Practical considerations and capabilities for laser assisted direct metal deposition

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Abstract

Laser assisted direct metal deposition refers to the additive layered manufacturing technology for building components from a computer-aided design (CAD) model. A motion control program, developed from the CAD model of a desired metal component, is used to control the motion of a laser focal spot to trace all areas of the part, typically a planar layer at a time. Metal powders, injected into the laser focal zone, are melted and then re-solidify into fully dense metal in the wake of the moving molten pool created by the laser beam. Successive layers are then stacked to produce the entire component volume of fused metal representing the desired CAD model. Development of this technology has been pursued at both Los Alamos and Sandia National Laboratories and has resulted in the Directed Light Fabrication (DLF) and Laser Engineered Net Shaping (LENS™) processes. These processes have been proven feasible for fabricating components from nearly any metal system to near-net shape accuracy with mechanical properties approaching and in some cases exceeding the properties found in conventionally processed wrought structures. Single step processing by LENS and DLF produce cost savings realized by elimination of conventional multi-step thermo-mechanical processing. Design features such as internal cavities or over-hanging features can be made without joined assemblies. Hard to process materials such as intermetallics, refractory metals, and high temperature alloys can be processed in a single step. Functionally graded compositions can be created within three-dimensional components to vary the properties to match localized requirements due to the service environment. The technology offers the designer a rapid prototyping capability at the push of a button, without the need to fabricate dies or use forming equipment or extensive machining and joining processes to produce a part. Future development is still required for these processes to be commercially accepted and used in industry. Parts are deposited with a surface roughness of 10 μm, arithmetic average, making a secondary finishing operation necessary for some applications to achieve high accuracy and polished surface texture. Residual stress measurement and control is also required to avoid distortion of deposited components. Motion path and control code needs to be optimized to reduce overall process time from the CAD model to the finished part. © Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

The idea of fabricating useful plastic, metal and ceramic components by the build-up and addition of layers of material has led to the establishment of the current rapid prototyping industry. As early as 1934 [1], manual layered build-up of metal using oxy-fuel welding was invented, however, accuracy and resolution of features was poor. Cladding technology followed using primarily arc and laser welding processes combined with wire and powder feed, however, limitations in accuracy and resolution still prevented building of useful metal components.

Development of laser and microprocessor technology for accurate control of laser beam position used to solidify liquid polymers or thermo-plastic powders, led to the invention and application of accurate layered deposition technology of polymeric materials in the early 1980s. Development of computer-aided-design
CAD and computer-aided-manufacturing (CAM) technology provided the coupling between the representation of a desired component in three-dimensions and the deposition process to produce the part from the design. Tessellation of the part boundary surfaces (representing the part surface by small connected triangular facets) and planar slicing of the model to form deposition layers led to the development and use of stereo-lithography file formats (.stl) for layered deposition. Plastic components fabricated with this technology were primarily used for models to verify form and fit without meeting service requirements for high strengths and densities. But in the early 1990s the technology became linked to fabrication of metal components by making patterns for investment casting which has proven a fast and economical rapid prototyping method.

However, depositing metals directly by layered deposition technology, instead of making patterns, would eliminate the extra steps required for investment casting of metals and permit one-step fabrication of metal components from a CAD design. Various techniques have been tried including: deposition of liquid metal, laser assisted chemical vapor deposition (CVD), selective laser melting and re-solidification of a bed of metal powder or plastic coated powder and laser melting and re-solidification of powders continuously fed into the laser focal zone. These processes combine the developed technologies of powder metallurgy, solidification metallurgy, CAD–CAM and rapid prototyping. Additionally, similar processing is being applied in the direct fabrication of ceramics by depositing the material in layers with a binder followed by drying and firing to form a densified ceramic component.

