Additive Manufacturing and Metal Parts

Jim McGuffin-Cawley
Case Western Reserve University
1.3.1 Processing Operations

- **Shaping Operations** alter geometry.
- **Property-Enhancing Operations** add value by changing physical properties without necessarily changing shape.
- **Surface Processing Operations** are performed to clean, treat, coat, or deposit.

• **additive manufacturing (AM), n**—a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.
Direct or Indirect Fabrication
Background: Advanced Manufacturing Partnership

A Pilot Institute for the National Network for Manufacturing Innovation (NNMI)

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NAMII – Executive Director
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A Defense-wide Manufacturing S&T team-led, Multi-agency collaboration between industry, government and universities

• Public-private partnership

• Shared facilities open to industry
  — Especially attractive to small businesses

• Enabling technology transition and commercialization

• Addressing Technology Readiness Level (TRL) / Manufacturing Readiness Level (MRL) 4-7
  — Bridge the gap in Manufacturing Innovation

• Educational plan to train the future workforce

• Sustainable within 3 years

A Model for Manufacturing Innovation Institutes within NNMI
A REGIONAL Center of Excellence, with a vision for NATIONAL PRESENCE
Present NAMII Consortia
Projected NAMII Consortiums in 18 months

*based on 2012 Wohlers Report of active AM organizations and discussions to date
"20% of output of 3D printers is now final products, rather than prototypes. By 2020 it may be 50%." – The Economist (2011)

Government agency investments and interest - throughout NASA, DoD, and DOE
Future of 3D printing is bright, says SXSW panel

During a panel at South by Southwest, several experts in the field discussed what 3D printing means for the future of production and agreed that there's huge potential.
Just As Key 3D Printing Patents Get Closer To Expiring, Intellectual Ventures Patents 3D Printing DRM

from the *good-luck-with-that* dept

3D printing is on the verge of really going mainstream, in part because of improvements in the technology, but in large part because the key patents that have limited that advancement are getting close to *expiring*. Of course, as it takes off, though, expect a ton of people to try to "tax" the success with new patents of their own. And, of course, it comes as little surprise that Intellectual Ventures will be a player in that space. Though its first attempt might backfire...

Technology Review has a story about [Intellectual Ventures getting a new patent on DRM for 3D printing](https://www.technologyreview.com/s/600177/intellectual-ventures-gets-new-drming-patent-for-3d-printing/). You can see the patent (8,286,236) yourself. It's a pretty broad patent that seems to cover a broad array of "authorization" measures for manufacturing based on a data file.

We've talked in the past about how patents too often get granted for taking something known or common and basically saying "on the internet" on it. Perhaps the next wave of patents will be the same kinda thing, but "... with 3D printing." Of course, patenting DRM might actually have a good, if unintended, result: perhaps it will scare people and companies away from making the mistake of trying to DRM up 3D printing files, and leave the system much more open. Though, given the historical comparisons, that seems unlikely...
### Consumer 3-D Printers

Printers that let people print objects from plastic at home

<table>
<thead>
<tr>
<th></th>
<th>Cube</th>
<th>Up! Plus</th>
<th>Series 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Print volume:</strong></td>
<td>5.5 inches per side</td>
<td>5.5 inches per side</td>
<td>9 inches per side</td>
</tr>
<tr>
<td><strong>Price:</strong></td>
<td>$1,299</td>
<td>$1,499</td>
<td>$1,400</td>
</tr>
<tr>
<td><strong>Introduced:</strong></td>
<td>January 2012</td>
<td>2010</td>
<td>June 2012</td>
</tr>
<tr>
<td><strong>Manufacturer:</strong></td>
<td>3D Systems</td>
<td>Delta Micro Factory</td>
<td>Type A Machines</td>
</tr>
</tbody>
</table>

Sources: 3D Systems, Delta Micro Factory, Type A Machines
“…The big drawback for consumers is that 3-D printers are still tricky to use and very limited in what they can make. The objects they produce are not just fairly crude but quite small, since the thermoplastic will warp at larger sizes. What’s more, thermoplastics are just the kind of cheap, brittle material many people hate. The hardware requires precise calibrations that will be beyond the patience of many users and operating the software is significantly more complicated than clicking “Print” from a Word document…”

Update: Stratasys and Objet Merger
Published April 19, 2012 | By John Newman

Unless you don’t pay attention to 3D printing news or have been hiding under a rock, you’ll know the big story of this week is the merger of Stratasys and Objet into a single additive manufacturing (AM) juggernaut. You can see the basics of our coverage here. Today we’re going to update the story with some new information provided by Stratasys.

To begin, if you missed it in the other post, the new company will retain the Stratasys name. The old Stratasys will also maintain control of the company with 55% control of the stock, and the merger was a stock-for-stock deal. Objet will appoint four people to the new company's board of directors, and Stratasys will appoint five people, but the fifth must be approved by Objet. Combined stock for the new company has an equity value of around $1.4 billion.

