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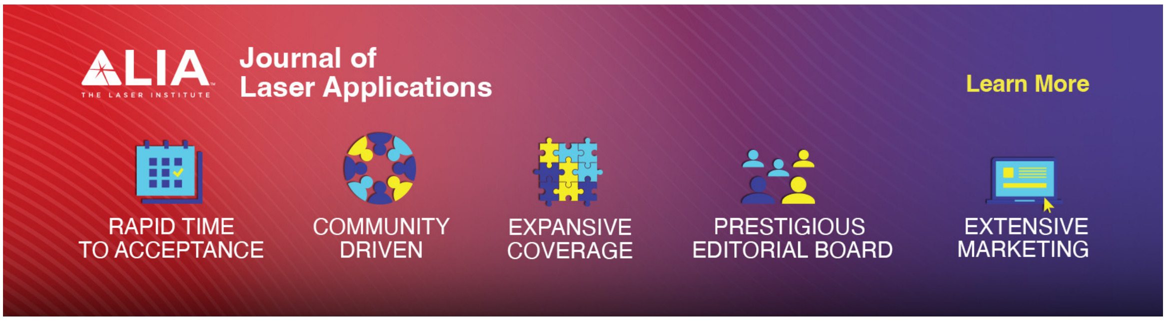

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ABSTRACT

This paper provides guidelines and advice to researchers and engineers in the field of laser cladding and related direct energy deposition techniques to help establish a standardized approach to quality assessment and productivity metrics. Factors considered are deposit geometry, porosity, cracking, dilution, build-up/coverage rate, and powder catchment efficiency.

Key words: laser cladding, laser direct energy deposition, quality, porosity, cracking, powder catchment efficiency, productivity

I. INTRODUCTION

Although there is a very large body of research work on laser cladding and related direct energy deposition (DED) techniques, there are no clear guidelines about which quality and productivity parameters are important to the relevant branches of industry, nor are there any general rules about what constitutes a high-quality deposit. It is the aim of this paper to provide such guidelines for researchers in the area.

The great majority of laser DED/cladding research concentrates on the comparison of individual clad tracks like the one marked "A" on the left hand side of Fig. 1.[1–4] Although such research is interesting and informative, it has minimal industrial relevance, as the commercial applicability of individual deposited tracks is very low. It is, therefore, not obvious whether the geometry of any particular single track is better than another. However, the eventual aim of the process is usually the production of surfaces covered in overlapping tracks (like those labeled $\mathbf{A_1}$ to $\mathbf{A_n}$ on the right of Fig. 1 and presented in cross section in Fig. 2), which require minimal machining to create a flat surface. (In a limited number of cases, a rough, "as clad" surface is required rather than a flat, machined one.)

Some initial guidelines about what to aim for can be stated which are true for single or multiple tracks:

(1) Minimal fluctuations in track height (to minimize post-cladding machining and areas with insufficient clad material).
(2) No porosity or undercut (undercut can lead to trapped pores between tracks).
(3) No cracks.
(4) An acceptable level of substrate-cladding dilution.
(5) Maximum coverage or build-up rate (for maximum productivity).
(6) Maximum powder capture (for minimum powder recycling and optimum process efficiency).

The following sections discuss these points in detail, dividing them into quality and productivity considerations.

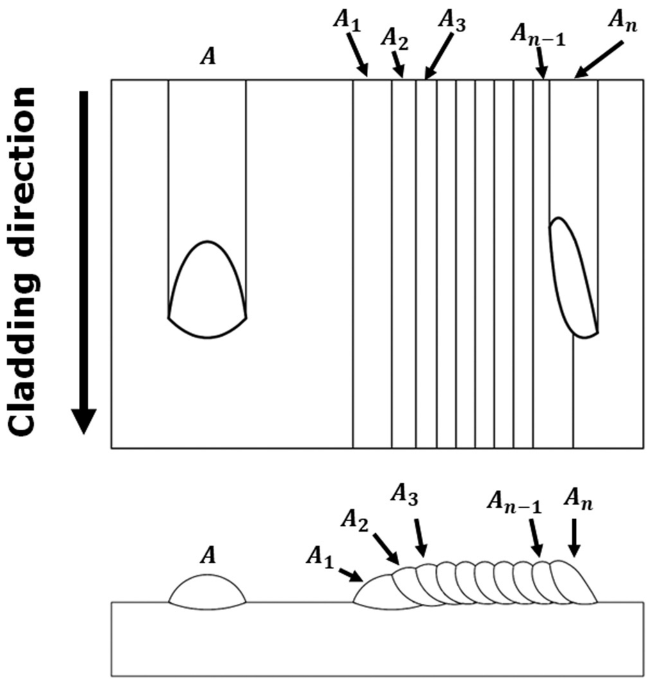

FIG. 1. Schematic plan views and cross sections of a single clad track and a set of overlapping tracks making a clad surface.

