cross sections obtained at different LBIDs at a laser power $P$ of 2 kW, a powder mass flow $\Phi_m = 8$ g/min, and a workpiece feeding velocity $v_f = 10$ mm/s, are shown. It can be seen that the shape of the deposited layer and the dilution are strongly influenced by the LBID. In the presented case the depth $h_{\text{md}}$ of the U-shaped dilution increases with variation of the LBID from Ring towards Gaussian-like. At LBIDs with a high intensity at the center, due to the low LBI and the higher heat conduction into the workpiece at the edges of the deposited layer, a lack of dilution and insufficient melting can be observed at the edges of the cross-section. Additionally, in the case of the Tophat(+) and Gaussian-like LBID, an undesirable plasma plume above the melt pool was observed. The related mean values and the $\pm \sigma$ error bars of the geometrical characteristics of the deposited layers are presented in Fig. 11b. The clad wi-
are expected at larger laser beam diameters based on variation of LBID in the case of axial powder feeding. Consequently, additional qualitative changes towards higher stability and robustness of the process are observed benefits of the annular laser beam and axially fed powder deposition process, a very high powder catchment efficiency $\eta_p$ above 80% can be achieved. Additionally, as expected, an increase in the feed velocity $v_f$ causes a decrease in the $h_{\text{depth}}$ whereas an increase in the powder mass flow $\Phi_m$ results in an increase of $\eta_p$. With respect to the LBID, the $\eta_p$ increases when the LBID is varied from Ring towards Gaussian-like. However, with an increase in the laser beam power $P$, the observed LBIDs influence becomes less pronounced. Consequently, additional qualitative changes of the process and potential benefits of the annular laser beam based variation of LBID in the case of axial powder feeding are expected at larger laser beam diameters $d_o$.

6. Discussion and conclusions

In the paper an annular laser beam (ALB) based deposition head, which enabled axial delivery of the metal material, was presented together with its application to metal droplet, wire and powder direct deposition. In general, application of the annular laser beam and an axially fed material, results into increase of deposition process symmetry, which contributes towards higher stability and robustness of the process. This is especially evident in the case of metal droplet generation and deposition, which is a dynamically inherently unstable process [17] and has been stabilized by means of the application of an annular laser beam. Additionally, ALB based droplet generation, in comparison to other metal droplet generation processes, offers flexibility in the diameter, temperature and deposition time for each individual droplet, as well as flexibility in the used wire diameter and material, including materials with high melting points.

In the case of laser direct wire deposition besides to the process symmetry an important advantage arising from of the application of an ALB and axial wire feeding is that the proportion of the energy input into the workpiece (WIP) and the wire can be well defined. It has been shown that WIP strongly influences the process stability and deposited layer geometrical properties. The highest process stability and robustness were achieved in the case of the largest investigated WIPs.

From the stability point of view, laser beam direct powder deposition appears to be the most robust process. However, a stable process does not necessarily result in the desired properties of the deposited layer. At present, one of the observed benefits of the annular laser beam and axially fed powder is high, above 80% powder catchment efficiency. Additionally important benefits are expected from the influence of LBID, which can be varied from Ring to Gaussian-like, on the properties of the deposited layer.

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