Six-axis direct metal deposition technology enables creation/coating of new parts or remanufacturing of damaged parts with near net-shape.

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Direct Metal Deposition is an advanced additive technology that enables repair and rebuild of worn/damaged components that are hard to weld by common practices (Fig. 1). Examples of such components are gas turbine blades and stator vanes. Besides remanufacturing, DMD can build wear-resistant coatings and features on complex high-value components. With its closed-loop feedback system and six-axis deposition capability, DMD can coat and/or rebuild parts with very complex geometry.

This article presents an overview of the DMD process and a few specific case studies involving applications in the gas turbine industry.

Process overview

DMD is a proprietary laser-aided manufacturing (LAM) process that originated at the University of Michigan and is being further developed and commercialized by POM Group Inc. Although LAM has played a key role for repair of aerospace components for more than a decade, DMD provides a major advancement of the technology. The preliminary work on direct metal deposition of aluminum has been demonstrated to provide metal properties equivalent to those of wrought material, thus making it potentially useful for the direct fabrication of parts. Since then, the technology has been advanced significantly and has been applied to a wide range of alloys and components. The potential is limitless, and many groups are actively evaluating it for commercial possibilities.

To begin the process, an industrial laser beam under CNC control is focused onto a workpiece, producing a melt pool. A small amount of powdered metal is injected into the melt pool, building up the part in a thin layer. The beam is then moved to the next location based on CAD geometry, tracing out the part layer by layer.

DMD machines are equipped with a three-axis/five-axis head with an additional rotary axis on the work table that allows deposition of almost any geometry. POM has developed large DMD workstations (DMD505) for hardfacing and repair of large dies, molds, and components. Smaller and more compact machines (DMD105D) are available for building/cladding smaller parts and pursuing materials research (Fig. 2b). Recently, a robot based DMD system (Fig. 2a) has been developed, enabling repair/cladding applications in the field.

Some of the main features of the system are:

- Co-axial nozzle design gives full five-axis deposition capability along with local shielding by inert gases. (Side powder-feed systems can only deposit linearly in motion.)
- “Moving optics” capability allows processing of large heavy parts.
- Patented closed-loop optical feedback system monitors and controls the melt pool in real time, resulting in a near net shape part (Fig. 2c).
- Proprietary tool path software translates CAD data into the nozzle motion for six-axis deposition.
- Multiple powder delivery system allows deposition of different materials simultaneously or consecutively at specified locations, enabling on-the-fly production of alloys/composites.
- Deposits are fully dense and create a true metallurgical bond with the substrate/part.

DMD has been successful on a broad range of materials, including tool steels, stainless steels, high-speed steels, and alloys of nickel, cobalt, titanium, aluminum, and copper.

- User-friendly and multi-functional software has been developed for normal production jobs and for R&D activities.
Table 1 — DMD versus conventionally fabricated nickel, cobalt, and titanium alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>Condition</th>
<th>Tensile strength, MPa</th>
<th>Yield strength, MPa</th>
<th>Elongation, %</th>
<th>Hardness, HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN 625 DMD</td>
<td>As deposited</td>
<td>796</td>
<td>598</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>IN 625 wrought</td>
<td>927°C Annealed</td>
<td>897</td>
<td>483</td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>Stellite 31 DMD</td>
<td>As deposited</td>
<td>1182</td>
<td>903</td>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>Stellite 31</td>
<td>As cast</td>
<td>662</td>
<td>386</td>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>Ti-6Al-4V DMD</td>
<td>As deposited</td>
<td>1163</td>
<td>1071</td>
<td>6</td>
<td>38</td>
</tr>
<tr>
<td>Ti-6Al-4V (V) wrought</td>
<td>Annealed</td>
<td>950</td>
<td>880</td>
<td>14</td>
<td>36</td>
</tr>
</tbody>
</table>

Feedback system

The DMD Closed Loop Feedback System is the key tool for producing a near net-shape product. The system consists of high-speed sensors with optics that look at the melt pool. The sensors collect the melt pool image, which is then directly fed into a dedicated controller. The controller extracts the melt pool dimensional data from this signal.

The software algorithm processes the input data, and controlled power to the laser generator is output with a very fast response time. Tight control of the laser power means tight control of the layer thickness, and this results in the near net shape of the final product. The feedback system also allows control of heat input by controlling melt pool dimensions. This in turn leads to minimal heat-affected zone and a better microstructure with superior properties.

