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ACHIEVING THE POTENTIAL OF DIRECT FABRICATION WITH LASERS

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Abstract

Direct laser fabrication (DLF) is a layer by layer deposition technique with unique possibilities for development compared with other layer by layer methods associated with rapid prototyping such as steroelithography, selective laser sintering or laminated object manufacture.

This paper discusses the potential for the development of DLF by placing the technique in the context of the laser cladding technology from which it has emerged, reviewing the current stage of development and by developing some of the principles and concepts that underlie the advanced levels of development.

Keywords; Direct laser fabrication, DLF, laser cladding, variable composition, graded layers, shaped microstructure materials.

1. Introduction

Layer by layer deposition strategies for rapid prototyping have led to the development of a range of techniques which include stereolithography, laminated object manufacture and selective laser sintering amongst others. The rationale for all of these techniques is the reduction in time to market involved in the production and testing of preproduction models. It has been shown that considerable cost savings and market advantage can be delivered in this way. When sterolithography is combined with investment casting ("Quickcast") it becomes possible to produce production quality components in cast form in the required material but the rate of production is still relatively slow. For direct laser fabrication (DLF), a layer by layer deposition strategy based on laser cladding, further possibilities become available. It is a measure of the challenge facing those developing DLF that the major elements of the science and technology required to deliver these potentialities are largely undeveloped. This paper sets out to offer a perspective on this challenge.

The stages required in achieving the full potential of DLF are shown schematically in Figure 1. It can be seen that DLF is possibly the only layer by layer technique that is capable of achieving the higher potentialities of this development for components of any reasonable size. (This statement excludes microdeposition and micromachining strategies which might achieve similar results on a small scale).

To develop the full potential of DLF it is necessary to detail the background of the technique in laser cladding, to define the current state of the art and then develop what principles and concepts underlie the advanced levels of development

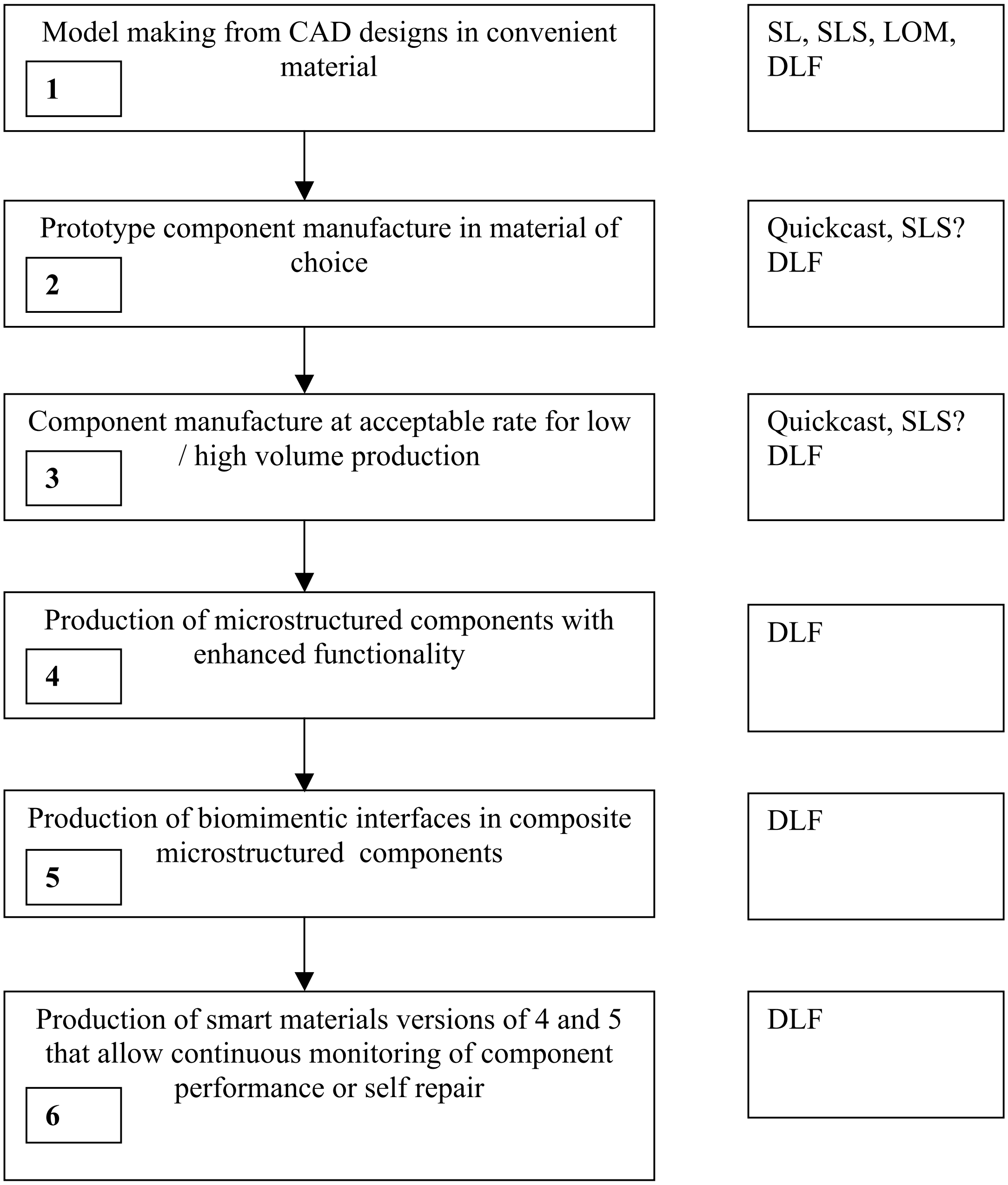


Figure 1 *Schematic of levels of potential of achievement in layer by layer deposition techniques*

