Additive Manufacturing: Overview, Technologies, and Safety

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Introductions

Thomas Brezoczky – VP of Engineering at Velo3D
• 25+ years’ experience in semi-conductor capital equipment, medical devices, solar with < 30 patents issued

Dan Christiansen – Mechanical Engineer at Velo3D
• 3+ years' experience in AM machine operation, applications, fundamental research, and lab safety
Content

• What is Additive Manufacturing (AM)?
• The major categories of AM
• Specifics of AM via Powder Bed Fusion
• Hazards
• Current standards & safety requirements
• Questions
What is Additive Manufacturing?

• Additive rather than traditional “subtractive” manufacturing
• 3D model is sliced into many 2D layers
• Each layer deposited and fused onto previous layer to build up a part
• Materials include polymers, ceramics, and metals

Arthur Fiedler Memorial – photo courtesy of bostonbronzeandstone.com
Benefits and Applications

Benefits:
- Small batches and custom parts made economical
- Little waste
- Increased complexity does not increase cost
- Traditionally impossible geometries

Current applications:
- Medical devices
- Injection molding tools
- Aerospace
- Motorsports
The 7 Types of Additive Manufacturing

All AM is done in layers, but the way the layers are formed and fused can vary

• VAT Photopolymerisation – large bath of liquid photopolymer resin is selectively cured with a UV light
• Material Jetting – drops of liquid polymer are dispensed individually and cured with a UV light
• Binder Jetting – powdered material is selectively coated in binding liquid
• Material Extrusion – “hot glue gun” method commonly seen in hobby printers
• Sheet Lamination – layers are cut from sheets and bound together using ultrasonic welding
• Directed Energy Deposition – 4 or 5 axis arm deposits material via wire or powder feed with a laser or electron beam heat source, similar to automated welding
• **Powder Bed Fusion** – powder layers are selectively sintered or melted with a laser or electron beam, commonly called PBF, DMLS, EBM, SHS, SLM, and SLS.
Powder Bed Fusion

**DMLS Process**

1. 3d Geometry model
2. Layer of powdered material is applied to building platform
3. Powdered material is solidified into a cross-section of a model with laser
4. Building Platform is lowered
5. The next layer of powder is applied
6. The process repeats itself until the part is complete
7. Unused powder is removed
8. Finished Part

Image courtesy of EOS
Build Chamber

- 200mm² to 2m² build area, depending on process
- Vacuum or pressurized/atmospheric inert environment (Argon, Nitrogen, or Helium)
- Build surface between 30-800°C, depending on process
- Filtered protective window
- Protective locks and power cutoffs in case of leaks or improper use
Additive Manufacturing “Factory” – Example 1

• Much smaller footprint than traditional factories
• Separated into:
  • Office space
  • Printers
  • Post processing (furnace, powder recycling, grinding, machining)
  • Storage areas (powder, build plates, consumables, spare parts)
• Generally each area is separated by a fire rated wall and places where powder is out have PPE requirements
• Not every group follows this formula, there is no “standard” at this point
Additive Manufacturing “Factory” – Example 2
Hazards of Powder Bed Fusion Equipment

- Metal powder hazards
  - Explosions
  - Fire
  - Inhalation
  - Slipping
- Laser or electron beam
  - Direct/indirect exposure
- High voltage electronics
- High pressure gas
  - Inert environment: argon, nitrogen, helium
- Post processing
  - Grinding
  - Heat treatment
  - Welding
  - Powder recovery and recycling
- 24hr operation
Common Metal Powders

- Materials include
  - Cobalt Chrome
  - Stainless Steels
  - Nickel Alloys
  - Titanium Alloys
  - Aluminum Alloys
  - Copper Alloys
- Size can vary from 1-500µm in diameter, most are 10-50µm
- Generally shipped in 5-10kg containers
- Made via gas atomization, plasma atomization, plasma rotating electrode
Powderpart Inc. Accident

- November 2013 – explosion at Powderpart Inc. in Woburn, MA
- Failed to eliminate known sources of potential ignition and follow pertinent instructions from equipment manufacturers, and did not alert the Woburn Fire Department to the workplace presence of hazardous materials, according to OSHA.

In addition to the fire and explosion dangers, other serious hazards included:
- The use of unapproved electrical equipment.
- Electrical equipment and wiring that were unsuitable for a hazardous location.
- Failure to train employees on chemical hazards and safeguards.
- Failure to supply employees with all necessary protective clothing, equipment and training.
- No written respiratory protection program.
- Failure to post danger tags in potentially explosive areas.

