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A versatile model for the prediction of complex geometry in 3D direct laser deposition

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ABSTRACT

We present a versatile model for the prediction of the geometry of laser clad depositions formed by overlap of individual tracks and layers as a 2D cross-sectional model that can be used for prediction of 3D structures. The main strength of our approach lies in the ability to achieve physically sound predictions of the geometry of deposition based entirely on experimental parameters that can be easily adjusted during the deposition process. As far as applications are concerned, with our model we are able to make predictions for any number of clad tracks and also any number of layers. We present two different ways of validating our model with experimental results, i.e. using a prediction based on the first track geometry and second, also a complete a priori prediction based on combined experimental dependencies in laser deposition process. The model therefore requires some level of prior experimental work to be conducted to calibrate the model for a particular set up which in turns makes the model very computationally simple and easy to apply. Good agreement with experiments in both scenarios is concluded.

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1. Introduction

In direct laser deposition the protective coatings and even 3D objects can be deposited on low-cost substrates. The process can be described as an addition of material on the surface of a substrate, where the energy source is a high power laser beam. The resulting thickness of the clad is typically 50 µm to 2 mm in a single track. Thicker layers can be achieved by building additional layers on top of the preceding coating. High quality thick coatings with metallurgical bonds and minimal heat input into the work piece can be achieved by laser cladding through powder injection. For an overview reference is made to [1].

Due to interaction between many complex physical phenomena the complete physical description of the cladding process is rather complex and depends on a number of parameters such as laser beam spot size, laser beam energy distribution, carrier and shielding gas used, powder feeding process, geometry of the substrate etc. Despite this complexity three key parameters can be identified that can be controlled in the experiment and strongly determine the geometry of final coating. These are: laser power P [W], laser beam scanning speed S [mm/s] and powder feeding rate F [mg/s]. These are referred to as the principal processing parameters. Our previous work has shown particular statistical relationships between these processing parameters and basic geometrical

characteristics of the laser track for coaxial [2], and side laser cladding nozzles [3].

In each single scan the beam is followed by an area of a few mm where a rapid solidification takes place. Fig. 1 shows a schematic of a typical transversal cross-section of a single track produced by laser cladding, as well as how a coating is produced via track overlap. Principal geometrical characteristics of the track are highlighted: the width is referred to by w , height is H , and clad angle α . This type of geometry is also applicable to other types of processes involving moving heat sources such as electron beam [4] or electric arc [5]. The final profile of the coating formed by overlap is determined by the width of the clad and its height and the profile of the first track, Fig. 1, where we define an overlapping ratio OR , which relates track width with distance D between the centres of neighboring tracks:

$$OR = (w - D) / w \quad (1)$$

OR relates to the fraction of the original track that is overlapped by the successive track. Correlation between cladding/welding process parameters and defining features of single clad tracks have been reported in several studies, such as a back propagation network technique which has been applied to model weld bead geometry in gas metal arc welding process [6]. The effects of input variables on the geometry of the weld were studied in submerged arc welding using a full factorial design matrix [7]. Regression relations between the processing parameters and clad characteristics were attained using a mapping technique for the graphical representation of clad profile produced.

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Fig. 1. Schematic representation of the recursive cladding track overlap model, see also [23].

If we consider that the laser cladding process is based on heat transport among the laser beam, the substrate and powder, and mass transfer between the powder flow and the molten surface we arrive at the conclusion that in order to describe the process it might be useful to define so-called *combined parameters*, [8]. Sets of 'combined parameters' have been proposed and tested to correlate laser cladding processing parameters to the final laser track width and height for coaxial and lateral geometry of the powder feeder [1,9,10]. Furthermore, for example, the influence of main parameters on single bead geometry in hybrid layered manufacturing was investigated by Suryakumar et al. [11]. From these studies it follows that for an entire family of these deposition techniques it is possible to find correlations that predict the height and width of a single deposited track over a wide range of the processing window. Furthermore in order to improve the understanding of the process for predicting the characteristic geometrical features several models were developed for laser powder deposition [1,12–15].