2. Process description

The processes addressed here are Directed Light Fabrication (DLF) [3–10], developed at Los Alamos National Laboratory, Los Alamos, New Mexico and Laser Engineered Net Shaping (LENS™) [11–19] developed at Sandia National Laboratory, Albuquerque, New Mexico. Both processes supply a continuous powder feed to the laser focal zone where the powder is melted and re-solidifies in the ‘wake’ of the molten pool as the laser beam scans across the part. Fig. 1 schematically describes the process showing a computer system representing the development of the CAD model and the hardware system where deposition of the part takes place. Motion paths developed either in stereolithography format (LENS™) or CNC tool-path format (DLF) command motion for one to five motion axes. Additional axes or robotic control could allow additional degrees of freedom if required. Processing is performed usually in inert gas (argon, helium, nitrogen) environments, typically to reduce oxidation. Multiple powder compositions can be fed simultaneously or sequentially to produce alloying at the focal zone or provide choice of material relative to location within a desired part. The motion path provides the control commands for the laser, powder feed and motion system to produce linear beads of material that are laid side by side with a designated amount of overlap. Each bead is typically started and terminated at the part boundary until an entire cross-sectional planar layer is formed by deposition of overlapping beads. The laser beam then indexes away from the part by the layer thickness controlled by the motion system. Laser power, powder feed rate, and traverse velocity are controlled.

![Directed Light Fabrication](image)

Fig. 1. Schematic representation of the DLF process. Five axes of motion are used and the system can deliver up to four different powder compositions. Processing is typically performed in argon or other inert gas with oxygen impurity below 5 ppm.
Fig. 2. Schematic representation of a plate being deposited by overlapping traverses of the molten pool across the width dimension of the plate. As-deposited properties of the solidified material depend on the molten pool characteristics produced by the process parameters chosen and the heat flow characteristics away from the pool.

to produce a full density layer for any given material. Successive layers are stacked and the entire part or specific feature of a part assembly is built additively. Features or assembly components that require deposition in planar layers at angled orientations to the parent or base feature can be deposited by tilting the laser beam-powder delivery head or tilting the work piece so that the beam axis is normal to the deposition plane. This capability provides a means of producing overhanging features without building underlying support structure typically required in plastic rapid-prototyping processes.

Fig. 2 schematically shows a plate type of structure being built. A small molten pool is created at the focal zone of the laser beam that can vary in size from one-half to five times the focal-spot diameter of the laser beam, depending on the power and velocity of the moving spot. For example, the Nd-YAG laser used in DLF processing is focused to 0.5 mm and has been used to produce solidified features 0.3–2.5 mm thick with a single pass by varying the laser power and translation speed. Thicker components are made with multiple over-lapping beads. The small molten pool is surrounded by solid material and is held in its place by surface tension, permitting ‘overhead’ deposition, much the same as welding in an overhead position. Molten pool size is also affected by underlying heat sinking of the substrate or previously deposited material. High heat flow away from the molten pool shrinks the pool width and low heat flow increases the pool width, making compensation desirable by controlling laser power and velocity process parameters.

Control of the molten pool determines the properties of the resulting solidified product. Bead-to-bead overlap and layer thickness must correlate to the molten pool width and depth to produce a fully dense product. Cooling rate and solidification velocity at the solid–liquid interface of the molten pool, affect the size, orientation and composition of microstructural features, which determine the strength and ductility of the deposit.

3. Part fabrication

Representative parts produced with this technology are shown in Fig. 3. Overhanging part features, assemblies and massive structures deposited represent the capability of the process. A typical development cycle to produce a part involves part design in three dimensions, motion path development, and optimization of process parameters to achieve full density at maximum deposition rate. Before the final or best part is produced, iterations of both the motion path and process parameter establishment are often performed, unless information from a process knowledge base on similar parts can be used. For parts with multiple features, this development cycle is often repeated for each feature. Once the motion path and process parameters are optimized the final part or multiple parts are produced. Changes to dimensions or geometry after the initial optimization require motion path regeneration followed by direct deposition without the need for more

Fig. 3. Injection molding die insert (left), part assemblies and overhangs (center) and light reflector (right) are examples of parts made with the DLF process. Deposition times ranged from approximately 1 h for the shell type parts to 70 h for the die insert in an unattended process.
process optimization. Hence a designer can produce a prototype and modify it quickly after the initial optimization is performed on the first part. Each new material and each new part or feature geometry makes the optimization cycle a prerequisite to building the best part. However, establishment of a knowledge base of part processing expertise over time can eliminate much of the development required.