Stratasys, Inc. and Objet Ltd. Combining to Create a Leader in 3D Printing

Building for Future Growth

Stratasys and Objet merge. Courtesy of Stratasys.
NAMII Selects Project Call Awardees

Posted on Mar 20, 2013

Timeframe for NAMII’s Next Program Management Review Meeting and Project Call Are Also Announced

Youngstown, Ohio. — March 20, 2013. NAMII, the National Additive Manufacturing Innovation Institute, awarded on August 2012, and driven by the National Center for Defense Manufacturing and Machining (NCDMM), is proud to announce the awardees of its initial call for additive manufacturing (AM) applied research and development projects from NAMII members. NAMII will provide $4.5 million in funding toward these projects with the matching cost share from the awarded project teams totaling $5 million.

“As a collective, NCDMM and NAMII found that the submitted proposals detailed highly innovative additive manufacturing project ideas, featuring applied research and development, efficient use of digital data, high sustainability, and aggressive education outreach and workforce training plans,” said NCDMM Vice President and NAMII Director Ed Morris. “The down-select process proved to be intense. NAMII’s fundamental objective is to spawn the creation of new, innovative products and the corresponding U.S. jobs to support them based on the unique capabilities of additive manufacturing. NCDMM and NAMII have selected seven projects that best integrate with the four NAMII thrust areas of technology development, technology transition, advanced manufacturing enterprise, and education/workforce outreach.”
• “Maturation of Fused Depositing Modeling (FDM) Component Manufacturing”
  – Rapid Prototype + Manufacturing LLC (RP+M)
  Led by small business part producer, RP+M, in partnership with equipment manufacturers and large industry system integrators and the University of Dayton Research Institute, this project will provide the community with a deeper understanding of the properties and opportunities of the high-temperature polymer, ULTEM™ 9085. Some of the key outcomes from this project include a design guide; critical materials and processing data; and machine, material, part and process certification.

• “Qualification of Additive Manufacturing Processes and Procedures for Repurposing and Rejuvenation of Tooling”
  – Case Western Reserve University
  Led by Case Western Reserve University, in partnership with several additive manufacturers, die casters, computer modelers, and the North American Die Casting Association, this project will develop, evaluate, and qualify methods for repairing and repurposing tools and dies. Die casting tools are very expensive — sometimes exceeding $1 million each — and require long lead times to manufacture. The ability to repair and repurpose tools and dies can save energy and costs, and reduce lead time by extending tool life through use of the additive manufacturing techniques developed by this team.
Figure 6. A) Illustration of the process used to produce a customized ceramic, hydroxyapatite, part to repair the injured skull of a patient [56]. The focus is clearly on data handling. CAT scan data is used to define the geometry of the desired part. It is converted to so-called ‘stl’ format (a triangular tessellation) and then scaled to account for shrinkage that will occur during firing, which can be up to 25% by linear dimension. B) The clear benefit is the lack of a need for tooling as each such part will be unique.
Qualification of Additive Manufacturing Processes and Procedures for Repurposing and Rejuvenation of Tooling

Figure 3: Heat checked inserts
Figure 5 illustrates Tasks 3-7.

Aluminum Die Cast Housing

Heat Checked Areas (x3)

9” diameter

Tooling geometry

Heat checked area

300# insert (17” x 17” x 4”)

Machine Heat Check Area Out

Build and Re-Machine

Figure 5: Illustration of Tasks 3-7
• “Thermal Imaging for Process Monitoring and Control of Additive Manufacturing”
  – Penn State University Center for Innovative Materials Processing through Direct Digital Deposition (CIMP 3D)

Led by Penn State University, in partnership with several industry and university team members, this project will expand the use of thermal imaging for process monitoring and control of electron beam direct manufacturing (EBDM) and laser engineered net shaping (LENS) additive manufacturing processes. Improvements to the EBDM and LENS systems will enable 3D visualization of the measured global temperature field and real-time control of electron beam or laser power levels based on thermal image characteristics. These outcomes will enable the community to have greater confidence on part properties and quality using these technologies.

