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On the geometry of coating layers formed by overlap

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ABSTRACT

A recursive model is presented for the prediction of the profile of a coating layer formed by single track overlap. A known shape of single track is assumed and on the base of simple physical assumptions the recursive sequence is deduced to construct an entire profile of such coatings. Calculations of these profiles for different basic shapes and overlaps of tracks show the dependence of coating thickness, waviness and cladding angle on these parameters. A generalized formulation of the model based on purely geometric considerations allows for an application towards different types of cladding processes, including multilayer cladding and 3D depositions. The model is tested experimentally for the laser cladding process in two different set-ups. The cladding track is formed by a continuous deposition of metallic particles into the melt-pool formed by a high power laser beam that continuously moves over a substrate. Good agreement with the parabolic shape of a single track and experimental observations of height and waviness was concluded for a wide range of overlap ratios.

1. Introduction

Surface engineering techniques are devoted to the formation of surfaces with excellent functional properties such as high hardness, excellent wear and corrosion resistance. At present there are numerous techniques available that rely on a variety of physical and technological processes. Several techniques, which produce thick coatings (~1 mm) by welding or cladding, are limited in lateral dimension and the partial overlapping of individual deposition tracks is required to coat wider regions. A typical example is the laser cladding process [1], in which a high power laser beam scans the substrate surface creating a melt pool, in which additional material is fed in the form of metallic powder. Rapid solidification occurs in an area behind the beam, typically a few mm wide during a single scan. Partial overlapping of such laser tracks results in wider and thicker coatings. Fig. 1 shows a typical transversal cross-section of a single track produced by laser cladding. Principal geometrical characteristics of the track are highlighted: width is referred to by w, height is H, clad area A_c, melted area A_m and clad angle α. The lower part of Fig. 1 shows an example of a laser clad tool steel coating formed by overlapping of individual laser tracks.

Similar single track geometries could be obtained by cladding or welding processes, where other types of moving heat sources are applied, such as electron beam [4] or electric arc [5]. It is clear that the width of the clad and its height, as well as the profile of the first track determine the final profile of the coating formed by overlapping tracks together with an overlapping ratio OR, i.e. relating track width with distance D between the centers of neighboring tracks:

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

OR quantifies the fraction of the track that overlaps with its forerunner. Second part of Fig. 1 shows the cross-section profile of a coating formed by 33% OR.

Several studies report on the correlation between processing parameters of cladding/welding and characteristic features of single cladding tracks. For instance, a back propagation network technique has been applied to model weld bead geometry in gas metal arc welding process [6]. A full factorial design matrix was used for the submerged arc welding to study the effects of input variables on the geometry of the weld [7]. A mapping technique for the graphical representation of clad profile produced in this process was used, resulting in regression relations between the processing parameters and clad characteristics. The sets of 'combined parameters' have been used to correlate laser cladding processing parameters to the final laser track width and height for coaxial and lateral geometry of the powder feeder [1,8,9]. The main parameters that influence single bead geometry in hybrid layered manufacturing were studied by Suryakumar et al. [10]. These aforementioned studies demonstrate 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 processing windows. Also, several models were developed for laser powder deposition [11–15] in order to improve the understanding of the process and to predict the characteristic geometrical features. However, none of these publications predict the shape of the cross-section profile of a single track. In some publications the shape is simply assumed to be part of a

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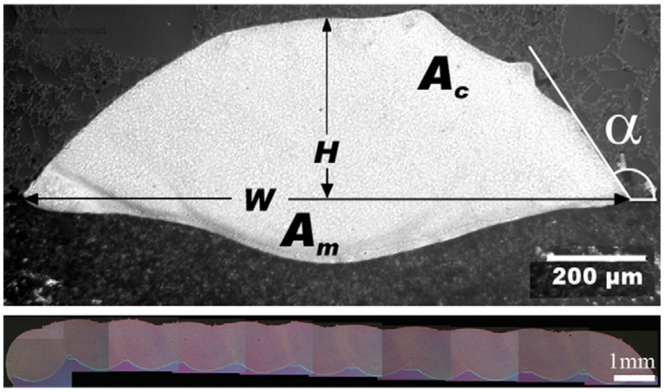

Fig. 1. Transversal cross-section of single laser track (top) and tool steel laser clad coating formed by 33% overlap (bottom) [2,3].

known function [5,8,10,16–19]. In others one or even more functions are selected and tested in comparison with experimental observations [6,20,21]. The most commonly used geometrical shapes are parabolic, part of a circle arc, sinusoidal, elliptical, and also some exotic functions are selected [20]. To date there is no unique functional form that could predict the shape of transversal cross-section of single clad track for all, or even a particular cladding process. From the experimental observations of the shapes of the clad tracks using a wide range of processing parameters for different processes it seems that parabolic, arc and sinusoidal shapes fit the experimental observations. In some cases when a very wide track forms, for instance during laser cladding with scanning optics [22], a shape approximated by elliptical function can be used. In general we can say that the bead shape formation is the interplay of several physical phenomena such as gravity, electromagnetic force, viscosity, surface tension, Marangoni flow, dilution with the substrate and directional solidification. It is therefore very difficult to calculate its final shape.