2. The background in cladding

Laser cladding has been used successfully to modify surface properties of materials, particularly for improved wear and corrosion resistance [1]. This process is usually classified into either preplaced power cladding [2] or blown powder cladding [3]. To achieve the required flexibility and accuracy of the powder delivery system a computer controlled hopper powder feeder is used to feed the powder or a mixture of different powders into a laser generated melt pool [4].

In other variants of the process, now less often employed, the added material can be supplied in the form of wire or sheet. The powder feed (blown powder) method is coming to be the most applied version of the process because of the improved process flexibility and controllability that it produces.

In the system developed by Steen, Weerasinghe, Takeda et al at Imperial College [3 -7] , as shown in Figure 2, and then further developed at University of Liverpool [8-11] computer control of the powder feed system, allows one or more of the feeder screws in each hopper to be controlled to give the required powder flow rate during the formation of a laser clad track. By additional variation of the laser input power, the beam diameter and the substrate traverse speed, a range of operating conditions can be established which enables the control of the parameters required to produce the coating layer of the required thickness and quality.

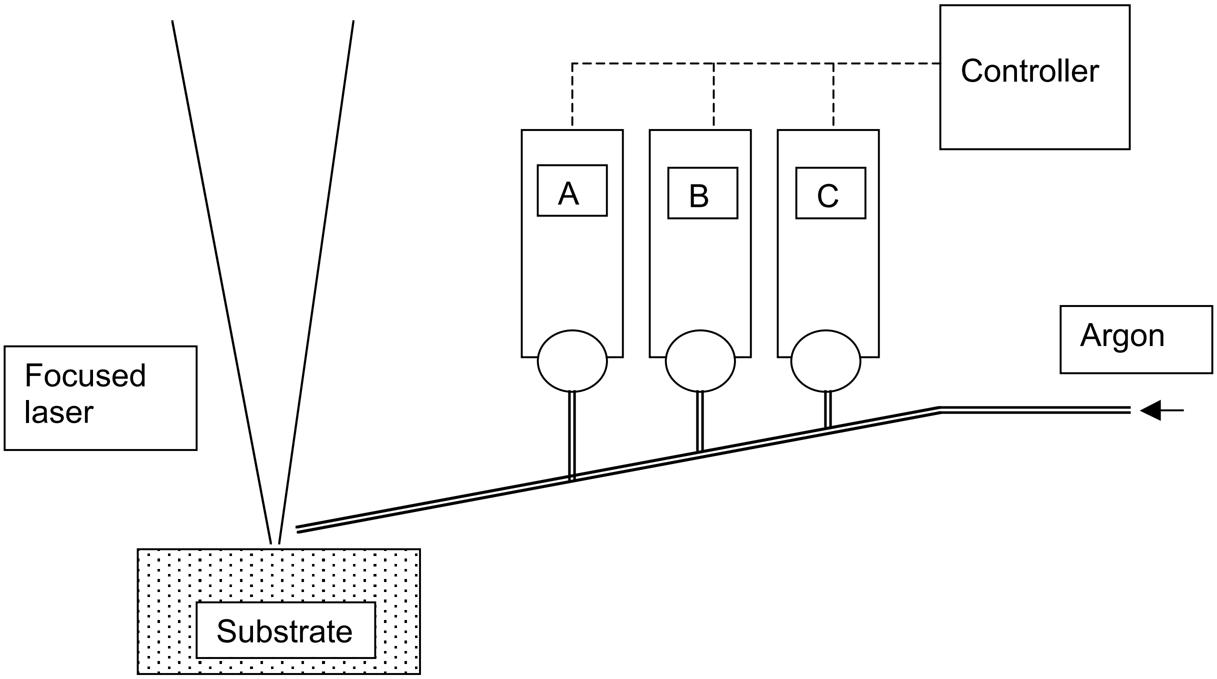


Figure 2. *Laser cladding with blown powder employing multiple powder feed hoppers*