• “Rapid Qualification Methods for Powder Bed Direct Metal Additive Manufacturing Processes”
  – Case Western Reserve University

Led by Case Western Reserve University, in partnership with leading aerospace industry companies and other industry and university team members, this project will improve the industry’s ability to understand and control microstructure and mechanical properties across EOS Laser Sintering and Arcam Electron Beam Melting (EBM®) powder bed processes. Process-based cost modeling with variable production volumes will also be delivered, providing the community with valuable cost estimates for new product lines. The outcomes from this project will deliver much needed information to qualify these production processes for use across many industries.
"Sparse-Build Rapid Tooling by Fused Depositing Modeling (FDM) for Composite Manufacturing and Hydroforming"

- Missouri University of Science and Technology

"Fused Depositing Modeling (FDM) for Complex Composites Tooling"

- Northrop Grumman Aerospace Systems

Two projects focusing on fused depositing modeling (FDM) are to be co-led developed in close collaboration by Missouri University of Science and Technology and Northrop Grumman Aerospace Systems, in partnership with other small and large companies and the Robert C. Byrd Institute’s Composite Center of Excellence. These projects address a key near-term opportunity for additive manufacturing: the ability to rapidly and cost-effectively produce tooling for composite manufacturing. Polymer composite tools often involve expensive, complex machined, metallic structures that can take months to manufacture. Recent developments with high-temperature polymeric tooling, such as the ULTEM™ 9085 material, show great promise for low-cost, energy-saving tooling options for the polymer composites industry. In addition, these projects will explore the use of sparse-build tools, minimizing material use for the needs of the composite process. Composites are high-strength materials that are used in a wide range of industries and can be used for lightweighting, a key strategy for reducing energy use.
Layer Formation (reworded)

- Fluid flow
- Powder bed
- Droplets or particles
- Extrusion or wire
- Powder Feeder
- Solid sheet
Localized solidification
- Photopolymerization
- Binder jetting
- Directed energy deposition to fuse
- Cooling
- Solid state bonding (ultrasound)
Direct Fabrication of Metal Parts
Layer Formation (reworded)

- Fluid flow
- **Powder bed**
- Droplets or particles
- Extrusion or wire
- Solid sheet
Localized solidification
• Photopolymerization
• Binder jetting
• Directed energy deposition to fuse
• Cooling
• Solid state bonding (ultrasound)
Figure 2: Ciraud's invention

Figure 3: Housholder's invention
## Technical Data

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building volume (including building platform)</strong></td>
<td>250 mm x 250 mm x 325 mm (9.85 x 9.85 x 12.8 in)</td>
</tr>
<tr>
<td><strong>Laser type</strong></td>
<td>Yb-fibre laser, 200 W or 400 W (optional)</td>
</tr>
<tr>
<td><strong>Precision optics</strong></td>
<td>F-theta-lens, high-speed scanner</td>
</tr>
<tr>
<td><strong>Scan speed</strong></td>
<td>up to 7.0 m/s (23 ft./sec)</td>
</tr>
<tr>
<td><strong>Variable focus diameter</strong></td>
<td>100 - 500 µm (0.004 - 0.02 in)</td>
</tr>
<tr>
<td><strong>Power supply</strong></td>
<td>32 A</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>maximum 8.5 kW / typical 3.2 kW</td>
</tr>
<tr>
<td><strong>Nitrogen generator</strong></td>
<td>integrated</td>
</tr>
<tr>
<td><strong>Compressed air supply</strong></td>
<td>7,000 hPa; 20 m³/h (102 psi; 706 ft³/h)</td>
</tr>
<tr>
<td><strong>Argon supply</strong></td>
<td>4,000 hPa; 100 l/min (58 psi; 3.5 ft³/min)</td>
</tr>
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## Dimensions (B x D x H)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
<td>2,200 mm x 1,070 mm x 2,290 mm (86.6 x 42.1 x 90.1 in)</td>
</tr>
<tr>
<td><strong>Recommended installation space</strong></td>
<td>min. 4.8 m x 3.6 m x 2.9 m (189 x 142 x 114 in)</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>approx. 1,250 kg (2,756 lb)</td>
</tr>
</tbody>
</table>

## Data preparation

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Software</strong></td>
<td>EOS RP Tools; EOSTATE Magics RP (Materialise)</td>
</tr>
<tr>
<td><strong>CAD interface</strong></td>
<td>STL. Optional: converter for all standard formats</td>
</tr>
<tr>
<td><strong>Network</strong></td>
<td>Ethernet</td>
</tr>
</tbody>
</table>
DirectMetal 20 (EOSINT M 250 Xtended):
A fine grained bronze-based matrix that contains Ni.
A 20 µm minimum recommended layer thickness.
Typical achievable part accuracy of ±50 µm.
A minimum wall thickness of 0.6 mm.
A yield strength of 200 MPa.
A maximum operating temperature of 400°C.

DirectSteel 20 (EOSINT M 250 Xtended):
A fine grained steel-based matrix that contains Ni.
A 20 µm minimum recommended layer thickness.
Typical achievable part accuracy of ±50 µm.
A minimum wall thickness of 0.7 mm.
A yield strength of 400 MPa.
A maximum operating temperature of 400°C.

