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Improving laser cladding productivity with 'ABA' cladding

Daniel Koti[a,*], John Powell[a,b], K.T. Voisey[a]

[a]University of Nottingham, Faculty of Enginnering, University Park, Nottingham NG7 2RD, United Kingdom
[b]Laser Expertise Ltd., Acorn Park Industrial Estate Harrimans Lane, Nottingham NG7 2TR, United Kingdom

* Corresponding author. Tel.: +44-751-238-4934; *E-mail address:* daniel.koti@nottingham.ac.uk

Abstract

Laser Cladding is one of several processes within Additive Manufacturing and usually involves the production of a clad surface by adding parallel, overlapping lines of clad material to the surface of a substrate. In this work a new laser cladding technique ('ABA' cladding) is investigated wherein a series of separate, or only slightly overlapping clad tracks are laid down initially (the 'A' tracks), and these are later interleaved with tracks which can use different parameters (the 'B' tracks). The influence of the process parameters was examined in the laser cladding of AISI 316L stainless steel and Stellite 6 powders using a coaxial powder delivery nozzle. 'ABA' cladding was found to have considerable benefits over traditional laser cladding including: Improved powder catchment efficiency and coverage rates, more predictable metallurgy and dilution levels, and the ability to clad combinations of different alloys on the substrate surface.

Keywords: Laser cladding; Powder melting; Additive manufacturing; ABA cladding; Directed Energy Deposition; Laser Metal Deposition

1. Introduction

Laser cladding dates back to the 1970s [1,2] and involves the melting of a cladding alloy onto a metal substrate using pre-placed [3,4] or blown [3,5-7] powder which is laser melted to create a clad track. Traditionally, successive tracks are overlapped side by side to create a clad surface like the one shown in cross-section in Fig. 1. This process has been used to coat a range of metals with expensive wear, abrasion or corrosion-resistant alloys.

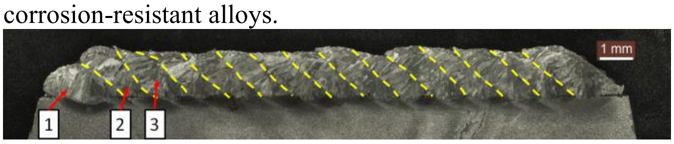

Fig. 1. A cross-section of a typical 'AAA' clad surface is created by laying down parallel, overlapping tracks.

Laser cladding is also a cornerstone of many Additive Manufacturing (AM) production processes, the term "laser cladding" refers to the process of directed energy deposition, a method of additive manufacturing in which focused thermal energy is used to fuse materials by melting as they are being deposited (ISO/ASTM 52900).

For the purposes of this paper, the traditional cladding process could be called 'AAA' cladding because the clad tracks are ostensibly identical. However, this similarity only becomes apparent once a few tracks have been laid down. In the early stages of the process, the previous tracks affect the shape of subsequent ones in various ways. This point is rarely discussed in the literature [8] but is clear in the cross-sections of clad layers presented by most researchers in the field [9 - 13]. This point is apparent when comparing the cross-sectional morphology of tracks 1, 2 and 3 on the left of Fig. 1, and is illustrated schematically in Fig. 2. In this area, there can be large differences in local clad track height, cross-section and metallurgy. For example, because it is the only track laid upon a flat surface, track 1 will have a different melt pool geometry which will affect powder capture and the level of dilution of the

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cladding alloy with the substrate compared to subsequent tracks.

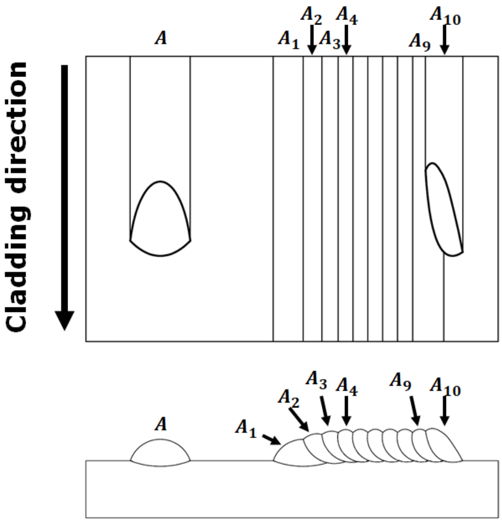

Fig. 2. Schematic showing how 'AAA' cladding builds up a surface by adding subsequent tracks to an initial A track.