II. QUALITY CONSIDERATIONS

A. Deposit geometry

Figure 1 outlines a fundamental problem found when trying to produce a flat clad surface from ostensibly identical overlapping tracks. Before the second track is laid down, the first track (A) is a solo clad track with a cross section that is approximately a segment of a circle. Subsequent tracks have a different cross-sectional geometry as they are laid down on the "shoulder" of the previous track. This means that several tracks need to be laid down before a repeating cross sectional track geometry is established. The final track of a layer also has a different geometry because it is not partially remelted by a subsequent track.

Laser clad surfaces usually need to be machined to a flat surface before use, and this will involve the removal of part of the clad deposit. The amount of material that needs to be removed should be minimized because machining is an expensive process in itself, and the wasted powder and energy used to create the discarded layer is also costly. Post-cladding machining is minimized

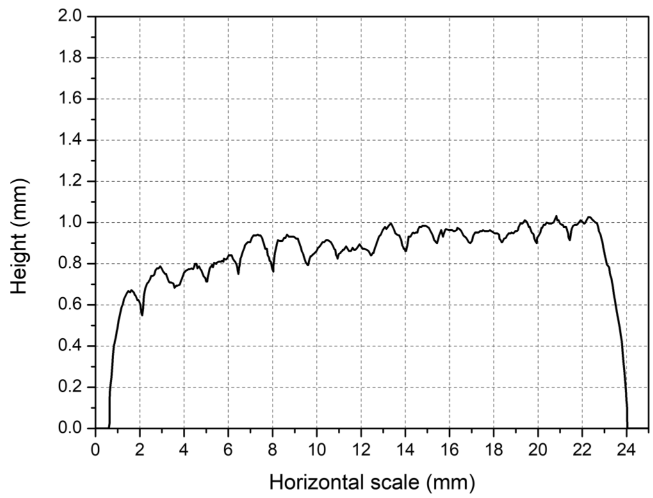

FIG. 3. A typical example clad layer cross section profile. The biggest variation in clad height is the macroscopic waviness between tracks rather than along the length of any single track.

by creating clad surfaces that have a minimum fluctuation in cross sectional height.

One important consideration when looking at multiple, overlapping tracks is that the maximum fluctuation in clad height often occurs between tracks rather than along the length of the individual tracks (see Fig. 3). For this reason, the maximum height variation of the surface needs to be measured over a substantial area or at least in two orthogonal directions (for several tens of millimeters if possible). Maximum height variation in roughness is usually given as Rz but roughness measurement devices often gives a value for local Rz, which ignores macroscopic waviness of the sample surface. For this reason, we suggest that waviness (Wz) is the appropriate roughness metric for clad surfaces and similar DED products. It should be noted, however, that in some industrial applications where a rough surface is preferred, the as-deposited surface is used without post-cladding machining.

B. Porosity

Pores in clad tracks are negative features that need to be minimized or avoided altogether. Pores within the body of the clad layer can be revealed during postcladding machining and give rise to an open pored, rough surface rather than the generally required smooth one. Open pores of this type can also be stress raisers that

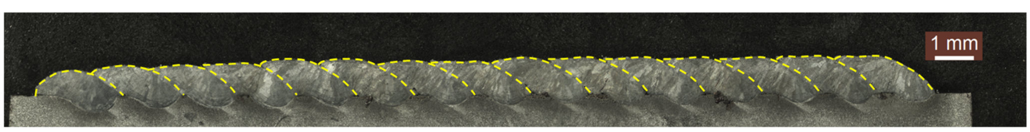

FIG. 2. A macroscopic cross section of a typical clad layer made from overlapping tracks.

can have a deleterious effect on the tensile strength and fatigue life of the clad component.[5]

The sources of porosity in laser cladding and DED include moisture in the powder or powder feed gas, a melt pool with too short a lifetime, excessive powder flow or powder feed gas, and impurities in the cladding material or the substrate. Problems can be reduced or eliminated by the following control measures:[6]

- Remove scale, rust, paint, grease, oil, and moisture from the substrate.
- Eliminate moisture from the powder and gas.
- Keep the cladding pool molten for long enough (e.g., by preheating) for gas to escape.
- Minimize the sulfur content of the substrate to prevent generation of hydrogen sulfide.
- Reduce cladding speed or increase laser power.