This leads to the main quantities which can be expressed as follows: the amount of powder supplied per unit length of the laser track F/S and the total heat input per unit length of the laser track P/S . It has been shown experimentally that over a wide range of processing parameters the clad height, H , depends linearly on the F/S parameter with the laser power having a minimal effect (on the height in comparison to F/S). Likewise, w , of the laser track linearly depends on $P/\sqrt{S}$. These empirical dependencies were observed for both side and coaxial cladding setups with high values of the correlation coefficient ($R > 0.9$) for cladding of Ni and Co based coatings on iron base substrates, see in particular references [3,2].

Experimental and model observations have confirmed these dependencies for a wide range of cladding and substrate materials [16,17]. The shape of the cross-section profile of a single track is, however, predicted in none of these approaches. In some works the shape is simply assumed to be part of a known function [5,10,11,18–20]. Furthermore, many additional functions have been selected and tested for the purpose of comparison with experimental results [6,21,22]. Overall, the most commonly used geometrical shapes could be generalised as parabolic, arc, trigonometric or elliptical functions [21]. Until our recent work [23] there was no unique functional form that could predict the shape of transversal cross-section of single clad track for all, or even a specific cladding process. Parabolic, arc and sine function shapes fit best with experimental observations of clad shapes based on wide range of processing parameters. Elliptical functions on the other hand are appropriate for very wide tracks which might for example be formed during laser cladding with scanning optics [24]. Generally speaking, the bead shape depends on the interplay of several physical phenomena such as gravity, electromagnetic force, viscosity, surface tension, Marangoni flow, dilution with the substrate and directional solidification. For this reason the calculation of the final shape becomes very difficult. Prediction of the profile shape of a whole coating formed by overlap of individual tracks then becomes even more complicated. Li and Ma [18] proposed an additive model where the resulting coating profile is calculated in each cross-section point as a simple addition of individual profiles mutually shifted by a factor $w(1 - OR)$. Such an

approach can be rejected because of the unrealistic waviness at the top of the coating profiles as well as at the side slope of the last overlapping track. This prediction is unrealistic due to surface tension of the melt pool which does not allow for such waviness. Furthermore, in this model the cladding angle α is not changed with geometrical overlap when comparing the first and the last track. Modification of the cladding angle during overlap has been observed experimentally and linked with the formation of an inter-run porosity [25].

The aforementioned models therefore do not sufficiently predict the final coating height, surface waviness and final cladding angle from the shape of single track and overlap ratio. In the past the overlapping factor, which determines the coating height and waviness without inter-run porosity, has always been derived indirectly from experiments.

There exists another group of models of laser cladding process which try to model all physically involved processes, introducing necessary approximation in equations and solve these numerically, for example see Qi et al. [26]. These models try to present a full theoretical prediction based on combination of physical phenomena. For instance, a model where the attenuation of the laser power due to incoming powder during cladding is taken into account with a consideration of a clad geometry [13]. Several authors have attempted to give a 3D analytical solution to compute clad geometry by comparing various physical processes [1,27–30]. Further models have tried correlating laser power with clad mass by considering energy distribution in laser cladding [31] or using 2D finite element model to consider melting of powders in liquid pool [12]. Limitation of these is their high complexity, that they are numerically demanding, limited in input of the whole process window and that they do not show always a good agreement with experiment.

Our model does not constitute all physically present processes in details, considering that they simply result in a particular shape of a clad track.

A simple prediction of geometry of coatings based on overlap of individual tracks has been reported by us in [23]. A recursive model was proposed for predicting the profile of such a coating using simplified physical assumptions. There is another group of models of laser cladding process attempting to address all physically involved processes, i.e. including approximations in algebraic equations and solve these numerically [13,26]. Limitation of these is their complexity, that they are numerically demanding, limited in input of the whole process window and that they do not show always good agreement with experiment.

The assumptions in the model are: first, the width of the track is controlled by the size of energy source (in the case of laser cladding by the width of laser beam) and stays constant during the track overlap; second, the character of the track profile shape is controlled by physical factors such as viscosity, surface energy of the melt, gravitational force, etc. and is not changed by overlap; and finally, the amount of the clad material is constant during delivery in successive cladding tracks.