In general, several tracks need to be laid down before a repeating cross-section is created and the final track also has a unique morphology because it does not undergo secondary melting by the partial overlay of a subsequent melted track. In the illustration in Fig. 2 a repeating pattern of cladding is not established until track A4. Tracks A4 to A9 are identical and A10 is the final track.

These start and finish anomalies are one of the drawbacks of 'AAA' cladding because they give rise to local perturbations in clad surface morphology, dilution and heat-affected zones [8-12].

A more major commercial consideration, however, is the powder catchment efficiency of the process. The metal powder which is propelled towards the melt pool interacts with the shoulder of the previous track (see Fig. 2). The pool is inclined in one direction and there are a considerable number of escape routes for the ricocheting powder particles.

Powder catchment efficiencies noted in the technical literature cover a large range but are frequently substantially below 50% [14-19].

In order to establish a more controllable and efficient process, this paper investigates the concept of laying down more widely spaced clad tracks using one set of parameters ('A' tracks), and then filling in the gaps between these tracks with ones made with a different set of parameters (the 'B' tracks). In this way, all 'A' tracks will be identical in shape and dilution etc. and the same will be true of all 'B' tracks.

This work investigates the possible advantages of 'ABA' laser cladding compared to traditional 'AAA' cladding. In particular the work compares the performance of the two techniques as regards powder catchment efficiency and deposition/coverage rates.

Also, the possibility of cladding dissimilar metals as the 'A' and 'B' tracks is investigated.

2. Experimental methods

Laser cladding was performed using an IPG Ytterbium-doped, continuous-wave fibre laser with a maximum peak power of 2 kW operating with a coaxial nozzle powder feeder. In most of the experiments, the powder was AISI 316L stainless steel and the substrate was AISI 1023 bright drawn mild steel. Additional experiments were carried out which utilized Stellite 6 for the 'B' tracks. The powder feed rate was 25g/min in all cases. The powder catchment efficiency was calculated by comparing this feed rate with the number of grams per minute deposited, see equation 1.

$$E_{pc}(\%) = \frac{A_{track} \cdot v \cdot \rho}{PFR} \cdot 100 \quad (1)$$

Nomenclature

E_{pc} = powder catchment efficiency (%)

A_{track} = Cross-sectional area of a track above the original line of the substrate (mm^2)

v = Process speed (mm/min)

ρ = Density of cladding material (g/mm^3)

PFR = Powder feed rate (g/min)

The process speed (i.e. the movement speed of the CNC table) was varied from a value of 1.0m m/min to 3.2 m/min. Samples were created with a variety of inter-track spacings. Clad samples were sectioned, polished, and etched in aqua regia.

Fig. 3 shows a simplified diagram of an 'ABA' sample which gives details of how the samples were created and subsequently sectioned. The actual samples involved 8 similar, parallel 'A' tracks interspersed with 7 'B' tracks made in the same direction. Tracks were completed with different A-B lateral spacings. In the interests of brevity, only a selection of results is presented here.

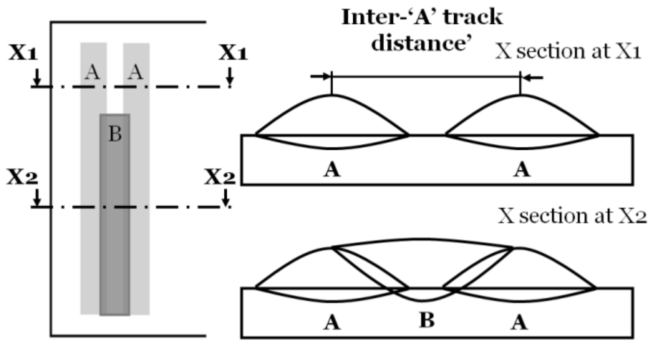

Fig. 3. ABA clad sample design.