Fined $64,400 and one employee in critical condition with 2\textsuperscript{nd}-3\textsuperscript{rd} degree burns over 65\% of his body
Relevant NFPA Policies

- 484 – Standard for Combustible Metals
- 652 – Standard on the Fundamentals of Combustible Dust
- 654 – Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids
- 69 – Standard on Explosion Prevention Systems
- Others: 1, 10, 13, 30, 33, 34, 51B, 54, 68, 69, 70, 80, 86, 91, 101, 220, 221, 496, 505, 600, 704, 780, 1081, 2112, 2113, 5000
- http://titanium.scholarlab.com/KevinKreitmanBonusPresentation.html
Standard Storage Procedures

- Powder is stored in original container or in stainless steel flask
- Powder that is not in use is stored in standard flame cabinets
- Separate flame cabinet used for “flammable” and “non-flammable” metals
- Only quantity of powder required for monthly operations is stored, no large supply is maintained, both for powder quality and safety reasons
- Spills are immediately cleaned with powder vacuum
- All floors in powder handling rooms are mopped at least weekly
- All flat surfaces (tables, equipment, shelves) are inspected and wiped periodically to ensure no large buildup of powder
Standard Handling Procedures

- Required PPE
  - P100 respirator
  - Lab coat
  - Eyewear
  - Gloves
- Vacuuming ATEX Approved
  - Spark-proof with liquid filled tank, grounded
- Enclosed and purged vibratory sieving
- Transporting
  - Depends on material
- Disposal
  - Hazardous waste
Potential Ignition Sources

- Hot surfaces
- Flames and hot gases
- Mechanically generated sparks
- Electrical apparatus
- Static electricity
- Lightning
- RF electromagnetic waves
- Ionizing radiation
- Adiabatic compression and shock waves
- Chemical reactions, including self-ignition

Image courtesy of safety108.com
Risk According to Powder Material, Size, and Composition

Risk and explosion size also increase with:
- Decreasing moisture content
- Increasing dust concentration
- Decreasing inert concentration
- Enclosed spaces

Figure 3—Comparison of energy release during controlled explosion tests of different powders\textsuperscript{10}

Figure 6—Effect of average aluminium powder size on the rate of pressure rise at different concentration levels\textsuperscript{21}

Figures courtesy of scielo.org
Example MSDS – Ti-6Al-4V

SAFETY DATA SHEET
Product: Spherical Ti-6Al-4V Powder (Fine)

(1) IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND COMPANY UNDERTAKING

Identification of the substance or preparation

Trade Name: Spherical Ti-6Al-4V powder (Fine)

Chemical Name: Titanium-Aluminium-Vanadium Alloy Powder

Synonym: Ti-6Al-4V Grade 5 Powder

Ti-6Al-4V Eutectic Powder

Use of the substance/presentation:
Powder metalurgy parts manufacturing, including metal injection molding, rapid prototyping, laser sintering. Coatings using plasma spray, cold spray.

Company/Undertaking Name: AP&C Advanced Powders and Coatings Inc.

Address: 3755 La Valandre, Suite 111

City: Expedition, Quebec, J7H 1R6

Canada

Phone: +1 450 431 1804

Fax: +1 450 431 1809

Emergency Telephone: 24-Hour Transportation Emergency Phone: CANATEC +1 613 295 0050

(2) HAZARDS IDENTIFICATION (EC)

This substance is classified as dangerous according to Directive 67/548/EEC and its amendments.

Classification:

Flammable

Physical/Chemical Hazards:

Flammable

(3) COMPOSITION/INFORMATION ON INGREDIENTS

<table>
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<tr>
<th>INGREDIENT NAME</th>
<th>CAS NUMBER</th>
<th>FORM</th>
<th>Ct Number</th>
<th>Ct Classification</th>
<th>EC Number</th>
<th>EC Classification</th>
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<tr>
<td>Titanium</td>
<td>7440-22-6</td>
<td>Solid</td>
<td>89.7</td>
<td>(see section 16 for full list of R-phrases)</td>
<td>1-849-2</td>
<td>R41</td>
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<td>Aluminum</td>
<td>7429-99-5</td>
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<td>88.4</td>
<td></td>
<td>8-118-17</td>
<td>R41</td>
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(4) FIRST AID MEASURES

Eye contact: Immediately flush eyes gently and thoroughly, including under the eyelids, with clean running water for 20 minutes.