The distribution of pores in clad layers may be aligned, clustered, or uniformly scattered,[7] and the present authors recommend a two-part porosity metric that indicates overall porosity as a percentage of the solidified melt, followed by an average pore diameter. For both numbers, a reduction in their value can be taken as an indication of an improvement in clad quality. Levels of porosity can be assessed by radiography, and computer interpretation of the x-ray images is now an established technique.[8]

As porosity is never a required feature of a clad track, we recommend that porosity should be zero in cladding and related DED processes.

C. Cracks

Cracks can form in laser-deposited single tracks or surfaces for all the usual reasons associated with welding. As clad surfaces tend to be thin compared with the substrate they are attached to, cladding/DED is susceptible to cold cracking mechanisms associated with the restraint of the cooling weld material.[9] Hot cracking, caused by the presence of low melting point constituents that fail in tension during solidification, can also be a problem. Alloys that have a wide solidification temperature range are particularly susceptible to hot cracking.[6]

The natural tendency to use high process speeds to maximize productivity can increase levels of cracking. The incidence of cracking can be reduced by reducing process speeds, increasing laser power, and the use of preheating/postheating. It is also important that the substrate surface is completely free of contaminants.

The number of cracks in a clad layer can be reduced by changes in process parameters or by changing the cladding alloy.[10] In some cases, this change in alloy can be brought about by increasing or decreasing the amount of dilution in the clad layer (see next section). Another option is to add a "butter" layer of an alloy that is compatible with both the substrate and the outer clad layer. "Cracks" can also be created as sharp interfacial flaws between the substrate and the deposited layer, and this is sometimes associated with poor wetting between tracks or at the lateral edges of individual tracks.[11]

Cracks of any type can compromise the mechanical stability of a clad layer, and the present authors would like to suggest that the presence of cracks is so deleterious to the clad product that their presence should be eliminated. If cracks are unavoidable in a particular application, then they should be minimized. It is important to remember that reducing the size of cracks does not necessarily improve the performance of a product. Several small cracks can be a worse outcome than a few larger cracks.

Surface cracks can be identified by several nondestructive testing techniques including visual inspection, magnetic particle inspection, and liquid penetrant inspection.[12,13] Subsurface and surface defects can be identified by ultrasonic testing,[14] radiography,[8] and thermography.[15]

D. Dilution

Dilution is widely used as a measure of quality in laser cladding and is generally understood to mean how much of the substrate has been melted into the final clad layer. Cladding materials are expensive and designed to offer high levels of hardness or corrosion resistance to the surface. Excessive dilution usually diminishes the surface hardness or corrosion resistance. For this reason, low levels of dilution are generally preferred in laser cladding, though some dilution is unavoidable, as some interfacial mixing of the substrate and the clad material is required to make the welded bond. Target dilution values vary but tend to be in the range of 3%–5%.[16]

However, in some cases, high dilution levels might be beneficial to the properties of the clad layer by lowering hardness, increasing ductility, and reducing, or eliminating, cracking and porosity. Some applications also demand relatively high levels of dilution to ensure a good substrate-cladding material bond.

For example, the surface properties of aluminum alloys can be enhanced by laser cladding with other metals or superalloys. Researchers in the field recommend a dilution of at least 10% to create a successful bond in some cases.[17,18] Laser cladding high entropy alloys are another application where high dilution levels can be useful. HEA coatings with low dilution levels usually have poor formability, and this can be improved by increasing the level of substrate melting.[19]

Dilution is usually expressed as a percentage, where, for example, 20% dilution indicates that the solidified clad melt is made up of a mixture of 80% cladding alloy and 20% substrate alloy by volume.

However, it should be borne in mind that dilution levels generally give an indication of the overall percentage of the substrate melted into the clad and do not indicate the steep dilution gradients that may exist within the clad layer. If a sample has, for example, an estimated 10% dilution, then the local dilution level of 0.1 mm from the substrate-clad interface might be 60%, but on the clad outer surface, the level might be 2% or lower. At any melt-solid interface, such gradients will be very steep in transition from the clad layer to the substrate. Also, samples created under different processing parameters might exhibit widely different dilution gradients dependant on the level of stirring forces generated in the melt. Given these complications, it is not surprising that most researchers only present overall dilution levels, which can be useful in comparing results within a parameter set.