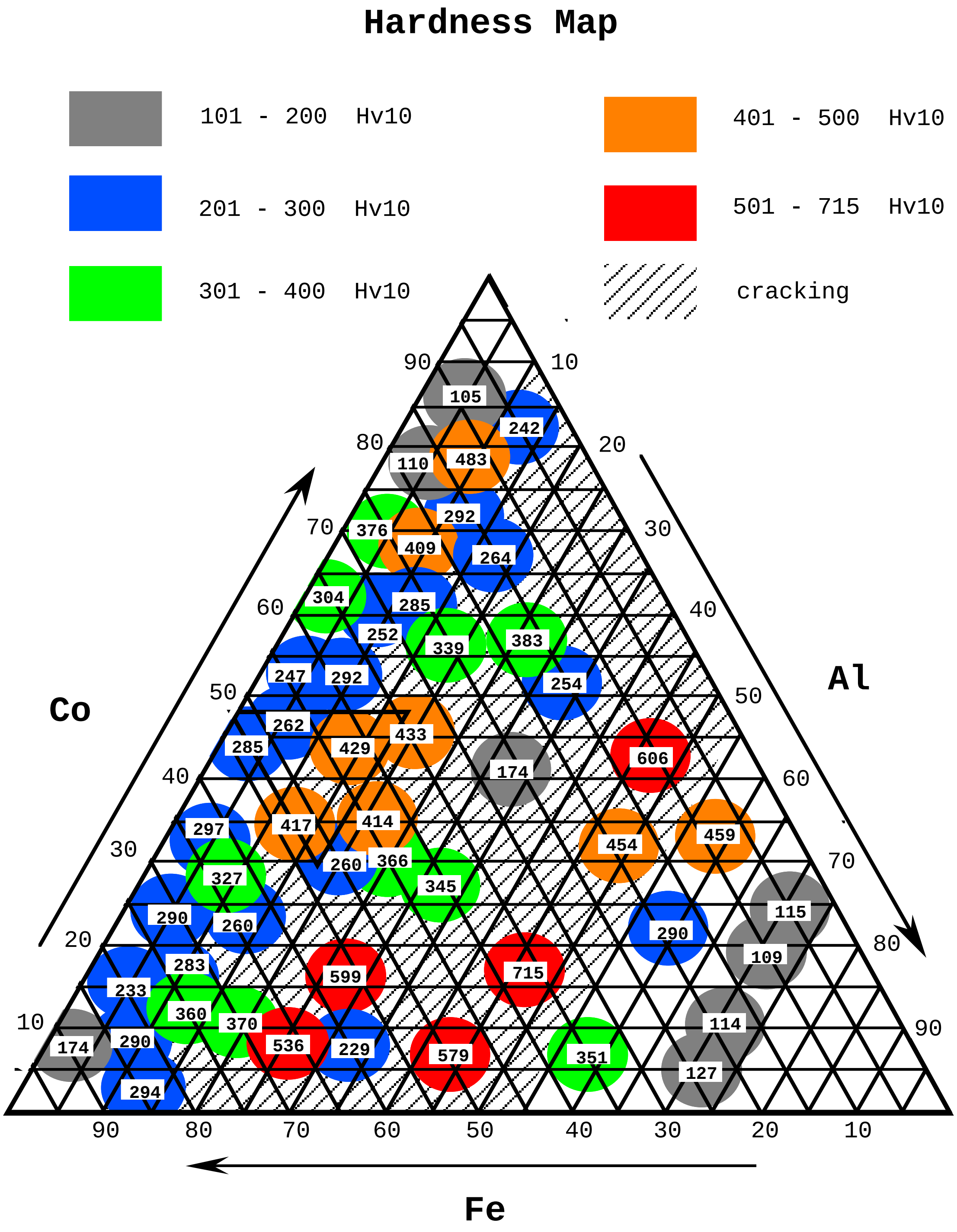


Figure 3 *Variable composition cladding results for Fe-Co-Al system: Vickers hardness as a function of composition*

The laser employed in work at Liverpool [8-11]was an Electrox 2 kW or an OPL 1.5 kW continuous wave CO_2 laser. Variable composition cladding, produced by control of the relative feed rates in the powder hoppers, was used as a means of alloy development. Evaluation techniques that are applicable to the laser melt tracks include the determination of hardness (Figure 3), wear resistance and microstructure. As shown in Figure 4 for the case of wear resistance, it is possible to select a compositional range of interest from an earlier more coarse scanning of the system to produce a more detailed and accurate assessment.

A primary objective of the cladding process is to achieve porosity free added layers with good bonding to the substrate and with low dilution of the added layer in the substrate. It was found [1 – 6] that there are three basic cross sections of such clad tracks (Figure 5). These sections illustrate the limits of successful low dilution fusion bonded cladding

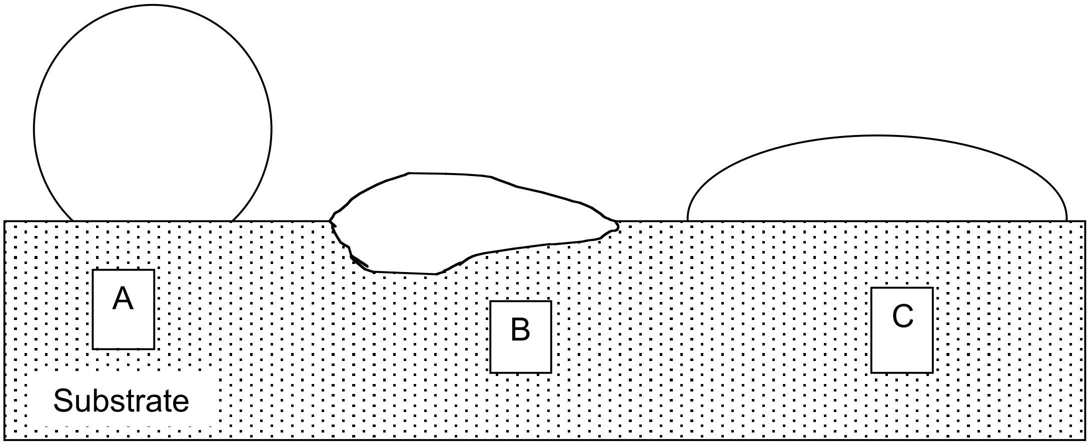


***Figure 5**. Examples of the three basic types of track transverse sections produced under different processing conditions: (A) aspect ratio incorrect for overlapping, (B) some dilution appearing, (C) good low dilution fusion bonded track.*