The mathematical formulation of the recursive model is presented as follows:

The width of the single track w is defined by the distance between points A_1 and B_1 on a horizontal axis, see Fig. 1. The profile of the first

Fig. 2. Double layer coating model with 80% overlap and 150% offset.

track is given by a known type function F_1 . A hypothetical position of the second, 'shifted' laser track with the same profile as F_1 is marked by a dashed profile between points A_2 and B_2 . The overlap ratio OR is defined as the distance between points A_2 and B_1 divided by the track width w . The profile of the second overlapped track F_2 has to be found on the base of function F_1 and physical assumptions made above. Similarly, all other profiles F_n are calculated recursively on the base of the previous one.

It is assumed that function F_1 has an integral over an interval (A_1, B_1) and that this function is equal to zero outside of this interval. Let $z = (1 - OR)$. The left point and the right point of n -th track are: $A_i = wz(i - 1)$, $B_i = w + wz(i - 1)$, $i = 1, 2, \dots, n$. Profile of F_i starts always on the previous profile F_{i-1} at point A_i :

$$F_i(A_i) = F_{i-1}(A_i) \quad \text{for } i = 2, 3, \dots, n \quad (2)$$

the profile of F_i goes to zero at point B_i :

$$F_i(B_i) = 0 \quad \text{for } i = 1, 2, \dots, n \quad (3)$$

and finally, the amount of the material added in i -th track is the same as in the first track. Therefore:

$$\int_{A_i}^{B_i} F_i dx = \int_{A_1}^{B_1} F_1 dx + \int_{A_i}^{B_{i-1}} F_{i-1} dx \quad \text{for } i = 2, \dots, n \quad (4)$$

The right side of Eq. (4) represents the amount of new material added, plus material from previous track inside the overlap zone. Eqs.

Fig. 4. Dependence of relative coating height and waviness calculated by recursive one layer model on overlap ratio and their exponential fits.

(2)–(4) are sufficient for model calculations when the functions F_i are functions of the same type determined by 3 parameters.

The model allows for a substitution of any function that satisfies the above criteria and is thus highly versatile. Parabolic, sine, arc and elliptical functions were evaluated in the model. It has been shown previously, see [21,23], that parabolic and circular shapes lead to the best experimental fit for a wide range of selected functions.

Furthermore, it was shown that this recursive model converges to a stable shape, in other words a constant height and waviness are achieved after a few tracks, thus confirming our physical expectations. The method of creating coatings via overlap of individual tracks leads to a wavy surface at the top layer which has to be post-treated by machining before most real-life applications where a smooth surface is required. For that reason it is useful to consider an *effective coating thickness*. This represents the final thickness after machining when a smooth surface is achieved and it depends on the coating height and coating waviness. The lowest point on a wavy surface, the 'valley' between overlapped tracks, corresponds to the *effective coating thickness*. This can be more easily understood by considering comparative quantities: *relative waviness* and *relative coating height*. Relative surface waviness of the coating is defined based on previous studies, [32], as: $(\max(F_i(x)) - \min(F_i(x))) / \max(F_i(x))$ ($i \geq 1$) for a single layer coating. Relative coating height is the height of the coating measured from the substrate compared to the height of an individual track.

The purpose of this work is to build on these previous developments [23,33,34], extending the recursive model to multilayer coatings (created via overlap of individual tracks in laser cladding) so that the final height and surface roughness of an arbitrary coating can be predicted. Furthermore the goal is to produce a complete prediction of the

Fig. 3. Prediction of the recursive model for multilayer coatings showing a) relative coating height and b) relative coating waviness plotted as a function of overlap ratio. The fits were in a) Lorentzian and in b) exponential decay.

Table 1

Values of constants in Eqs. (6a) and (6b) for relative coating height and relative coating waviness calculated using reciprocal model for the parabolic function of single track shape.

	A	β	C
Height	0.0454	0.205	0.862
Waviness	1.05	−0.253	−0.0327

deposited clad geometry, as a 2D cross-sectional model that can be used for prediction of 3D structures, based purely on initial processing parameters that can be adjusted in each experiment, i.e. to make a prediction a priori. The work is applicable to any range of processing parameters and any type of set-up that produces a geometrically stable coating (i.e. attached to the substrate, free of substantial deformations, etc.).

2. Recursive model extensions

In this section we explore two important extensions of our existing recursive model for single layers [23]. A very relevant extension for applications in practice is the prediction for a multi-layer coating where additional layers are deposited on top of existing layer(s). Second, we propose an extension that is important from a processing viewpoint, namely predicting the geometry entirely based on experimental processing parameters. This allows an a priori estimation, in contrast with previous work.