DirectSteel H20 (EOSINT M 250 Xtended):
A grained alloy steel that contains Cr, Ni, Mo, Si, V and C.
A 20 µm minimum recommended layer thickness.
Typical achievable part accuracy of ±50 µm.
A minimum wall thickness of 0.7 mm.
A yield strength of 800 MPa.
A maximum operating temperature of 400°C.
**MaragingSteel MS1 (M 270):**
A pre-alloyed ultra high strength steel in fine powder form.
A 40 \(\mu\)m minimum recommended layer thickness.
Typical achievable part accuracy of \(\pm 40 - 60\ \mu\)m.
A minimum wall thickness of 0.3 - 0.4 mm.
A yield strength of 1,000 MPa, \(\pm 100\ \text{MPa as built.}\)
A maximum operating temperature of 400°C.

**CobaltChrome MP1 (M 270):**
A fine powder mixture that produces parts in a cobalt-chrome-
molybdenum-based superalloy.
A 20 \(\mu\)m minimum recommended layer thickness.
Typical achievable part accuracy of \(\pm 20 - 50\ \mu\)m (small parts).
A minimum wall thickness of 0.3 mm.
A yield strength of 960 MPa, \(\pm 50\ \text{MPa (XY).}\)
A maximum operating temperature of 1,150°C.

**Titanium Ti64 (M 270):**
A pre-alloyed Ti6AlV4 alloy in fine powder form.
A 30 \(\mu\)m minimum recommended layer thickness.
A minimum wall thickness of 0.3 - 0.4 mm.
A yield strength of 1,090 MPa, \(\pm 70\ \text{MPa.}\)
A maximum operating temperature of 350°C.
A mechanism patented by PHENIX SYSTEMS allows you to adapt to the shape and average size of the grains of powder.

This function can be programmed and adjusted to suit any type of ceramic or metal powder with a granulometry equal to or greater than a micron.

There is already quite a wide range of material that can be used:

► Metal
  • Stainless steels
  • Tooling steels
  • Non-ferrous alloys
  • Super alloys
  • Precious metals

► Ceramic
  • Alumina

SINT-TECH offers a range of powders suitable for the process developed by PHENIX SYSTEMS. The granulometry of these powders was selected in order to ensure an optimised result when used in conjunction with systems from the PX range and the earlier PM range.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST4404D</td>
<td>316L stainless steel</td>
</tr>
<tr>
<td>ST2709B</td>
<td>Maraging steel</td>
</tr>
<tr>
<td>ST2724G</td>
<td>Chrome-coalt alloy</td>
</tr>
</tbody>
</table>
About AM250

The AM250 features a vacuum chamber evacuation followed by high purity argon gas in order to create a high quality atmosphere, crucial when building in reactive materials such as titanium, where oxygen content must be minimised. Gas consumption is minimised by the use of a fully sealed and welded chamber that also contributes to robustness. It's also possible to run the system with non-reactive materials under nitrogen gas.

The AM250 features an external powder hopper with valve interlocks to allow additional material to be added whilst the process is running. It is possible to remove the hopper for cleaning or to exchange with a secondary hopper for materials change, using the universal lift. The powder overflow containers are outside the chamber and feature isolation valves so that unused materials can be sieved and reintroduced to the process via the hopper while the system is running. The safe change filter and system powder handling, via the glovebox, help to minimise user contact with materials and process emissions.

The AM250 has been designed with the manufacturing industry in mind, with a simple touch screen user interface and robust construction. From series production of implantable devices to complex lattice structures or detailed aerospace geometries, the AM250 is capable of fulfilling the requirements of a manufacturing system. With the extended Z-axis option it is possible to build parts up to a maximum height of 360 mm.
### Speciation

<table>
<thead>
<tr>
<th>Specification</th>
<th>AM250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. part building area</td>
<td>250 x 250 x 300 mm (X, Y, Z)</td>
</tr>
<tr>
<td></td>
<td>Z axis extendable to 360 mm</td>
</tr>
<tr>
<td>Build rate*</td>
<td>5 cm³ - 20 cm³ per hour</td>
</tr>
<tr>
<td>Scan speed</td>
<td>up to 2000 mm/s</td>
</tr>
<tr>
<td>Positioning speed (max.)</td>
<td>7000 mm/s</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>20 - 100 µm</td>
</tr>
<tr>
<td>Laser beam diameter</td>
<td>70 µm diameter at powder surface</td>
</tr>
<tr>
<td>Laser options</td>
<td>200 or 400 W</td>
</tr>
<tr>
<td>External dimensions**</td>
<td>1700 x 800 x 2025 mm (L, W, H)</td>
</tr>
<tr>
<td>Weight</td>
<td>1225 kg gross, 1100 kg net</td>
</tr>
<tr>
<td>Power supply</td>
<td>230 V 1 PH, 16 A</td>
</tr>
<tr>
<td>Available materials</td>
<td>Stainless steel 316L and 17-4PH, H13 tool steel, aluminium Al-Si-12, titanium CP, Ti-6Al-4V and Ti-6Al-7Nb, cobalt-chrome (ASTM75), inconel 718 and 625</td>
</tr>
<tr>
<td>Materials in development</td>
<td>We have a range of materials in development, please contact us for an up to date list.</td>
</tr>
</tbody>
</table>

* Build rate is dependent upon material, density & geometry. Not all materials process at the highest build rate.