3. Results and discussion

3.1. Improvements in powder catchment efficiency

Fig. 4 shows the powder catchment efficiency for a sequence of tracks which made up 'AAA' cladding with the following parameters;

- Laser Power: 1800W
- Cladding speed: 1.0 m/min
- Powder feed rate: 25g/min
- Inter-track spacing:1.5mm

It is clear that, for 'AAA' cladding, the initial 'A' track has a higher powder catchment efficiency (57%) than any of the subsequent tracks. The second track has an efficiency of only 35% and, after the first four tracks, the process becomes stable, with an average powder catchment efficiency of 45% (11.3g/min). This figure is considerably below the powder catchment efficiencies measured for 'ABA' cladding using similar parameters for the 'A' tracks.

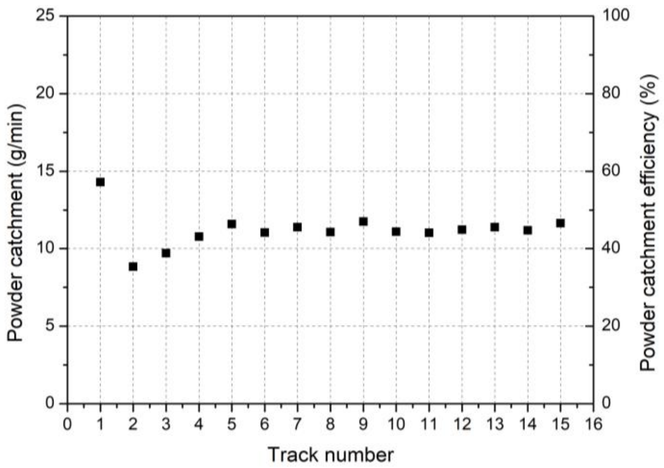

Fig. 4. Powder catchment efficiency for 'AAA' cladding. The efficiency was calculated from the cross-sectional area of each track as compared to the expected cross-section if 25g/min of powder was melted.

For 'ABA' cladding, there is no need to establish a build-up to a stable track geometry because all the 'A' tracks have the same melt pool geometry. This is also true of the 'B' tracks although in almost all cases of 'ABA' cladding it was found that the powder catchment efficiency when laying down the 'B' tracks was much higher than it was for the 'A' tracks.

'ABA' cladding presents the incoming powder cloud with a very effective powder catchment geometry for the 'B' tracks as the melt pool is effectively held in a valley between two previously deposited 'A' tracks, see Figs. 5 and 6.

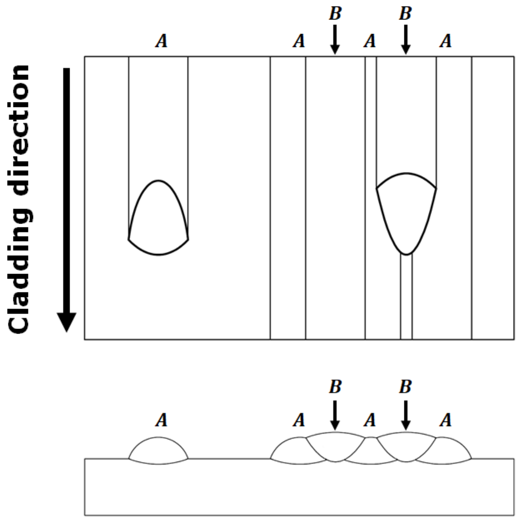

Fig. 5. A schematic of ABA cladding demonstrating the absence of start/finish anomalies and the pool geometry which results in improved powder capture.

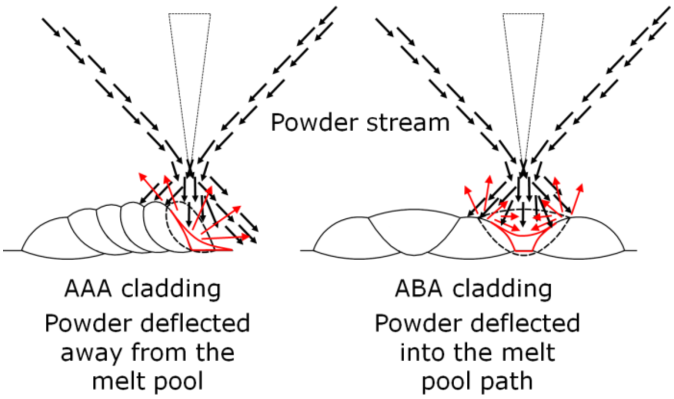

Fig. 6. In the case of AAA cladding a considerable proportion of the powder can be deflected away from the melt pool. In the case of ABA cladding more powder is deflected into the melt pool.