Profile (C) is the preferred section for overlapping tracks to cover an area. At high powder feed rates or low power densities profile (A) is produced while at low powder feed rates or high power densities profile (B) is produced. For a given traverse speed and powder flow there is an optimum spot diameter for maximising the cladding rate. A discontinuous clad or 'balling' of the track occurs when there is a lack of fusion bonding. Thus there are three limits for low dilution fusion bonded cladding:

- Onset of porosity (aspect ratio ≤ 5)
- Onset of significant dilution (upper energy balance)
- Loss of clad continuity (lower energy balance)

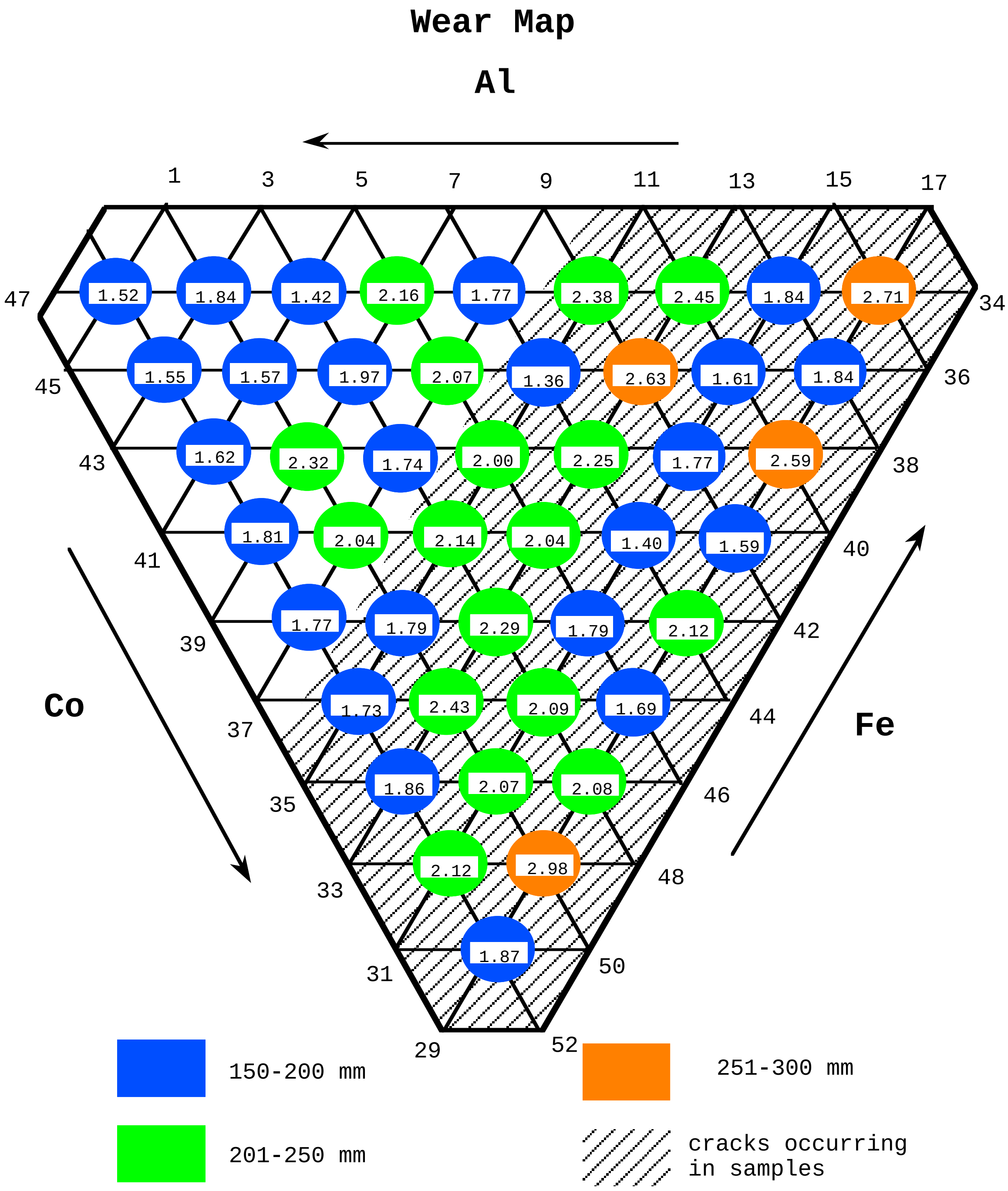


***Figure 4**. Variable composition cladding results for Fe-Co-Al system: Wear resistance as a function of composition for limited composition range deposited and assessed in more detail*

Curves showing the operating window for successful low dilution cladding were derived, as shown in Figure 6.