** Dimensions are without accessories.
2.10 FINE POWDERS—THE POURING PROBLEM

The emphasis on this chapter has been to consider methods and principles that lead to extremely fine, mono-sized, non-agglomerated powders for ceramic processing. If such powders are used in small-scale sintering tests, the advantages of well-dispersed spherical powders are very apparent (4.1). However, on an industrial scale, such powders would have to be used in large automatic filling moulds. This presents a problem, because particles < 1 \( \mu \)m diameter have poor pourability. The solution to this problem is to granulate
## DirectMetal and DirectSteel materials for EOSINT M 250 Xtended

<table>
<thead>
<tr>
<th>Volume rate (mm³/s) [4]</th>
<th>DirectMetal 20</th>
<th>DirectSteel 20</th>
<th>DirectSteel H20</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 µm layer thickness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- skin: 20 µm layers</td>
<td>2 - 8</td>
<td>1.5 - 2.5</td>
<td>0.5 - 3</td>
</tr>
<tr>
<td>- core: 60 µm layers</td>
<td>15</td>
<td>7.5</td>
<td>4</td>
</tr>
<tr>
<td>40 µm layer thickness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- skin: 40 µm layers</td>
<td>4 - 10</td>
<td>2 - 4</td>
<td>1 - 3</td>
</tr>
<tr>
<td>- core: 80 µm layers</td>
<td>16</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>60 µm layer thickness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- skin: 60 µm layers</td>
<td>6 - 12</td>
<td>2.5 - 5</td>
<td>-</td>
</tr>
<tr>
<td>- core: 60 µm layers</td>
<td>18</td>
<td>10</td>
<td>-</td>
</tr>
</tbody>
</table>
### Mechanical properties of laser sintered parts

<table>
<thead>
<tr>
<th>Property</th>
<th>DirectMetal 20</th>
<th>DirectSteel 20</th>
<th>DirectSteel H20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density in skin areas (g/cm³)</td>
<td>7.6</td>
<td>7.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Density in core areas (g/cm³)</td>
<td>6.3</td>
<td>6.3</td>
<td>7.0</td>
</tr>
<tr>
<td>Remaining porosity (min., %)</td>
<td>8</td>
<td>2</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Tensile strength (MPa, MPIF 10)</td>
<td>up to 400</td>
<td>up to 600</td>
<td>up to 1100</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>200</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>80</td>
<td>130</td>
<td>180</td>
</tr>
<tr>
<td>Transverse rupture strength (MPa, MPIF 41)</td>
<td>700</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>DirectMetal 20</td>
<td>DirectSteel 20</td>
<td>DirectSteel H2O</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------------</td>
<td>-------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td><strong>Hardness (HB, HV, HRB) [5]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- after micro shot-peening</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>380 - 420 HV, 38 - 42 HRC</td>
<td></td>
</tr>
<tr>
<td>- after hard coating [7]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 2000 HV</td>
<td>&gt; 2000 HV</td>
<td>&gt; 2000 HV</td>
</tr>
<tr>
<td><strong>Surface roughness (µm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- without post-processing</td>
<td>Ra 9</td>
<td>Ra 10</td>
<td>Ra 10</td>
</tr>
<tr>
<td></td>
<td>Rz 40 - 50</td>
<td>Rz 50</td>
<td>Rz 40 - 50</td>
</tr>
<tr>
<td>- after shot-peening</td>
<td>Ra 3</td>
<td>Ra 4</td>
<td>Ra 5</td>
</tr>
<tr>
<td></td>
<td>Rz 15</td>
<td>Rz 15</td>
<td>Rz 25</td>
</tr>
<tr>
<td>- after polishing</td>
<td>Rz up to &lt; 1</td>
<td>Rz up to &lt; 1</td>
<td>Rz up to &lt; 1</td>
</tr>
</tbody>
</table>

Fig. 2. An SEM picture of EOS powder.

Fig. 3. Optical micrograph.