The improved powder catchment of the 'B' tracks of 'ABA' cladding means that 'B' tracks will have a greater cross-section than 'A' tracks if the same process parameters are used for both types of track. This can result in an uneven, ridged, clad surface, as shown in Fig. 8a. An optimized cladding process should result in a level clad surface which minimizes any post-processing costs. In order to level out the surface, the cladding speed for the 'B' tracks was increased. This strategy also increases the coverage rate of the overall cladding process.

Fig. 7 presents powder catchment efficiency results for 'ABA' cladding produced with increasing 'B' track speeds at the following parameters:

- Laser Power: 1800W
- Cladding speed ('A' tracks): 1.0 m/min
- Cladding speed ('B' tracks): 1.0 – 2.0 m/min
- Powder feed rate: 25g/min
- Inter-track spacing: 2.1mm and 3mm

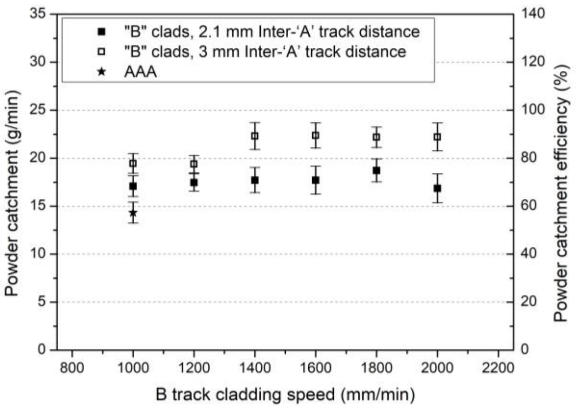

Fig. 7. Powder catchment efficiency for the 'B' tracks of 'ABA' cladding at various cladding speeds (powder feed rate is 25g/min in all cases).

The 1.0 m/min results in Fig. 7 include the catchment efficiency for the eight 'A' tracks laid down before the 'B' tracks were added at a range of cladding speeds. This value (57%) is the same as for the first track of the 'AAA' sample discussed in Fig. 6, as these 'A' tracks were laid down with the same parameters. The rest of the data in figure 7 give details of the powder catchment efficiency of the 'B' track weld pools at different processing speeds for two inter-track distances. The powder catchment enhancement for 'ABA' cladding is clear in these results. For an 'A' track inter-track spacing of 2.1mm the average powder catchment efficiency for the 'B' tracks over this range of cladding speeds was 70%, with a range from 67% to 75%. For a larger 'A' track inter-track spacing of 3mm, the average powder catchment efficiency for the 'B' tracks was 85% over a range from 77% to 89%.

As the 'B' track maximum average, in this case, was 85% and the 'A' track average was 57% this gives an average powder catchment efficiency for the process of 71%. This figure is a substantial improvement on the average value of AAA cladding of 45% (see fig. 6.).

Figs. 6 and 7 support the idea that, within limits, a broadening of the separation between the 'A' tracks will result in better powder capture.

3.2. Improvements in coverage rate

As Fig. 8 demonstrates, an improved, flat clad surface was achieved in this case when the cladding speed of the 'B' tracks was double that of the 'A' tracks. This increase in speed for half of the tracks involved obviously improves the coverage rate. It is difficult to produce precisely similar clad surfaces from both techniques so direct comparison is not possible but, taking Fig. 6 and 7 as an example, the average powder catchment efficiency of the 'ABA' technique (with 'A' track separation of 3mm) is approximately one and a half times that of the 'AAA' method and a similar increase in general cladding productivity could also be expected in this case. It is worth noting that the 'ABA' technique is applicable to spiral cladding of rods and tubes as well as other surface geometries.