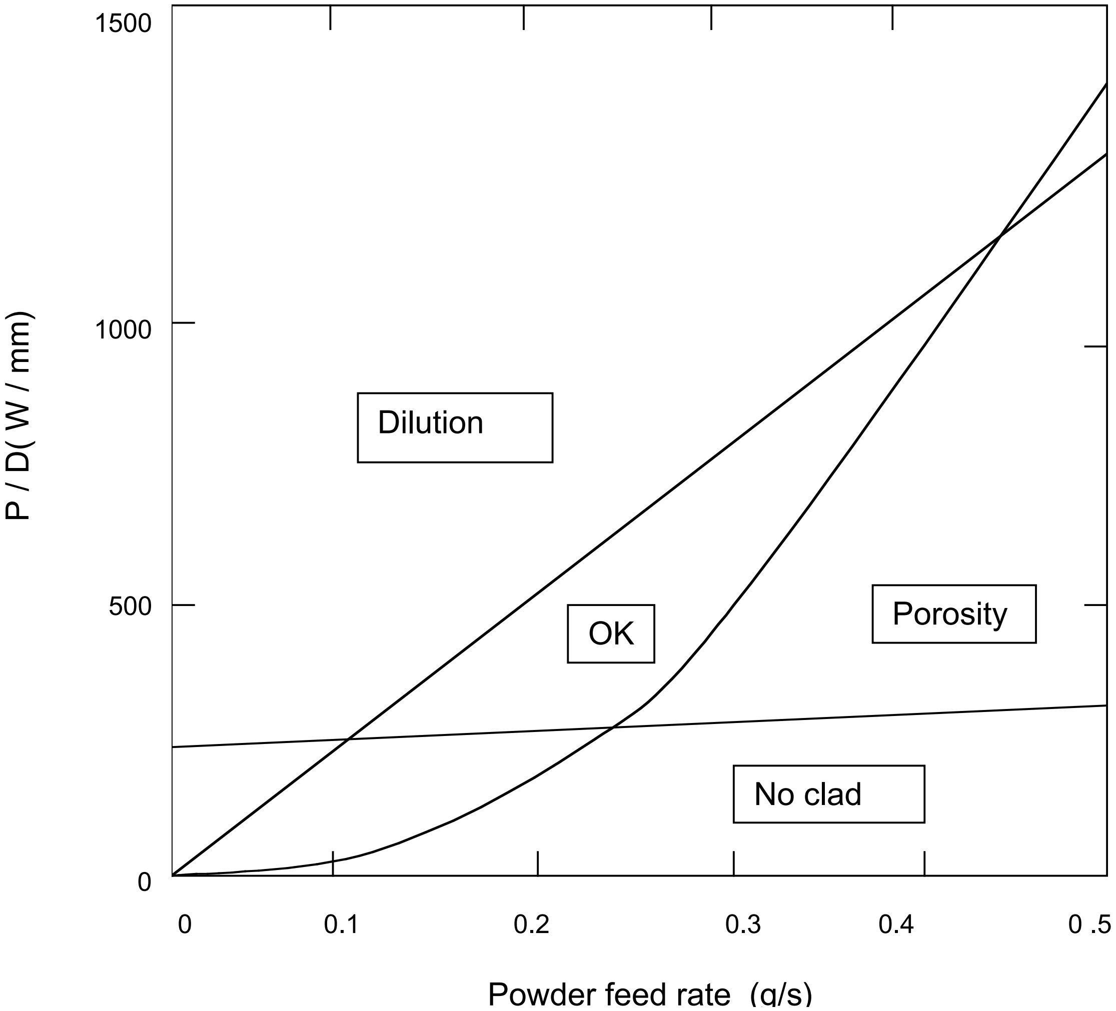


***Figure 6**. Approximate operating curves suggested by Steen. 'OK' signifies low dilution fusion bonded clad tracks*

The three limits marked on this operating chart are defined by:

<u>A dilution parameter</u> For surface cladding it is normal to attempt to limit the percentage dissolution of the added layer in the substrate to 10%. A dilution parameter was defined as

$$j = P / Dm_r \qquad 1)$$

where P is laser power (W), D is incident beam diameter (mm), m_r is the powder feed rate (g/s) and j is the dilution parameter to avoid significant dilution (J/g mm). Various factors which affect the dilution parameter are:

-increasing temperature of the melt pool during continuous cladding causes dilution to increase,

-preheating the powder reduces the thermal load of the powder thereby increasing levels of excess energy thus increasing dilution.

-powder feed angle: at glancing angles the powder catchment efficiency in the melt pool was reduced hence excess energy was available to cause dilution,

- the degree of overlap: the larger the overlap, the smaller the dilution due to increased thickness,

- beam mode structure: A TEM01 mode has a more even power intensity distribution than a TEM00, hence dilution is reduced. Factors which do not affect dilution are:-

  - transverse speed of substrate
  - particle velocity
  - particle size.

An interrun porosity parameter: For overlap cladding, clad tracks of type A (Figure 5) will lead to porosity since pores will remain at the overalp of the tracks. This occurs when the aspect ratio falls below 5, i.e. thicker clad layers and higher mass flow rates. A good correlation exists between the aspect ratio of a single track and the onset of interrun porosity in multiple overlapped tracks. It was found that an aspect ratio (width/height) greater than 5 was required for successful overlapping of tracks. A porosity parameter is defined as:

$$g = \frac{P\upsilon}{m_r^2} \tag{2)}$$

where υ is transverse speed (mm/s) and g is the porosity parameter .