The most common method of estimating overall or average dilution used by researchers[20–25] divides the cross-sectional area of the substrate melt by the area of the whole melt. This gives us a

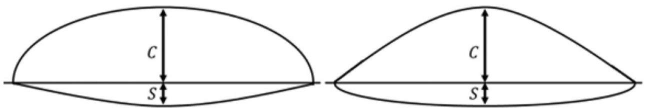

FIG. 4. Two clad tracks with the same D_{HEIGHT} but different D_{AREA}.

value we can call D_{AREA},

$$D_{AREA} = (A_S/(A_C + A_S)) \times 100, \quad (1)$$

where As is the cross-sectional area of the melted substrate and Ac is the cross-sectional area of the clad layer above the original top surface of the substrate.

Another common method of estimation[26–29] simply divides the maximum depth of melt penetration into the substrate by the overall melt depth of the clad layer (see Fig. 4). This gives a value we can call D_{HEIGHT},

$$D_{HEIGHT} = (S/(S + C)) \times 100. \quad (2)$$

However, Fig. 4 demonstrates that, in some cases, D_{HEIGHT} is not equivalent to D_{AREA}.

In Fig. 4, the two clad cross sections have the same width, depth, height, and, therefore, the same D_{HEIGHT}. However, the differences in geometry mean that the D_{AREA} of the left-hand track is 18% and that of the right-hand track is 30%.

From this observation, it is clear that D_{HEIGHT} does not give a reliable estimation of overall dilution levels for single tracks. Differences between D_{HEIGHT} and D_{AREA} will also exist, but to a lesser extent, for any clad layer of overlapping tracks, as the clad layer is not rectangular in cross section.

We, therefore, recommend that D_{AREA} should be used in preference to D_{HEIGHT}. It is also worthy of note that D_{AREA} only gives an average volumetric measurement. In the field of metallurgy, alloy combinations are usually given in weight %. If average wt. % results are required, then the D_{AREA} calculation needs to take the relative densities of the substrate and the cladding feedstock into account.

Detailed chemical dilution analysis is based on measured values created by the spectrographic (e.g., EDX) analysis of the samples.[30–33] EDX and related techniques can give information about dilution gradients in cases where the average dilution measurement needs clarification.

III. PRODUCTIVITY CONSIDERATIONS

A. Coverage or build-up rate

From the manufacturing engineer's point of view, there is a requirement to minimize costs. The costs of laser cladding and related DED processes include the expenditure on electricity, staff, overheads, and raw materials (powder, etc.). An increase in productivity is usually associated with a reduction in the time spent creating a product and, thus, a reduction in some or all of these costs.

Researchers are usually primarily concerned with analyzing the process itself, often comparing KPI's between several process parameters. Industrial users are interested in quality and productivity, wishing to optimize both.

Coverage rate or build-up rate is a measure of productivity, which describes how quickly the required clad surface is created. Obviously, this is heavily dependent on the required thickness of the finished, machined, clad layer. Coverage rate might, therefore, be measured in several ways:

(1) area of substrate covered per unit time (mm^2/min);
(2) volume of clad layer per unit time (mm^3/min); and
(3) mass of clad layer applied per unit time (g/min).

An increase in any of these would imply an increase in productivity, but a rapidly applied rough surface (high Wz) might have a lower coverage rate than a slowly applied smoother one, as extra postcladding machining required would reduce the thickness of the final clad layer.

Researchers are often interested in improving industrial performance so the present authors suggest that any comparative measure of cladding processes should take into account the thickness of the final, machined surface.

As researchers generally do not know the required thickness of the clad layer, they cannot state that, for example, sample A, a 0.2 mm thick layer laid at 10 mm^3/s, is a better or worse result than sample B, a 0.4 mm layer also laid at 10 mm^3/s. However, a distinction between the two is important and would not be supplied by a mass or volume per unit time metric. The present authors, therefore, suggest that the area covered is not multiplied by the clad thickness in any such measurement of the coverage rate. From an industrial point of view, the two figures (area/time and thickness) are more usefully presented as a compound metric as follows:

Coverage rates:
Sample A: 50 $mm^2/s \times 0.2$ mm,
Sample B: 25 $mm^2/s \times 0.4$ mm,

with the thicknesses being the final, machined flat thickness (i.e., maximum clad height minus surface waviness).