The situation becomes even more complicated when one would like to predict the profile shape of the coating formed by overlapping tracks. In the additive model proposed by Li and Ma [16] the resulting coating profile is calculated in each cross-section point as a simple addition of individual profiles mutually shifted by a factor $w(1 - OR)$. Fig. 2a shows the example of this model calculated for coatings formed by overlapping of parabolic shape of single track with H/w ratio of 0.2.

One may object to this approach due to the unrealistic waviness at the top of the coating profiles as well as at the side slope of the last overlapping track. Surface tension of the melt pool does not allow for such waviness. It is clear from the analysis of the shape in Fig. 2a that geometrical overlap according to this model does not change the cladding angle α when comparing the first and the last track. Modification of the cladding angle during overlap is experimentally observed and is also the cause of formation of an inter-run porosity [23]. At any rate, our model should be able to predict the correct coating height and its surface waviness as a function of overlap ratio.

Example of another geometrical model present in the literature is schematically shown in Fig. 2b. Material from the overlapped area ABC is used to fill the area CDE between adjacent tracks. In a number of publications the optimal scan spacing is calculated [5,20,21,24] for which these two areas are equal, and which according to this model leads to a minimal surface coating waviness.

A more advanced model [10] based on the same assumption improves the surface profile between points *ED* by modeling it via circles, convex and concave for area ABC smaller and larger than CDE, respectively.

We stipulate that none of the above mentioned models sufficiently predicts simultaneously the final coating height, surface waviness and final cladding angle from the shape of single track and overlap ratio. To date, an overlapping factor which determines the coating height and waviness without inter-run porosity has always being derived

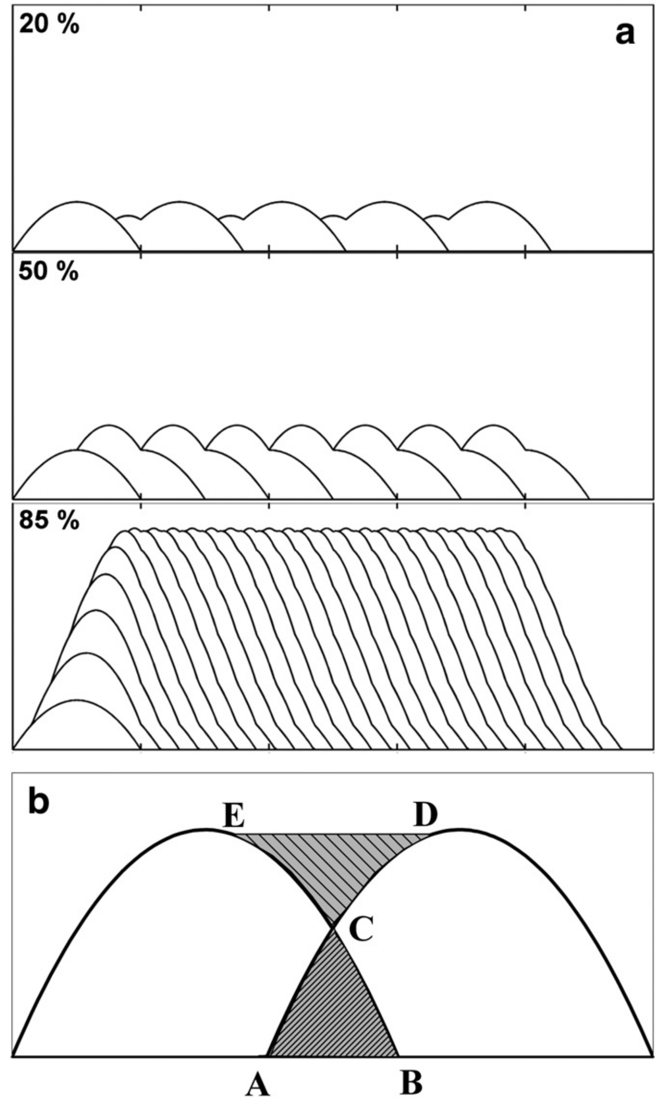

Fig. 2. Transversal cross-section profiles modeled by: a) Simple additive model [16] for different overlappings using a parabolic shape of single track with H/w ratio of 0.2. b) Geometrical filling model [5]; (scales in horizontal and vertical direction are different).

indirectly from experiments. This work is aimed at designing a new model that will be able to predict all above mentioned coating parameters just from the geometrical shape of single track experimentally observed. The model has to be confronted experimental outcome of the laser cladding process.

2. Recursive model description and study

2.1. Model assumptions

Here we present a simple geometrical model for track overlapping in which each track is added recursively onto the previous one for any overlap ratio OR of the tracks. In the formulation of our model for track overlap the following assumptions are made:

i. The width of the track is controlled by the dimensions of the energy source (in case of laser cladding by the width of laser beam) and stays constant during the track overlap;
ii. The character of the track profile shape is controlled by physical factors such as viscosity, surface energy of the melt, and gravitational force and is not changed by overlap;