A fusion parameter: This is the lower limit for good quality continuous clad tracks. It is defined by the energy/unit area absorbed by the substrate:

$$L = P[1 - r - s] / [D\upsilon] \tag{3)}$$

where r is reflectivity, s is a shadow effect factor (to allow for the partial occlusion of the laser beam by the powder stream) and L is the fusion parameter (J/mm). The operating region is larger for higher traverse speeds due to the lack of dependence of the dilution parameter on substrate velocity.

The relevance of this analysis for DLF is apparent. At the lower limit of laser power, there will be a requirement that the fusion parameter requirement is satisfied (first at the substrate and then during added layer on added layer deposition) in order that melting takes place and a coherent well bonded deposit is produced. The requirement that the porosity parameter is satisified will be relevant for instances of DLF where track overlap is required. At the moment much research work has been carried out by building components with walls comprising single tracks and in this case the overlapping of the tracks is clearly not important. However, in the deposition of most sophisticated component shapes, this restriction will need to be lifted and consideration will need to be given to the problem of porosity arising form the overlap of tracks of low aspect ratio. Quantitatve investigation of the porosity parameter for materials systems in DLF will be of vital importance. Finally, the dilution parameter will require consideration in DLF. It is not important to consider diluton as such since, once the initial layer has been produced on the substrate, the dissolution of added material would be into a similar material. However, in more sophisticated applications of DLF the extent of the melt back on the addition of each layer (the DLF equivalent of the dilution parameter) will have a strong influence on the overall heating and cooling rates experienced by the as built component (with a further possible effect on cracking) and on the control of composition in the building of layers of graded composition . The gathering of data on the control of DLF for a given level of dilution (melt back) of, say 5 or 10 per cent which is sufficient to establish metallurgical bonding but which minimises dilution would appear to be desirable.

3. The development of DLF

Direct laser fabrication (DLF) derives from the technique of laser cladding which was developed to provide corrosion and wear resistant coatings. The Laser Group at University of Liverpool began in 1992 investigating the build up of laser clad layers to produce engineering components [12]. At about the same time, Mazumder and co-workers at University of Illinois at Urbana-Champaign [13, 14] were investigating the layer by layer deposition of aluminium alloys and tool steels. In 1994 the development of variable-composition cladding was undertaken by Liverpool in an EU SCIENCE programme in collaboration with Instituto Superior Tecnico, Lisbon [15]. The process was advanced from simple layering to the building of three dimensional fully dense metallic parts. The build materials investigated were cobalt alloys and stainless steel. The feasibility of building as-cast shapes in aerospace alloys from CAD designs was proven [16 -18].

The Fraunhofer Institute for Laser Technology (ILT), Aachen, Germany, has developed Controlled Metal Build-up, which involves the manufacture of parts by a successive layer and machining strategy [19,20]. The ARL, Naval Laboratory at Penn State University USA [jointly with John Hopkins University under R&D funding from DARPA in collaboration with the Office of Naval Research] has done work using a 14 kW carbon dioxide laser to produce relatively large parts in titanium alloy (Ti-6Al-4V) under a controlled atmosphere. Tensile strength, Charpy impact values and fatigue test results matched that of conventional material produced by casting or HIP [21]. This has also included work on DLF of Nickel-Aluminium Bronze alloys [22]. AeroMet Corporation of Eden Prairie, Minnesota, USA has been established to exploit the Penn State work with the process being named “Lasform”. This has included work on titanium alloys but without significant systematic investigation of microstructure / properties.

Laser deposition has also been developed [23-25] at Sandia National Laboratories under the name of LENS (laser engineered net shaping) and it is being further developed by Lockheed Martin Corporation. A 1.8 kW continuous wave Nd:YAG laser was used to produce DLF components by processing of 316 stainless steel or Inconel 625 powders in an argon atmosphere. Good dimensional accuracy and surface finish (to 8 µm accuracy) was achieved at low power settings (325 W and low powder flow rates) but rate of deposition is slow (5 cubic cm / hr). Subsequent work has led to the production of a system based on this technology by Optomec [26]. Work at National Research Centre, Ontario has produced high precision parts in stainless steel at slow deposition rate but with an accuracy of 1 –2 µm [27]. The potential of DLF for producing compositionally graded materials and materials with novel internal geometries has been demonstrated in early work from University of Michigan [28 -30].

This work has shown that fully dense parts with epitaxial growth between the layers can be produced. Hence, although the precursor materials are in powder form, the technique shares little in common with powder metallurgy routes (which depend on sintering for consolidation and inevitably result in a degree of retained porosity). Functional properties equal to those of equivalent conventional cast and wrought materials have been demonstrated. The ability to directly form complex three dimensional shapes has been shown. DLF is being considered as a route for the direct fabrication of low volume components, particularly where there are process advantages in the ability to generate complex internal geometries that are not available by conventional means. For example, Mazumder has shown that plastic extrusion dies for the automobile industry can be manufactured by DLF in such a way that the positioning of cooling channels (to carry cooling water) around the workpiece can be made layer by layer in a 'conformal' way that radically reduces the cooling time required per component .

4. New technology: new design

New design possibilities are the key to the future development of DLF. In conventional composite materials there is normally a sharp interface between the reinforcement and the matrix phases. This can lead to mismatch, particularly during heating and cooling cycles. The ability to produce graded interfaces afforded by DLF is a powerful advantage of the technique. The principle is shown in Figure 7. It is straightforward to see the connection between this and the production of layers of variable composition by DLF.