2.1. Multi-layer recursive parabolic model

When considering multi-layer coatings an additional processing variable emerges, i.e. the offset. It represents a value that indicates where a consecutive layer starts, relative to the previous layer. It is indicated as a percentage of the width of the single track:

$$OS\% = \frac{A(1,2)}{B(1,1) - A(1,1)} * 100\% \quad (5)$$

where A is a starting point of a track and B is an endpoint, as in Fig. 1. The (i, j) notation refers to (# of track, # of layer). As an example 50% offset would mean the first track of the new layer starts in the middle of the first track of the previous layer, 100% would mean first track of new layer starts where first track of previous layer ends.

The first track of the second layer can span multiple tracks of the previous layer and with an added offset it can start from an arbitrary track of the previous layer. This leads to a change in the recursive equations for consecutive layers as well as for consecutive tracks within the new layer. For the first track of the consecutive layer the boundary conditions

change as the base is no longer flat but it depends on the waviness of the previous layer. The new boundary conditions also take into account the area of the previous layer. The sum calculates the area of all the tracks that are under the first track of the new layer, which can span a number of tracks starting points depending on the track width and overlap percentage, see Fig. 2.

Extending the recursive model predictions to an arbitrary number of layers it is now possible to predict the surface height and surface waviness of the final coating. Thereby if, for example, a particular final height and final waviness are required, it is possible to estimate how many layers should be deposited and which OR should be used. This can be easily seen by considering relative coating height and relative coating waviness as a function of OR for coatings made up of different numbers of layers and also for different offset, Fig. 3.

For the relative coating height of multiple layers the influence of the offset was negligible in all cases. For relative coating waviness there is a clear influence of the offset for low OR which diminishes at approximately 50% overlap. Moreover, the relative coating waviness does not depend on the number of layers but it depends on the offset where all the values lie within the plots of example offsets – the waviness oscillates between 50% and 100%. Both plots were normalized relative to the height of a single track.

2.2. Prediction of coating geometry from processing parameters

So far, all predictions were made on the base of the geometry of single deposition track. However, assuming a parabolic shape, only width and height of this track are necessary. If it would be possible to predict these quantities directly from the processing parameters P, S and F than application of recursive model would be directly connected to experimental processing parameters.

Using numerical fits it is possible to obtain mathematical expressions relating relative coating height and relative coating waviness to OR on the basis of above recursive model and parabolic shape of single track profile. As Fig. 4 clearly demonstrates these fits are excellent in overlap ratio interval 0.0–0.8. Points on Fig. 4 denote calculated values of relative coating height and waviness as a function of overlap, and lines are their exponential fits. The following expressions for relative coating height, H_{rel} , and relative coating waviness, W_{rel} are obtained

$$H_{rel} = A_H e^{\frac{OR}{\beta_H}} + C_H \quad OR < 0.8 \quad (6a)$$

$$W_{rel} = A_W e^{\frac{OR}{\beta_W}} + C_W \quad OR < 0.8 \quad (6b)$$

A, β and C are constants that were determined numerically and are listed in Table 1. It has to be noted that the relative coating height and

Fig. 5. Plots of measured clad height and clad width against combined parameters with the straight line fits shown. The error bars are smaller than the size of the marker.

Table 2
Empirical constants (Eqs. (7) and (9)).

α [m ² /kg]	γ [m]	δ [m ^{1/2} W ⁻¹ s ^{-1/2}]	ω [m]
0.0222	0.374	0.00359	1.05

the relative coating waviness only depend on the overlap ratio, i.e. $H_{rel} = f(OR)$ and $W_{rel} = f(OR)$.