Fig. 4. An SEM micrograph.
It was found that the dimensional errors along the axis were ranging from 0.003 to 0.082 mm. The average deviations were −0.043 mm in the X-axis, −0.018 mm in the Y-axis and 0.025 mm in the Z-axis. The values along the Y-axis were the most accurate. Obviously, different amounts of inaccuracy were found in the X-axis and Y-axis. Moreover, significant inaccuracy was found in the diameters of the cylindrical feature, ranging from 0.025 to 0.34 mm. This value may be unacceptable for tooling applications. Instead of a circular shape, an oval shape formation of the sintered part resulted in a large variation in the cylindrical features. Unequal shrinkage in the X and Y directions may have caused the circular profile of the parts to be distorted. The accuracy of the optical unit provided is crucial.
4. Conclusions

The EOS direct laser sintering process was able to produce 3D metal parts with very fine details, but the sintered parts were relatively soft, rough and porous. Optimisation of the process parameters and the working accuracy of the optical units was crucial to improve the part quality and accuracy. Powder handling and humidity control of the working area are important for better process control.

The experience and skill of the operator plays an important role in building a good part. Low melting point infiltration using silver alloy can improve the hardness. Nickel plating would be an option to improve the hardness and wear resistance of the parts. In order to get a better strength, a new material system has to be further developed.
Table 1. Powder characteristics *

<table>
<thead>
<tr>
<th>Powder characteristics</th>
<th>Materials</th>
<th>SS grade 316L</th>
<th>SS grade 904L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent diameter (weight by volume), μm</td>
<td>p10</td>
<td>5.3</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>p50</td>
<td>14.5</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>p90</td>
<td>25.2</td>
<td>18.5</td>
</tr>
</tbody>
</table>

* p10–p50–p90 are 10th, 50th and 90th percentiles of studied indexes. 10–50–90 percentiles are the values below which 10–50–90% of the observations may be found.

Table 2. Chemical composition (% wt.) of powders SS grade 316L and 904L

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>316L</td>
<td>Balance</td>
<td>11.0-12.0</td>
<td>17.0-18.0</td>
<td>2.0-3.0</td>
<td>0.00</td>
<td>1.0</td>
<td>0.045</td>
<td>2.00</td>
<td>0.030</td>
<td>0.02</td>
</tr>
<tr>
<td>904L</td>
<td>Balance</td>
<td>23.0-28.0</td>
<td>19.0-23.0</td>
<td>4.0-5.0</td>
<td>1.0-2.0</td>
<td>2.0</td>
<td>0.045</td>
<td>0.55</td>
<td>0.035</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Figure 3. Top view of tracks synthesized from SS grade 904L powder on substrate at different hatch distances: (a), (b), (c) – one, three, and five tracks at 60 μm hatch distance; (d), (e), (f) – one, two, and three tracks at 100 μm hatch distance.
Fig. 1. Top view of a laser sintered track from stainless steel grade 316L (~25 μm) powder on steel substrate. Laser power is 50 W, scanning speed is 0.10 m/s, thickness of the deposited powder layer is 40 μm.

Figure 4. Scheme of consecutive reduction of the powder consolidation zone during SLM.
Figure 4. Scheme of consecutive reduction of the powder consolidation zone during SLM.

Figure 5. Cross-sections of sintered tracks from SS grade 316L powder on steel substrate at different hatch distance: (a), (b) – 3 and 5 tracks at hatch distance 60 μm; (c), (d) – 2 and 3 tracks at hatch distance 100 μm.
Figure 6. Profile of a continuous sequence of tracks produced from SS grade 316L powder with 60 μm (a) and 100 μm (b) hatch distances.
Figure 7. Laser sintered thin walls from SS grade 316L powder. Thickness of powder layers varied from 40 to 80 µm with a step of 10 µm and 20 layers for each thickness, scanning speed is 0.04–0.18 m/s; laser power is 50 W.
E-Beam Melting using a powder bed
Full size γ-TiAl low pressure turbine blades manufactured with EBM.

3D CAD-model. 3D CAD-model with support structure. As-built blades still with support structure.

Powder Handling

In addition to the EBM machines Arcam offers a suite of auxiliary equipment for easy and safe powder handling that lives up to industrial standards. This includes explosion-protected vacuum cleaners (ATEX-classed), powder handling trolleys and the Arcam Powder Recovery System (PRS).