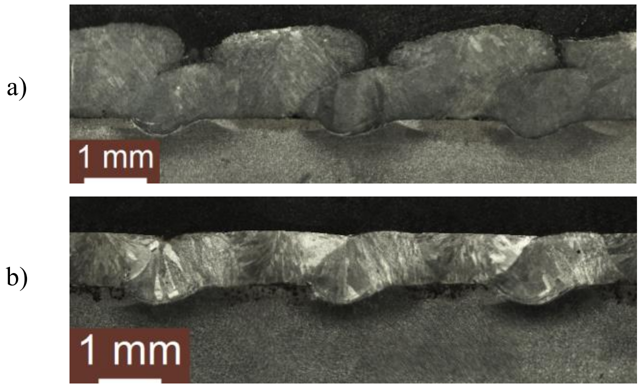

Fig. 8. ABA cladding with a) 'A' and 'B' tracks clad with the same parameters, b) 'A' tracks at 1m/min, 'B' tracks at 2m/min.

Productivity might also be improved by the point that, because of the nature of the process, 'ABA' cladding could involve wider spacing between the tracks compared to 'AAA' cladding. This means that fewer tracks could be needed to cover a particular surface area.

One further point in favour of 'ABA' cladding is that improved powder catchment reduces the need for powder recycling and minimizes the wastage of expensive alloy powders.

3.3. ABA cladding with different materials

In the early days of laser hardening, it was quickly realized that a continuous, hard surface was not always the most cost-effective way to use the technology. Individual stripes of the hardened zone were much faster (and cheaper) to produce and any softened (annealed) areas to each side of the hardened areas can wear away to provide conduits for lubricants [20,21]. The hardened stripes then locate the movement of the parts and minimize general wear. The same principle can be applied to 'ABA' cladding. Fig. 9 presents cross-sections of 'ABA' clad surfaces where the 'A' tracks are 316 stainless steel and the 'B' tracks are Stellite 6.

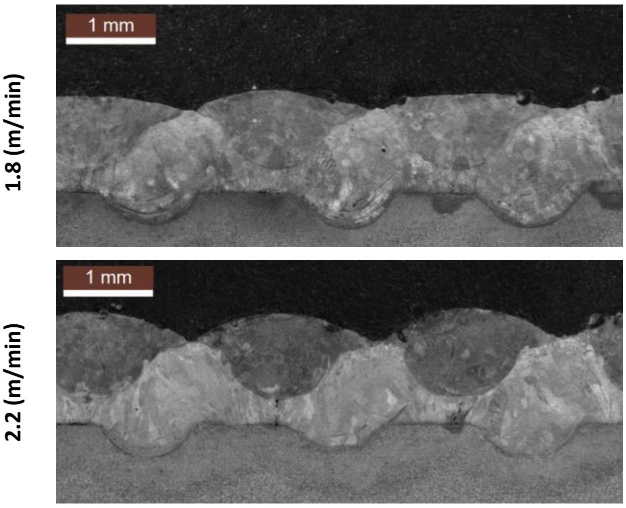

Fig. 9. ABA cladding with different materials. In this case, the 'A' tracks were 316 stainless steel, the 'B' tracks were Stellite 6.

This technique could be used to save costs on expensive superalloys or to allow incompatible clad/substrate combinations to be clad where an intermediate layer of 'A' material separates tracks of 'B' material from the substrate.

4. Conclusions

- 'ABA' cladding offers new opportunities to the cladding process as regards powder usage, coverage rates and cladding of different combinations of materials.
- In the case presented here powder catchment efficiencies were increased from an average of approximately 45% to 71%.
- Coverage rates in the above work were substantially improved using ABA cladding. Speeds of coverage were increased to 150% of their AAA cladding equivalent, although it is difficult to quantify the different clad surfaces generated.
- Different metals can be clad as an ABA sandwich. In this case, Stellite 6 'B' tracks were interspersed between 316 stainless steel 'A' tracks. This technique may have technical and commercial advantages which have yet to be explored.
- A further advantage of ABA cladding over the standard AAA technique is that there is no initiation phase to the process before repeatable tracks are laid down. This means that track morphology, dilution and local metallurgy will be more predictable and evenly distributed over the clad layer.