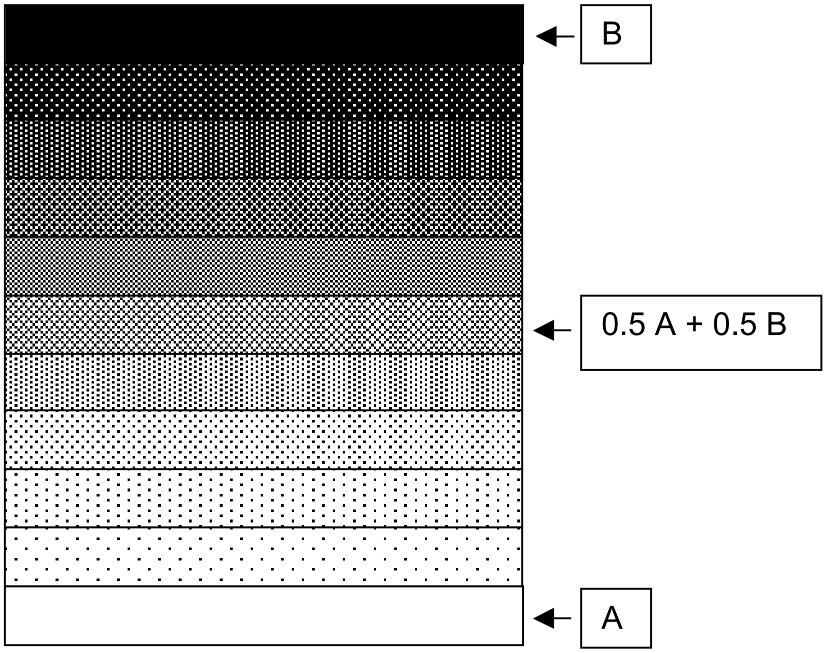


***Figure** 7. The principle of layers of graded composition. Note that the method of production in DLF is directly related to variable composition cladding.*

The development of macrostructured and microstructured components is presented by Ashby [31]. He notes that there appears to be a limitation on the means by which these components might be produced It is likely that DLF may provide the solution.

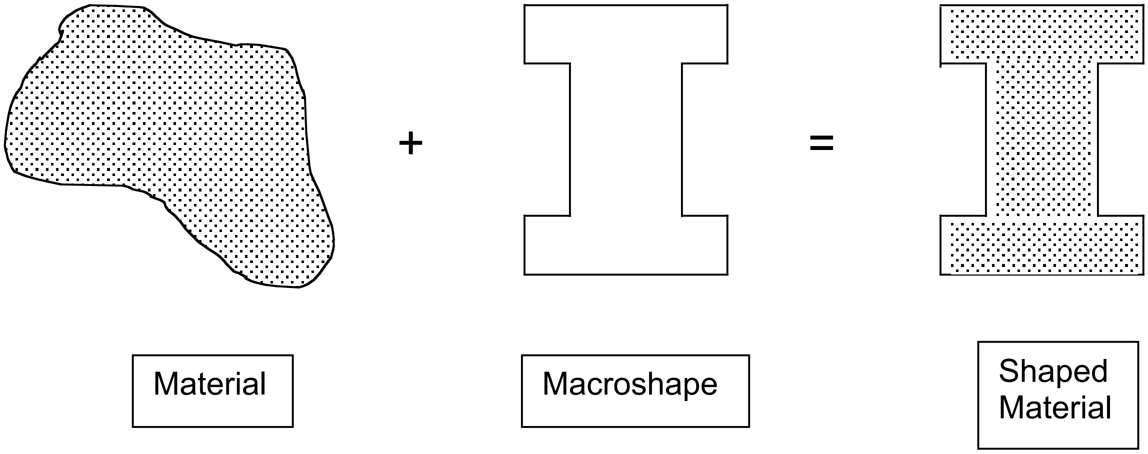


Figure 8 *The combination of materials properties with component shape produces more efficient component structures [31]*

Figure 8 shows the effect of macroshaping of a material in improving its efficiency in mechanical loading, as shown in the well–known example of the I–beam. Defining a shape factor Φ^{ε}_{B} for elastic bending as the ratio of the stiffness of the shaped beam to that of a solid circular section with the same cross section (and hence the same mass per unit length) gives a dimensionless parameter which is independent of size and which indicates the improvement in stiffness for a given mass that has been created by the macroshaping. For slender I beams this fator can be as high at 50.