Relations between the clad profile of the single laser track and the main processing parameters P , S and F were studied by us in the past. It has been shown experimentally [2,3] that the clad profile height, H , depends mainly on the scanning speed, S , and the powder feeding rate F , statistically described by the following dependence:

$$H = \alpha \frac{F}{S} + \gamma \quad (7)$$

where α and γ have the physical dimensions [m²/kg] and [m], respectively. Since the absolute value of the coating height, that is the height of the coating measured from the substrate, is a product of relative coating height and a single track height, H , we can combine Eqs. (5)–(7), to:

$$H_{abs}, W_{abs} = a \frac{F}{S} e^{\frac{OR}{\beta}} + b e^{\frac{OR}{\beta}} + c \frac{F}{S} + d \quad (8)$$

which is a function containing only constants a , b , c , d and β , processing parameters, F , S , and an overlap ratio, OR . The physical dimensions of the constants are [m²/kg] for a and c and [m] for b , d and β is dimensionless. Eq. (8) is valid for both: absolute height, H_{abs} , and absolute waviness, W_{abs} , though the constants will be different in each case. These constants are determined from the aforementioned constants in Eqs. (5)–(7) once the equations are combined.

Whilst Eqs. (7) and (8) appear to show a convenient and simple description of the single track and coating geometry, the description is incomplete as the overlap ratio OR is not a processing parameter. OR depends on the track width w and on the displacement, D , between

two successive tracks. Displacement refers to distance between centres of two successive tracks.

Previous experiments have also shown that width of the laser track, w , depends linearly on combined parameter $P/\sqrt{S}$ for both side and co-axial cladding [2,3]:

$$w = \delta \left(\frac{P}{\sqrt{S}} \right) + \omega, \quad (9)$$

where δ and ω have the physical dimensions [m^{1/2} W⁻¹ s^{-1/2}] and [m], respectively. Therefore, both relative coating height and relative coating waviness can be predicted directly from experimental processing parameters, which allows for a complete prediction of the shape of the coating based only on processing parameters. The fact that constants γ and ω in Eqs. (7) and (9), respectively, are not equal to zero is a consequence of the dependences being obtained experimentally with some statistical scatter (see Fig. 5). Eq. (8) has been derived on the base of these statistical relationships and therefore it also has a statistical meaning. In other words, some experimental results of laser cladding do not lie on this optimal line due to various physical effects which are not considered by the model. For this reason a larger statistical sample size is needed.

3. Results

3.1. Empirical constants for the prediction based on processing parameters

In order to compare the predictions of our model to experiments we first need to obtain empirical constants based on the aforementioned combined parameters. To this end we have prepared many single tracks with different combinations of laser power, scanning speed and powder feeding rate which have resulted in different combinations of track width and height. The resulting clad heights and widths were plotted against the controlling set of combined parameters, see Fig. 5.

Fig. 6. Profiles of coatings formed by overlap of individual tracks calculated for laser cladding with three different scanning speeds and three different laser track displacements. The units on the axes of all the plots are in mm.

Fig. 7. Profiles of coatings formed by overlap of individual tracks calculated for laser cladding with three different powder feeding rates (top), three different laser powers (bottom) and each with a different laser track displacement. The units on the axes of all the plots are in mm.

From these plots we are able to obtain the empirical constants via fits to straight lines. These laser clad experiments were done using Höganäs 3533-00 powder on SS304 substrate and clad using side cladding nozzle. The constants we have obtained are unique to the particular substrate, powder and to our laser set-up and these measurements need to be repeated if any of these is changed. The constants are listed in Table 2, referring to the constants in Eqs. (7) and (9).

3.2. Prediction of multilayer coating geometry based on processing parameters

Upon combining Eqs. (7) and (9) with the recursive model it is possible to predict the coating profiles based on overlap of individual tracks from P , S , F and displacement, D , between successive tracks. Fig. 6 shows the results of the model predictions for a range of displacements and scanning speeds. The laser power and powder feeding rate are kept constant between individual plots for a more direct comparison, with $P = 1000$ W and $F = 100$ mg/s. The plots were done for 3 layer coating with an offset of 100% and produced using empirical constants listed in Table 2.

In real experiments the height of the coating is observed to decrease with higher scanning speeds. This is a consequence of lower powder acquisition per unit length for a constant powder feeding rate. On the

other hand the height increases with increased overlap ration (smaller displacement). This is exactly what we predict in our model, Fig. 6. Furthermore, let us consider two more cases where we demonstrate model predictions for other sets of parameters. Fig. 7 shows a similar plot but for a range of feeding rates and laser powers, with a different set of parameters kept constant $P = 1000$ W, $S = 10$ mm/s and $F = 100$ mg/s, respectively.