Spherical metal powders supplied by Arcam are optimized for reliable and safe operation.
**ARCAM A2 TECHNICAL DATA**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build tank volume</td>
<td>250x250x400 mm and 350x350x250 mm (W x D x H)</td>
</tr>
<tr>
<td>Maximum build size</td>
<td>200x200x350 mm and Ø 300x200 mm (W x D x H)</td>
</tr>
<tr>
<td>Model-to-Part accuracy, long range¹</td>
<td>+/- 0.20 mm (3σ)</td>
</tr>
<tr>
<td>Model-to-Part accuracy, short range²</td>
<td>+/- 0.13 mm (3σ)</td>
</tr>
<tr>
<td>Surface finish (vertical &amp; horizontal)²</td>
<td>Ra25/Ra35</td>
</tr>
<tr>
<td>Beam power</td>
<td>50–3500 W (continuously variable)</td>
</tr>
<tr>
<td>Beam spot size (FWHM)</td>
<td>0.2 mm – 1.0 mm (continuously variable)</td>
</tr>
<tr>
<td>EB scan speed</td>
<td>up to 8000 m/s</td>
</tr>
<tr>
<td>Build rate²</td>
<td>55/80 cm³/h (Ti6Al4V)</td>
</tr>
<tr>
<td>No. of Beam spots</td>
<td>1–100</td>
</tr>
<tr>
<td>Vacuum base pressure</td>
<td>&lt;1x10⁻⁴ mBar</td>
</tr>
<tr>
<td>Power supply</td>
<td>3 x 400 V, 32 A, 7 kW</td>
</tr>
<tr>
<td>Size and weight</td>
<td>1850 x 900 x 2200 mm (W x D x H), 1420 kg</td>
</tr>
<tr>
<td>Process computer CAD interface</td>
<td>PC</td>
</tr>
<tr>
<td>CAD interface</td>
<td>Standard: STL</td>
</tr>
<tr>
<td>Network</td>
<td>Ethernet 10/100/1000</td>
</tr>
<tr>
<td>Certification</td>
<td>CE</td>
</tr>
</tbody>
</table>

¹ Long range: 100mm, Short range: 10mm, measured on Arcam Standard Test Part (ASTP).
² Measured on Arcam Standard Test Part (ASTP).

*Inside the Arcam EBM process – a melt pool in the Ti6Al4V powder bed is created by the powerful electron beam.*
Machined Part
[Green Stratiform Machining]
Machined Part
[Green Stratiform Machining]
Machined Part
[Green Stratiform Machining]
Application of Polymer Emulsion to Faying Surfaces

Polymer glue is applied with paint brush. V-block registers layers until glue dries.
Discrete Polymer Layer
Redistribution at Low T&P
Mechanical Test Specimen Blanks
Tensile bars after machining
5mm diameter x 20mm gauge length
Tensile bars after machining
5mm diameter x 20mm gauge length
Tensile bar being tested, moments before fracture
Tensile bars before and after testing
## Comparison of tensile properties, 316L SS

<table>
<thead>
<tr>
<th>Tensile Properties</th>
<th>UTS (MPa)</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work CAM-LEM</td>
<td>566</td>
<td>44%</td>
</tr>
<tr>
<td>with layers...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Previous CAM-LEM (1997)</td>
<td>539</td>
<td>45%</td>
</tr>
<tr>
<td>with layers...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PIM standard</td>
<td>448</td>
<td>40%</td>
</tr>
<tr>
<td>German (1990)</td>
<td>510</td>
<td>45%</td>
</tr>
<tr>
<td>Bloemacher (1992)</td>
<td>530</td>
<td>55%</td>
</tr>
<tr>
<td>Cohrt (1992)</td>
<td>500</td>
<td>50%</td>
</tr>
<tr>
<td>Typical Wrought</td>
<td>480 to 600</td>
<td>40 to 50%</td>
</tr>
</tbody>
</table>
Layer Formation (reworded)

- Fluid flow
- Powder bed
- Droplets or particles
- Extrusion or wire
- Solid sheet
Localized solidification
- Photopolymerization
- Binder jetting
- Directed energy deposition to fuse
- Cooling
- Solid state bonding (ultrasound)
LENS for Large Component Repair and Manufacture
Hermetically Sealed Class 1 Laser Safe Enclosure
Process Work Envelope
900 x 1500 x 900 mm

Fig. 1. Schematic of the LENS™ process [4].

**Figure 5.** Rotary axes for elevation and azimuth were added to the 3 existing linear axes in the LENS machine.
Layer Formation (reworded)

- Fluid flow
- Powder bed
- Droplets or particles
- Extrusion or wire
- Solid sheet
Localized solidification
• Photopolymerization
• Binder jetting
• Directed energy deposition to fuse
• Cooling
• Solid state bonding (ultrasound)
Click here to download Sciaky's Direct Manufacturing Product Sheet.

Sciaky's Additive Manufacturing Solution: Electron Beam Melting (EBM)

Figure 1. Schematic of electron beam freeform fabrication (EBF³) system components.

Figure 2. Ground-based EBF³ system at NASA Langley Research Center.

Figure 3. Portable EBF³ system at NASA Langley Research Center.
Figure 4. Examples of parts fabricated at NASA Langley using the EBF$^3$ process. (a) Ti-6-4 wind tunnel model; (b) 2219 Al square box; (c) 2219 Al airfoil; (d) 2219 Al mixer nozzle; (e) 2219 Al converging diverging nozzle; (f) Ti-6-4 guy wire fitting; (g) Ti-6-4 inlet duct; (h) Ti-6-4 truss node with flat attachment surface.