As-deposited material is fully dense, and its mechanical and physical properties are as good as or better than those of comparable cast or wrought materials. Table 1 shows tensile and hardness data of some typical materials, such as IN625, Stellite 31, and Ti-6Al-4V. The table compares DMD materials with wrought or cast materials. Note that the DMD materials can be fully stress-relieved, heat-treated, and aged to alter the microstructures for specific applications and to improve ductility or toughness.

Deposition software

Six-axis deposition software (DMDCAM) for additive manufacturing builds a CAM tool path directly from CAD data. It includes an Integrated Direct Metal Deposition database with process recipes as a part of the software. Contour, surface, and volume deposition paths are provided in three dimensions, and multi-layer deposition paths can be prepared in a single operation. Deposition paths for most of the leading controllers (such as Siemens, Fanuc, Delta-Tau) are also available.

Simulation and collision-detection modules are included for a “Ready to Use” deposition path. They detect any possible collision of the processing head and the part while creating the deposition tool path. The modules enable the user to search for alternate tool path strategies.

Vision system

The vision system has been developed for deposition on small parts with fine features, such as turbine blades. When a part is placed on the machine table, cameras grab an image of the area of deposition and the image coordinates are translated to machine coordinates. This eliminates manual part pick-up, which is practically impossible for very small components with fine features. Intermittent imaging can even allow inspection and adjustment of tool paths for required part geometry.

The vision software also has built-in tool pathing capability that allows direct-deposition path creation from the acquired image for simpler geometries. This is particularly useful for remanufacturing applications in which CAD data of a damaged or worn part is no longer available. Figure 3 shows an example of a turbine blade image grabbed by the vision system (left). This was followed by an automatic edge detection and subsequent tool path generation with/without offsetting the edge, as required by the user. A picture on the right shows the as-deposited blade.

Vision system software is capable of having different processing parameters at different points, as shown in Fig. 3 (left). This is critical for components with vast geometry variations, such as turbine blades in which the trailing edge can be very thin compared to the rest of the component.

Applications

DMD is suitable for a broad range of applications covering industries from automotive to aerospace, from injection molding to medical, from tool and die to oilfield/construction. Some applications are listed below:

- Repair and restoration of turbine components.
- Building of near net shape titanium features on blanks for high value titanium parts.
- Hardfacing of high wear areas.
- Conformal cooling for higher productivity in plastic injection molding/die casting.

Fig. 3 — Left: Demonstration of DMD vision system capability. Right: As-deposited turbine blade squealer tip.
• Tool reconfiguration for engineering changes to production tooling.
• Construction of medical components, such as prosthetic implants and scaffolds with functional properties.

Remanufacturing: One of the areas best suited for DMD is turbine blades/vanes repair. The concentrated heat of the laser allows blade tip build-up with minimum distortion. The vision system plays a significant role and offers precision part pickup and restoration. The vision capability, coupled with a closed-loop feedback system, results in a quality product that requires minimal post grinding. Figure 4 shows cross-section microstructures of the DMD area of a repaired turbine blade. Excellent process control leads to a fully dense microstructure, as observed in the vertical cross-section along with a small heat affected zone.

Lattice structures: Very intricate and complex features, and/or parts that contain such features are possible with DMD. An example of this is shown in Fig. 5, in which a mirror housing (Fig. 5a) sponsored by NASA was built from scratch. The closed-loop feedback control system allowed uniform build-up with no intermediate machining step.

The part was originally built from a solid piece of metal by electro-discharge machining, which is a slow process that generates a great deal of waste. Figure 5(b) compares the efficiency of the DMD and EDM processes in terms of material, energy, and time. Clearly, DMD requires only about a third as much material as EDM, and this results in a huge saving, especially for expensive aerospace materials such as nickel-base super alloys. In terms of process time and energy, DMD consumes only 4% and 80% as compared to a conventional process.

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Fig. 4 — Macro (a) and microstructures (b-d) of DMD deposited Ti-6Al4V. (b) the clad (c) the interface (d) the base material.

Fig. 5 — (a) A mirror housing built by DMD process. (b) Comparison of DMD and EDM process efficiency for building the housing.