Looking at Figs. 6 and 7 it can be clearly seen how the coating height and width relate to the processing parameters. The increase of feeding rate results purely into an increase of the coating height as it results from more material added whilst the width is kept the same as this is controlled by the laser power. On the other hand, the rise in laser power increases merely the clad width as the beam follows a Gaussian distribution resulting in a wider track at higher powers. The scanning speed affects both the width and height as this has an effect the amount on both the energy delivered per unit area from the laser beam and also on the amount of material that is delivered in the given time window per unit length.

Therefore, we demonstrate the possibility to predict the final geometry based merely on experimental processing parameters with physically sound predictions. Finally, we also show the possibility to predict the geometry for any number of layers with an arbitrary offset, see Fig. 8.

Fig. 8. Profiles of coatings formed by overlap of individual tracks calculated for laser cladding with different number of layers and also for different offsets between layers. The units on the axes of all the plots are in mm.

Fig. 9. Experiment-model comparison for single, double and triple layer coatings. Side cladding, comparison based on first track.

4. Experimental comparison and discussion

The experiment – model comparison was tested by laser cladding experiments. The laser cladding was performed onto a stainless steel 304 substrate bar with 40 mm in diameter. The laser cladding system consists of a continuous wave solid-state 3.3 kW fiber laser by IPG Photonics with a wavelength of 1.07 μm , feeding system consisting of Metco Twin 10C powder feeder, shielding and carrier gas (argon), powder injection and 5 axis CNC table. Furthermore the set-up allows for powder feeding using coaxial feeding nozzle and side powder feeding nozzles of different sizes. Circular laser spot size was 1.5 mm (defocus 18 mm) for side cladding and 1.2 mm (defocus 16 mm) for coaxial cladding.

There are two possibilities for comparing the model prediction to laser clads in practice. The model calculation can be made based on the measurement of geometry of first track, as per previous work [23] or based on the width and height of single track calculated from the combined parameters.

First, let us consider a multi-layer comparison constructed on the bases of the first track geometry. Fig. 9 shows a model comparison for side cladding with $P = 675 \text{ W}$, $F = 83.3 \text{ mg/s}$, $S = 5 \text{ mm/s}$, $D = 0.8 \text{ mm}$ for the single layer and $D = 1.0 \text{ mm}$ for dual and triple layer coatings which also have an offset of 60%. The single layer coating matches the model prediction very well as was demonstrated previously [23]. For the dual and triple layer there is a mismatch in the height which seems to increase with increasing layers in comparison with model.

It is important to note that the subsequent layers are now clad on a different substrate as the first layer becomes now the new apparent substrate. There are many factors which could play a role such as different surface roughness, heat capacity and laser beam absorption. Moreover, the subsequent tracks have been clad immediately one after another with a substantially different substrate temperature. We have therefore prepared a new clad where there was enough time given to

the first layer to cool down before applying the second layer, Fig. 10. It is clear that the general fit is much improved now as the height of the two layers is now comparable.

Similar results were found when making model comparison using the prediction based on combined parameters. The above examples are therefore representative for different sets of experimental conditions and for comparison based on both single track and a priori comparison based on combined parameters. For the later there is a caveat that the comparison fails for certain combinations of processing conditions that would correspond to points further away from a straight-line fit in Fig. 5. This is logically expected and such clads have been discarded.

Let us consider the case that layers number 2 + are now indeed clad on a new substrate, that is, not the actual substrate material but the previous clad being the new apparent 'substrate'. We would expect the result to be different compared to the first layer but that the subsequent layers should be nearly identical, as seen in Fig. 11 highlighting the similarity between the top layer for triple and double coating.

For an accurate prediction of multilayer coatings it would be necessary to treat the second layer therefore as the new starting layer of the clad and we would therefore need: either a special clad prepared where a single layer has been clad on top of an existing coating or a new set of empirical constants measured for different windows of processing conditions clad on top of an existing coating.