4. Accuracy and surface finish

A hexagonal cross-section, seven-hole-array structure shown in Fig. 4, was built to 356 mm in height from Inconel 690, a difficult to process high-temperature, nickel-base alloy. The nominal composition of Inconel 690 in wt.% is 58Ni, 29Cr, 9Fe. The part was deposited at a laser power of 160 W, speed of 12.7 mm/s, vertical layer increment of 0.25 mm, bead overlap of 0.27 mm, and the powder feed rate was approximately 9 g/min. Oxygen was controlled to less than 10 ppm in an argon atmosphere. Deposition time was 172 h at a rate of 0.04 lb/h in one continuous, unattended operation.

Dimensional inspection of the part features indicated hole diameters were produced within ±0.05 mm of the specified diameter for six out of the seven holes and were centered within ±0.13 mm of the specified location. Radial distance from the center of the cross-section to the center of the hexagonal faces was within ±0.076 mm. Surface roughness was 12 μm, arithmetic average, which is similar to investment cast surfaces. However, one hole was smaller because of an extra deposition pass inserted into the inside radius of the hole motion path, making it a 12.62-mm diameter, and two extra passes were inserted for motion outside the desired hexagon boundary making it 24.33 mm instead of the specified 23.8 mm. These extra passes could easily be removed from the motion path but a second part was not made.

5. Tensile properties

Material properties of deposits have been measured for several materials and are compared to conventionally processed material in Table 1. As-deposited tensile yield strength of DLF processed 316 stainless steel and Inconel 690 exceeded that of conventionally processed wrought material. Tensile elongation was 41% and 49% for the two materials. Tensile yield strength for Ti-6Al-4V, produced by DLF, fell in the equivalent range for wrought material, however, elongation was only 6% compared to 10% and higher for conventionally cast and wrought products.

Tensile data show that properties equivalent to wrought material can be achieved for some materials. This eliminates the need for multiple thermo-mechanical processing treatments in conventional processing. Chemical segregation in cast ingots, that make homogenization heat treatments and plastic deformation processing for grain refinement necessary in ingot metallurgy, are eliminated by using the direct deposition technology. Chemical homogenization is achieved through randomization of composition by using powders as input material and by limiting chemical diffusion in the liquid state to the boundaries of the small molten pool that is used to deposit the entire component.

6. Deposition microstructure

Fully dense material is desired for most part fabrication to achieve optimum mechanical strength to meet or exceed service requirements. Full density is achieved by optimization of both process parameters and motion.

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Fig. 4. Inconel 690 hexagon with seven-hole array made by DLF. Hole diameters are within ±0.05 mm and centered on a bolt circle within ±0.13 mm. Radial distance to hexagonal faces was within ±0.076 mm. Surface roughness is 12 μm, arithmetic average.
Table 1  
Tensile properties of DLF material compared to conventionally processed material

<table>
<thead>
<tr>
<th>Material</th>
<th>0.2 years MPa (ksi)</th>
<th>UTS MPa (ksi)</th>
<th>Elong (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type 316 stainless steel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLF (As deposited)</td>
<td>296 (43)</td>
<td>579 (84)</td>
<td>41</td>
</tr>
<tr>
<td>Wrought annealed</td>
<td>262 (38)</td>
<td>572 (83)</td>
<td>63</td>
</tr>
<tr>
<td>Investment cast 316</td>
<td>269 (39)</td>
<td>517 (75)</td>
<td>39</td>
</tr>
<tr>
<td><strong>Inconel 690 (58Ni–29Cr–9Fe)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLF (As deposited)</td>
<td>450 (65.2)</td>
<td>666 (96.6)</td>
<td>48.8</td>
</tr>
<tr>
<td>Hot rolled rod</td>
<td>372 (54)</td>
<td>738 (107)</td>
<td>50</td>
</tr>
<tr>
<td><strong>Ti–6Al–4V</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLF with mill anneal</td>
<td>958 (139)</td>
<td>1027 (149)</td>
<td>6.2</td>
</tr>
<tr>
<td>Wrought bar (annealed)</td>
<td>827–1000 (120–145)</td>
<td>931–1069 (135–155)</td>
<td>15–20</td>
</tr>
<tr>
<td>Cast + anneal</td>
<td>889 (129)</td>
<td>1014 (147)</td>
<td>10</td>
</tr>
</tbody>
</table>