B. Powder catchment efficiency

Although some laser cladding and DED processes use wire as a feedstock, the majority use powder. The powder used in these processes generally has a carefully controlled chemistry and specific physical properties (spherical particles with a certain size distribution) and is, therefore, expensive. The powder catchment efficiency of the process is simply the percentage of the powder fed into the cladding zone, which becomes part of cladding (in this case, we are talking about the premachined clad). Powder catchment efficiency is an important metric for the laser cladding industry as it has a direct influence on the cost of the process. It is, therefore, surprising that it is only rarely mentioned in research papers.

For technical investigations, the powder catchment efficiency (E_{pc}) can be calculated using cross sections of the clad layer and knowledge of the process parameters as follows:

$$E_{pc}(\%) = (T_{area} \times v \times \rho)/F_p \times 100, \quad (4)$$

where E_{pc} is the powder catchment efficiency (%), T_{area} is the cross-sectional area of a single track above the original line of the

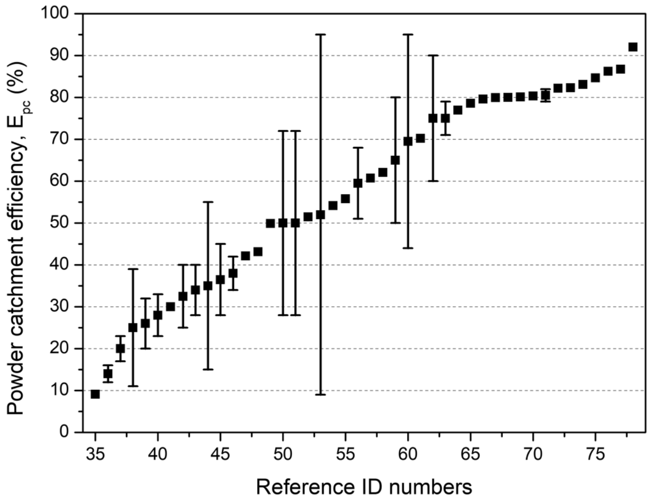

FIG. 5. Powder catchment efficiency results calculated from published experimental results.

substrate surface (mm^2), v is the process speed (mm/min), ρ is the density of the cladding material (g/mm^3), and F_p is the powder feed rate (g/min).

The work by the present authors has analyzed the powder catchment efficiency achieved in a large number of published experimental papers, and the results are presented in Fig. 5.[34–78] In some publications, the powder catchment values were explicitly noted by the authors, but in many cases, the catchment efficiency had to be calculated from the given process parameters and cross section images. The x axis numbers on this figure refer to the reference numbers of the papers listed at the end of this paper.

It is clear from Fig. 5 that the range of results of E_{pc} is very large—from below 10% to above 90%. Bearing in mind the cost of these powders, it is obviously important to maximize this value wherever possible. It is also worth noting that the process usually depends on the flow characteristics of the powder, and this can be badly affected by contaminants or powder particles, which have been fused together. This greatly restricts the reuse of powders, which were not incorporated into the clad.

It is the view of the present authors that E_{pc} should become an important, basic metric of any cladding/DED research or industrial work, and values below 50% should trigger concern about the industrial viability of the specific application in question.

IV. CONCLUSIONS

The present authors suggest the following guidelines for laser cladding and related DED processes;

A. Quality guidelines

- Research into individual clad tracks is of minimal industrial relevance.
- Fluctuations in clad surface height should be as small as possible to minimize postcladding machining and areas with insufficient clad material. Height fluctuations should be measured in two orthogonal directions to find the waviness (Rw).
- Porosity should be minimized and, if possible, eliminated.
- Cracks should be eliminated (small cracks are generally no better than large cracks).
- Measure average dilution by the area method.
- Average dilution should usually be in the target range of 3%–5%, but there are case-specific exceptions.

B. Productivity guidelines

- Production time should be minimized within the constraints of adequate quality.
- Coverage or build-up rate should be maximized within the constraints of required clad thickness.
- Coverage rates should be given as a compound metric of the form Xmm^2/unit time × Ymm (thickness).
- Powder capture efficiency (E_{pc}) should be maximized and should be a major metric for industrial process validity.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

John Powell: Writing – original draft (equal); Writing – review & editing (equal). **Daniel Koti:** Writing – original draft (equal); Writing – review & editing (equal). **Xabier Garmendia:** Writing – original draft (equal); Writing – review & editing (equal). **K. T. Voisey:** Writing – original draft (equal); Writing – review & editing (equal).

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