Using the assumption that upper layer coatings do not change from second layer upwards we can conclude it would be in most cases sufficient to simply apply a correction, as a percentage height increase, for upper layer coatings into our model. Fig. 12 shows experiment model comparison after a +15% correction (applied to the single track height for successive layers) for side cladding comparison based on a single track ($P = 675 \text{ W}$, $F = 83.3 \text{ mg/s}$, $S = 5 \text{ mm/s}$, $D = 0.8 \text{ mm}$, $OS = 0.8 \text{ mm}$), side cladding comparison based on combined parameters ($P = 675 \text{ W}$, $F = 83.3 \text{ mg/s}$, $S = 5 \text{ mm/s}$, $D = 1.0 \text{ mm}$, $OS = 1.0 \text{ mm}$)

Fig. 10. Side cladding with $P = 675 \text{ W}$, $S = 5 \text{ mm/s}$, $F = 83.3 \text{ mg/s}$, displacement 1 mm and 60% offset.

Fig. 11. Overlay of double (right) and triple (left) coating demonstrating that the upper coatings have the same characteristics.

and coaxial cladding based on the first track ($P = 600$ W, $F = 83.3$ mg/s, $S = 5$ mm/s, $D = 0.9$ mm, $OS = 0.9$ mm), respectively. Here it should be noted that the 15% correction gives the best agreement between model and experiment.

It was not possible to attain any kind of match for coaxial cladding based on combined parameters. It is important to note that the experimental constants were calculated based on experiments with side cladding. This shows that the constants are indeed some kind of property of a particular experimental set up. Therefore for a comparison with coaxial cladding a new set of constants would be needed. This can be understood that a different type of cladding (coaxial, side) requires a different type of powder feeding nozzle so we might expect different powder efficiencies. Therefore, the model using empirical constants also incorporates powder efficiency indirectly. Furthermore, the presented model that uses experimental results as its input parameters has its prediction value limited inside 'reasonable' processing parameters window for a given system.

Finally we can see from Figs. 6 and 7 that different sets of parameters result in different clad angle. This is of practical interest as clad angle relates to inter-run porosity.

5. Conclusions

A versatile method for the prediction of deposition geometry for coatings formed by overlap of individual tracks in direct powder deposition was presented. A full coating geometry can be predicted, on the basis of 2D cross sectional model, merely based on experimental processing parameters, namely for laser deposition: scanning speed, laser power, powder feeding rate and displacement between successive tracks. The recursive model as published previously [24] was limited to predicting single layer coatings only and required a first track to be cladded previously and then measured. The prediction was based on

the basis of this experimental observation which has to be conducted every time.

The mathematical description presented contains experimental constants that depend on the particular set-up. These have to be determined experimentally for different deposition conditions (side or coaxial powder feeding, type of laser used, etc.). The model leads to a full prediction of coating geometry. The model predictions also resulted in an excellent prediction for an overall shape, i.e. the height and the waviness, of the profile of the laser clad coatings.

In addition, we have presented a model for multilayer coatings thus leading to a prediction for any number of tracks and any number of layers. Experimental comparison has shown that second and subsequent layers behave differently, which can be attributed to a new apparent substrate due to cladding on the previous layer. As this is a simple model based merely on experimental processing parameters this is not taken into account, however, after a correction of 15% for upper layers we were able to provide accurate predictions for a range of different conditions.

Whilst the model does not take into account many physical aspects of laser cladding and of the particular set-up this is also a major advantage of the model. The model is therefore kept simple and as shown is still able to deliver accurate and very reasonable predictions with some small initial amount of experimental work required to calibrate the model. Furthermore, the basis of the model allows other (potentially more complex) functions to be used in the model. As a result, it can be highly flexible and is open for further development and calibration by the wide community. This could potentially allow for some more exotic set-ups and processes to be applicable.

The need for some experimental work to be done in order to determine the empirical constants places limitations on the applicability of our model but at the same time helps to keep the model both simple and versatile. The main objective is to provide a simple tool for applications in practice.

Fig. 12. Model experiment comparison with 15% correction. Top: side cladding, comparison based on single track. Middle: side cladding, comparison based on combined parameters. Bottom: coaxial cladding, comparison based on single track geometry.

The technique has application to 3D additive manufacturing where complex objects are created layer-by-layer and to a range of other applications such as gap filling or tool repair. In all of these applications prediction of final height and surface roughness is of particular interest.

Further work could include detail predictions of cladding angles compared with experiment in order to determine a relationship between cladding angle, inter-run porosity and the optimal processing parameters to minimise this type of porosity. Additionally further work is required for experimental comparison in non-metallic additive manufacturing.

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