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References

[1] Gnanamuthu DS. Laser Surface Treatment. Proc. Conf. Applications of lasers in materials processing. 1979. American Society for Metals.
[2] Steen WM, Powell J. Laser Surface Treatment. Materials in Engineering. Vol.2 No3. 1981.
[3] Powell J. Laser Cladding. (PhD thesis. Imperial College, London University) 1983.
[4] Kaplan AFH, Powell J, Gedda H. Laser:Powder:substrate interactions in laser cladding and casting. Int. J. of Microstructure and materials properties 5 (2/3):164 – 177 (Oct 2010). DOI: 10.1504/IJMMP.2010.035937
[5] Gedda H, Powell J, Kaplan AFH. A process efficiency comparison of Nd:YAG and CO_2 laser cladding. Proc. ICALEO 2002: 21st International Congress on Laser Materials Processing and Laser Microfabrication DOI: 10.2351/1.5066172.
[6] Siva Prasad H, Brueckner F, Kaplan AFH. Powder incorporation and spatter formation in high deposition rate blown powder directed energy deposition. Additive Manufacturing 35 (2020): 101413 doi:j.addma.2020.101413.
[7] Naesstroem H. Phenomena in laser based material deposition. PhD thesis Lulea University of Technology May 2021. ISBN: 978-91-7790-820-3.
[8] Ocelík V, Nenadl O, Palavra A, De Hosson JT. On the geometry of coating layers formed by overlap. Surface and Coatings Technology. 2014 Mar 15;242:54-61.
[9] Li Y, Ma J. Study on overlapping in the laser cladding process. Surface and Coatings Technology. 1997 Mar 15;90(1-2):1-5.
[10] Gao W, Zhao S, Liu F, Wang Y, Zhou C, Lin X. Effect of defocus manner on laser cladding of Fe-based alloy powder. Surface and Coatings Technology. 2014 Jun 15;248:54-62.
[11] Nenadl O, Ocelík V, Palavra A, De Hosson JT. The prediction of coating geometry from main processing parameters in laser cladding. Physics Procedia. 2014 Jan 1;56:220-7.
[12] Barr C, Da Sun S, Easton M, Orchowski N, Matthews N, Brandt M. Influence of macrosegregation on solidification cracking in laser clad ultra-high strength steels. Surface and Coatings Technology. 2018 Apr 25;340:126-36.
[13] Ya W, Pathiraj B, Matthews DT, Bright M, Melzer S. Cladding of Tribaloy T400 on steel substrates using a high power Nd: YAG laser. Surface and coatings technology. 2018 Sep 25;350:323-33.
[14] Lin J, Steen WM. An in-process method for the inverse estimation of the powder catchment efficiency during laser cladding. Optics & Laser Technology. 1998 Mar 1;30(2):77-84.
[15] Partes K. Analytical model of the catchment efficiency in high speed laser cladding. Surface and Coatings Technology. 2009 Oct 25;204(3):366-71.
[16] da Silva MD, Partes K, Seefeld T, Vollertsen F. Comparison of coaxial and off-axis nozzle configurations in one step process laser cladding on aluminum substrate. Journal of Materials Processing Technology. 2012 Nov 1;212(11):2514-9.
[17] Lee YS, Nordin M, Babu SS, Farson DF. Influence of fluid convection on weld pool formation in laser cladding. Weld. J. 2014 Aug;93(8):292-300.
[18] Chen L, Zhao Y, Song B, Yu T, Liu Z. Modeling and simulation of 3D geometry prediction and dynamic solidification behavior of Fe-based coatings by laser cladding. Optics & Laser Technology. 2021 Jul 1;139:107009.
[19] Donadello S, Furlan V, Demir AG, Previtali B. Interplay between powder catchment efficiency and layer height in self-stabilized laser metal deposition. Optics and Lasers in Engineering. 2022 Feb 1;149:106817.
[20] Gnanamuthu DS, Shankar VS. Laser Heat treatment of iron-base alloys.in; Laser Heat Treatment of Metals eds; Draper CW, Mazzoldi P. NATO ASI series E. Applied sciences No 115. pp 413-433
[21] Eberhardt G. Survey of high power CO_2 industrial laser applications and latest laser developments. Proc. First Int. Conf. on Lasers in Manufacturing. Brighton UK 1983 pp 13-19 pub; IFS publications.