Skin contact: Wash thoroughly with soap and water. Remove and properly dispose or launder contaminated clothing before wearing it again. Clean material from shoes and equipment. Seek medical attention.

(5) FIRE-FIGHTING MEASURES

Suitable extinguishing media:
Use approved Class D extinguisher or smother with dry sand, dry clay or dry limestone.

Not suitable as extinguishing media:
Do not use water, dry chemical, CO2, or halon.

Special protective equipment for fire-fighters:
Wear appropriate protective equipment and self-contained breathing apparatus (SCBA).

(6) ACCIDENTAL RELEASE MEASURES

Personal precautions:
Immediately contact emergency personnel. Remove all sources of ignition. Keep unnecessary personnel away. Use suitable protective equipment. Do not touch or walk through spill material.

Environmental precautions:
Keep spill material away from drains and runoff, ground water and soil.

Methods for cleanup:
Do not use compressed air to clean spills. Use non-sparking tools to clean up. Do not push power or liquid materials across the floor. Keep in small piles away from each other. Place collected material into non-sparking or anti-static containers, containing large quantities of sand, or other appropriate heat dissipation material. The use of plastic bags is not recommended, due to potential for static electricity buildup (inside plastic bags).

(7) HANDLING AND STORAGE

Handling:
Keep powder away from open flames and other sources of ignition. Try to maintain humidity above 50% to prevent electrostatic build-up. Maintain supply of “coarse” (rock-type) salt and/or “Class D” (for metal fires) fire extinguisher located near processing and storage areas. No smoking in area. Use non-sparking metal tools and equipment. Keep work areas clean and free of waste.

Storage:
Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (sparks or flames). Comply with local fire prevention and building codes for the storage of these materials.

(8) EXPOSURE CONTROL/PERSONAL PROTECTION

Exposure limit values:
Not available

SAFETY DATA SHEET
Product: Spherical Ti-6Al-4V Powder (Fine)

(9) PHYSICAL AND CHEMICAL PROPERTIES

General Information:
Appearance – Solid metallic powder, gray
Odor – None

Important health and environmental information:

pH:
Not applicable

Boiling point:
Not available

Flash point:
Not available

 Explosive properties:
Free dust cloud may form explosive mixture with air.

Oxidizing properties:
Not expected

Vapor pressure:
Not applicable

Relative density:
4.15 (Air=1)

Solvency:
Not available

Water solubility:
Insoluble

Partition coefficient:
Not applicable

Viscosity:
Not applicable

Vapor density:
Not applicable

Evaporation rate:
Not applicable

Other information:

Molten point:
1650-1670°C

Auto-ignition temperature:
420°C vary in particles in closed form.

(10) STABILITY AND REACTIVITY

This product is stable under normal storage conditions.

Conditions to avoid:
Static electricity, heat or ignition source

Materials to avoid:
Combustible materials, acid, oxidizing agents, halogenated hydrocarbons

Hazardous decomposition products:
None

[Image: VELSDP logo]
Example MSDS – Ti-6Al-4V

SAFETY DATA SHEET
Product: Spherical Ti-6Al-4V Powder (Fine)

(11) TOXICOLOGICAL INFORMATION
No scientific evidence was found of a health hazard from the inhalation of titanium powder in concentrations of air that do not exceed 10 mg/m³ total dust containing less than 1% quartz. The toxicity of titanium has been found to be relatively low. Skin contact with titanium powders may cause physical abrasion. Eye contact has shown particular irritation. This product is not considered carcinogenic, mutagenic, or teratogenic.

(12) ECOLOGICAL INFORMATION
No known significant effects on critical hazards.

(13) DISPOSAL CONSIDERATIONS
The generation of waste should be avoided or minimised wherever possible. Avoid disposal of spill material and runoff and contact with soil, waterways, drains and sewers. Disposal of this product, and any by-product should at all times comply with the requirements of environmental protection and waste disposal legislation and any national, regional and local authority requirements. Contaminated packaging materials, cleaning tissues, disposable gloves, and other contaminated materials should be disposed of in the same manner as the product itself.