Figure 6. Typical microstructures of 2219 Al deposit: a) shows dendrite growth in a deposit with high heat input and higher deposition layer height; b) shows less dendrite growth and formation of equiaxed grain structure in the bulk deposit with more moderate heat input and a smaller deposition layer height.[8]

Figure 7. Microstructures of EB$^3$ Ti-6-4 deposits: (a) low magnification shows columnar grain structure in LS plane, and (b) high magnification shows alpha-beta lath structure in ST plane.
Figure 8. Tensile properties at room temperature of EBF3 deposited 2219 Al as compared to typical handbook values [16] for 2219 Al sheet and plate.

Figure 9. Tensile properties at room temperature of EBF3 deposited Ti-6-4 ELI as compared to AMS 4999 Ti-6Al-4V minimum specification (standard grade Ti-6-4).[17]
An Alternative Use of Additive

(12) United States Patent
Nelson et al.

(10) Patent No.: US 8,328,471 B2
(45) Date of Patent: Dec. 11, 2012

(54) CUTTING INSERT WITH INTERNAL COOLANT DELIVERY AND CUTTING ASSEMBLY USING THE SAME

(75) Inventors: Joseph Nelson, Greensburg, PA (US);
      Linn Andras, Latrobe, PA (US);
      Thomas Muller, Greensburg, PA (US);
      Paul Prichard, Greensburg, PA (US);
      Brad Noffee, White, PA (US)

(73) Assignee: Kennametal Inc., Latrobe, PA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 378 days.

(21) Appl. No.: 12/797,249
(22) Filed: Jun. 9, 2010

(Continued)

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(Continued)

OTHER PUBLICATIONS
(Continued)
Another Well-Established Idea

United States Patent

Dudley

[54] MACHINE TOOL HAVING INTERNALLY ROUTED CRYOGENIC FLUID FOR COOLING INTERFACE BETWEEN CUTTING EDGE OF TOOL AND WORKPIECE

[76] Inventor: George M. Dudley, 69 N. Boxwood St., Hampton, Va. 23369

[22] Filed: Jan. 27, 1972

[21] Appl. No.: 221,322

[52] U.S. Cl. .......................... 29/106; 82/1 R
[51] Int. Cl. .......................... B26D 1/00; B23B 3/00
[58] Field of Search ............... 29/106; 83/170, 171; 82/1

[56] References Cited

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Primary Examiner—Harrison L. Hinson
Attorney, Agent, or Firm—Howard J. Osborn; John R. Manning

[57] ABSTRACT

This machine tool is utilized for cutting super alloys. The tool is associated with a source of cryogenic coolant which is routed internally through the tool. The coolant is discharged from the tool at a precise angle such that the stream of the coolant at the interface between the tool cutting edge and the workpiece is such that the chip cutting from the piece does not interfere with the coolant stream. The coolant passage is insulated to prevent boiling of the coolant until it reaches the cutting edge to obtain maximum heat dissipation.

2 Claims, 6 Drawing Figures
Gel-casting High Toughness Ceramics with Internal Passages at CWRU
3D machine

- Produces Epoxy Permanent Tooling
Epoxy/accrylate mold made by 3D machine for rocket nozzle
Solidscape

Two nozzle wax-based ink jet printing.

• Red wax (support) soluble in warm kerosene.

• Green wax (part) soluble in room temperature alcohol.
CAD Interface → Control Software → Control Electronics

X - Y Motion
Drop - On Demand Jets
Overhang Support

Z - Motion

Build Table
Build Substrate
Model
Planar Mechanism
CAD Representation of Cylinder Mold System
(Rhino, Robert McNeel & Assoc.)

- Outer Gating (stereolithography)
- Outer Lining (ProtoBuild™)
- Core Halves (ProtoBuild™)
- Inner Gating (stereolithography)
- Inner Lining (ProtoBuild™)
The joints of the assembled mold are sealed with a soft patching wax (Kindt-Collins) and held together with teflon tape. After the casting has gelled, the entire mold is immersed in ethanol. Leachable paths are designed such that all the wax parts are connected to the external surface. The wax liners and cores dissolve away in a few hours. The part is then submerged in PEG for drying. In some instances, parts are trimmed before immersion in the PEG.
Internally-Cooled Silicon-Nitride Cylinder

Demolded Untrimmed Green Part

Trimmed Green Part

Fired Part
Internally-Cooled Silicon-Nitride Plate

Green Gelcast Plate

View of Holes in Green Plate

Close-up View of Holes in Green Plate

Fired Holes 300μm
Summary

• Additive Manufacturing receiving emphasis.
• A range of techniques to produce metal parts.
• Complementary uses relevant to machining under development.