Path to maintain a continuous molten pool that sweeps the entire volume of the desired part. Fig. 5 shows 316 stainless steel layers (left photo) and cellular microstructure (right photo, higher magnification) within the layers. Continuity from layer to layer is maintained by melt back into previous layers as a new layer is added. Depth of melt back varies from a fraction of the previous layer to re-melting through multiple layers, depending on process parameters chosen.

Porous microstructures result primarily from gas evolution during solidification and lack of fusion between layers or adjacent passes of the molten pool. Fig. 6 (left) shows porosity in a W–25Re alloy made by fusing blended tungsten and rhenium powders. Spherical cavities are formed during melting and remain in the solidified microstructure. Residual gas in the starting powder material or decomposition products produced by laser heating and melting typically result in this type of pore formation. Fig. 6 (right) shows porosity resulting from lack of fusion at layer boundaries. Increasing laser power, lowering traverse speed, or using thinner layers can promote fusion and reduce or eliminate this type of void content.

7. Deposition of alloys, dissimilar metals, composites, functional grades

Unique alloy, dissimilar, and graded compositions, formed by pre-blending desired powder compositions or combining powders at the laser focal zone, provide the capability to control properties within a fabricated structure. Fig. 7 shows a transition from commercially pure titanium to Ti–20% Nb alloy. After building a pure titanium plate, Nb powder was proportionally added into the molten pool from a second powder feeder to form the 80Ti–20Nb composition. Laser power was increased from 200 to 320 W to produce complete melting of the Nb. Lower powers selectively melted the titanium and not the Nb to form a Ti matrix.

Fig. 5. Fully dense microstructure of a 316 stainless steel bar (left), showing the deposited layer structure (left) and cellular solidification microstructure within the layers (right).
Fig. 6. Porosity observed in DLF deposits is caused by residual gas content in starting powders evolving upon solidification, shown in the blended W-25Re powder alloy (left), or lack of fusion between layer boundaries in the niobium deposit (right).

Fig. 7. A transition (left) from commercially pure titanium (top section—left photo) to Ti-20wt/oNb was made by blending the two powders at the laser focal zone and raising the power from 200 to 320 W when the Nb was added. A microstructure (right) of non-melted Nb powder particles in a continuous Ti matrix (right) was formed at low power.

Powders can be either pre-alloyed or pre-blended and fed from one feeder into the molten pool to produce a desired composition. However, the capability to feed several different powders at the same time and control their feed rates individually provides added flexibility. Any desired alloy composition can easily be tried, eliminating the fabrication steps required for pre-alloyed powder. Segregation in blended powders, according to powder density, size, shape and surface characteristics, during agitation by feed systems is eliminated, by feeding powders separately. Functional grades of composition are made by ramping feed rates up or down proportionally with two or more feeders to obtain the desired compositional gradients.

8. Summary

The feasibility of depositing any metal and many intermetallics into near-net shape parts in a single processing step has been demonstrated using the DLF and LENSTM process technology. Accuracy is within ±0.12 mm with a 10-μm surface finish. Powder chemistry, particularly gas content, metallurgical stability, and distortion must be characterized for any particular component and material system. With this technology, materials that either can not be cast and thermo-mechanically processed, or that can not be consolidated successfully by powder metallurgy, can be formed. Features such as internal cavities, which can not be machined directly or require extensive welding and assembly, can be formed. Materials requiring multiple conventional processes can be formed in a single step, eliminating the need for dies and molds, capital equipment, and space associated with each additional process.

References