(14) TRANSPORT INFORMATION

<table>
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<tr>
<th>UN Number</th>
<th>UN 3089</th>
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<tr>
<td>Shipping Name</td>
<td>Metal powders, flammable, n.o.s. (Spherical Ti-6Al-4V Powder &lt; 45 μm)</td>
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<tr>
<td>Class</td>
<td>4.1</td>
</tr>
<tr>
<td>Packing Group</td>
<td>II</td>
</tr>
</tbody>
</table>

(15) REGULATORY INFORMATION

EU REGULATIONS
Hazard Symbol

Risk phrases:
- R11 - Highly flammable

Safety phrases:
- S16 - Keep away from sources of ignition – No smoking.
- S22 - Do not breathe dust.
- S23 - Do not breathe fumes.
- S33 - Take precautionary measures against static discharges.
- S334| GT - Wear suitable protective clothing and gloves.
- S43 - In case of insufficient ventilation, wear suitable respiratory equipment.
- S45 - In case of fire, use sand.
- S51 - Use only in well-ventilated areas.
- S60 - This material and its container must be disposed of as hazardous waste.

CANADIAN REGULATIONS

WHMIS Classification:
- Class B-4 – Flammable Solids

WHMIS Symbol:

(16) OTHER INFORMATION

NFPA Classification

Full Text of Revisions in Section 2 & 3
- R11 – Highly Flammable
- R15 – Contact with water liberates extremely flammable gases
- R16 – Explosive when mixed with oxidizing substances
- R17 – Spontaneously flammable in air

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Date of previous issue: January 15, 2013

Notice:

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein. Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.
NFPA Review Highlights – General Response for Powdered Metals

Technical committee on Combustible Metals and Metal Dusts (NFP 484) running from July 2015 to August 2017

- Debate over which standards apply to AM
- Debate over what is considered a combustible metal and how to test for it
- Debate over what is considered a pyrophoric material and how to test for it
- Debate over which standards apply to powdered metals, as there is overlap between 484, 652, and 654

- Specific committee to address AM:
  - Requirements to inert per NFPA 69
  - Require portable vacuums have interlocks for grounding and minimum liquid levels
  - Specify requirements on training for use of 3D printers and portable dust collectors/vacuums
NFPA 485 Combustible Metals Summary

Fire Prevention Requirements

• Inspection and Maintenance Programs Required
• **Housekeeping Programs** and Documents
  • Minimizes explosion and fire
  • Not allowing dust to accumulate resulting in flash fire or explosion
  • Limit bulk storage or accumulation of powders
  • Housekeeping frequency must be maintained.
  • Unscheduled housecleaning protocols must be established.

• Fire Protection
  • Automatic sprinklers – recommended to be disabled
  • Prohibited fire fighting agents
    • Water
    • Foam
    • Halon
    • CO2/N2
NFPA 485 Employer Summary for Emergency Response

- Established emergency procedures followed.
- Employees in areas handling materials must be trained annually:
  - Hazards of environment and procedures in case of fire or explosion.
  - Trained on proper evacuation procedures.
  - Familiarity with systems, alarms, safety equipment and fire extinguishing equipment.
  - Familiarity with firefighting methods and for isolating fires.
  - Hazards of dust clouds
  - Equipment and operation including emergency shutdown.
  - Review of emergency response plans.
Combustible Metal Fire Protection Facts

- Water applied to Titanium and some other non alkali metals disassociate to O and H when heated.
- CO2 applied to these metals can disassociate to C and O2.
- A combustible metals (Ti) fire must be carefully understood:
  - Water reacts and turns to steam and H.
  - Large fires are difficult to extinguish.
  - Letting fire burn and control surrounding is often best choice.
Questions?

• Email: Dan@velo3d.com
NFPA Review Highlights – General Response for Powdered Metals

- Rapid response is key
- Hazard risk assessment:
  - List of materials and metals in immediate vicinity
  - Building layout with main areas and equipment
  - Layout of surrounding facilities
  - Potential risk of continuing fire (large powder storage cabinets, flame cabinets, etc)
  - Explosion risk level
  - MSDS for all materials
  - List of extinguishing agents available and their locations
- Burning powder should, if possible, be deposited into a suitable fire-proof container (with non-sparking shovels)
- Correct extinguishant must be used (Class D)
- Once fire has been dealt with to the best of your ability, turn off equipment, close doors, and evacuate
- Care must be taken to thoroughly and safely clean facility. Wear appropriate PPE and collect debris in a suitable container for appropriate disposal