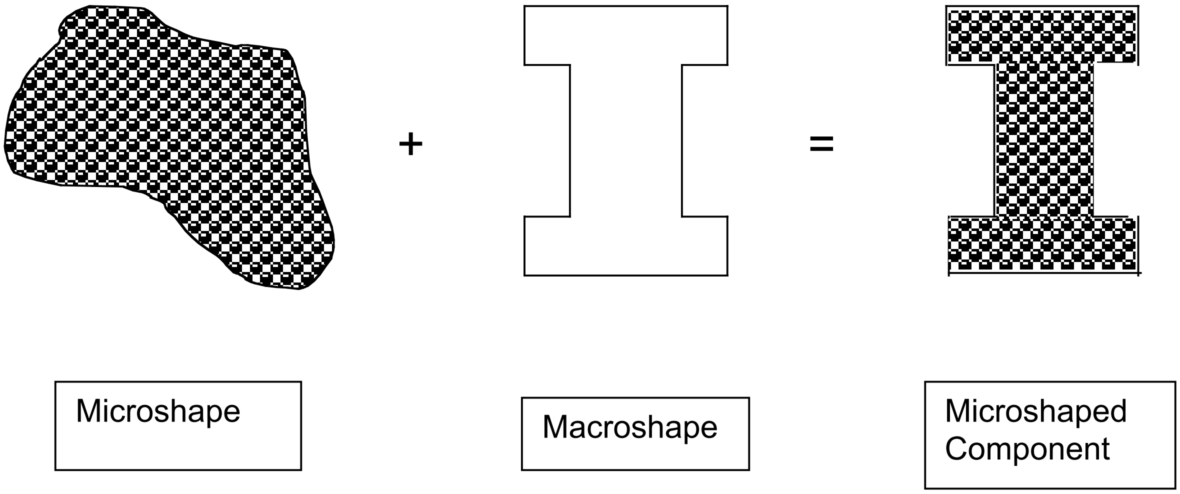
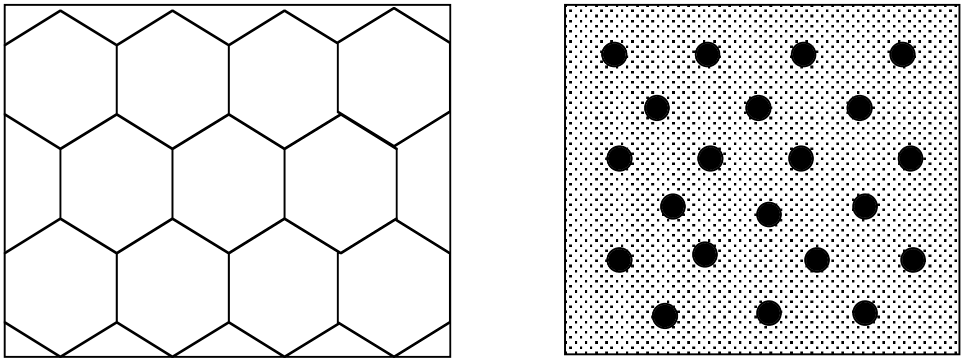


Figure 9 *Microstructured materials combined with macroshaping offers the potential to produce components of outstanding efficiency [31]*

If microshaping can be introduced (Figure 9), for example by the production of a honeycomb structure, further advantages in stiffness in bending for the lightest mass can be introduced. Defining a microstructural shape factor $\Psi^{e}{}_{B}$ as the ratio of the stiffness in bending of the microstructured beam to the solid beam (for given cross sectional area), Ashby shows that the effect of macroshaping and microshaping together is given by the product of the macrostructural and microstructural shape factors - as shown in Figure 9, further advantage can be achieved by the combination of microstructural shape.

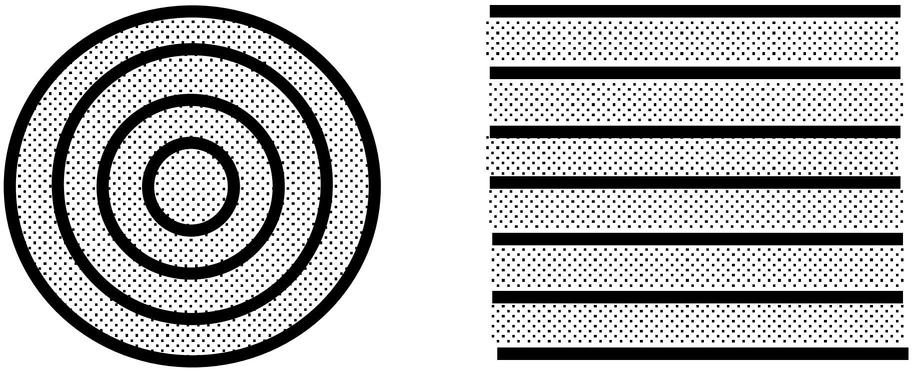
Layer by layer deposition by DLF is a means of producing microstructural; shaping of materials that is highly relevant to this situation. The feasibility of achieving this has been demonstrated in stereolithography where layer by layer deposition of polymers has been used to produce quasi-hollow honeycomb-like structures as precursors for investment casting. DLF can accomplish a similar level of microshaping in relevant materials and at realistic production rates.

The era of the deposition of novel structures and biomimetic structures is at its infancy. Some mechanically efficient microstructured components as described by Ashby are shown in Figure 10.



Prismatic cells

Fibres embedded in foamed matrix



Concentric cylindrical shells in foamed matrix

Parallel plates with foamed spacers

Figure 10 *Four mechanically efficient micro-structured component types [31]*

Mazumder has demonstrated the production by DLF of a microstructured composite (two metals) with an overall negative thermal expansion coefficient as a bulk component. The potential for the development of smart microstructures in which coupled elements function as sensors is considerable.

5. Conclusions

Direct laser fabrication offers unique potential as a means for manufacture of components from CAD data, avoiding the time requirements and costs associated with permanent tooling. The key to the understanding of the process lies in the relationship with laser cladding. However, the technique has the potential to be used in the production of components with outstanding properties that should usher in an era of lighter, stiffer, more adapted components.

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