Improving Additive Manufactured Parts with Aluminum Ion Vapor Deposition

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Executive Summary

Every year, additive manufacturing (AM) seems to gain further traction and prominence within the industry. New factories opening up. New methods of 3-D printing being developed. More and more parts made from AM materials. Aerospace companies, such as Boeing, are using 3D-printed titanium parts, which could potentially shave off millions of dollars in cost [1].

Yet even as AM becomes more widely adopted with an increasing number of companies beginning to trust the manufacturing process and resulting parts, the AM process still has some questions it needs to answer. At the forefront is the query: “How do we develop heat treatment processes that are both cost-effective and suitable for AM parts? And what standards and testing procedures should we use for approval?”

AM parts undergo heat treatment to ensure they achieve the desired dimensions, as well as metallurgical and physical properties. Part of the challenge for those that want to fully embrace AM, though, is that if they are to manufacture parts on a large scale, they need to find ways to do so more cost-effectively and while achieving the necessary metallurgical specifications without excessive post-processing.

One of the emerging solutions for surface improvement and corrosion enhancement of AM parts is aluminum ion vapor deposition (IVD). A physical vapor deposition process for applying pure aluminum coating to various parts, IVD has emerged as a way to eliminate surface imperfections and improve metal corrosion resistance.

In this paper, we will discuss the IVD process advantages when it comes to mitigating surface imperfections and providing corrosion and dissimilar metal protection, as well as the AM requirements for vacuum heat treatment processes. While going over ways to refine heat treatment processes for AM parts, we will also examine several methods for improving heat treatment costs.

Introduction

Leading the charge in the next generation of metal component fabrication is additive manufacturing, one of the most significant developments in modern industrial technology. After all, “No other technology has the potential to change the design process and appearance of new products so fundamentally” [2].

The additive manufacturing (AM) process – also known as 3-D printing – differs from subtractive manufacturing methods, such as machining, as it involves adding, melting and joining layers of powder metal on top of each other. AM parts then undergo heat treatment to ensure these parts achieve the desired dimensions, as well as metallurgical and physical properties.
The most popular powder metals used in AM are stainless steel, Inconel, magnesium, cobalt, titanium, copper, tool steels and aluminum. With the growth of AM, the ASTM International Committee on Additive Manufacturing Technologies has developed standard terminologies for AM. As part of that effort, they developed the ASTM F2792 standard (Table 1), which outlines categories of 3-D printing, five of which are suitable for metal AM.

**Table 1. ASTM F2792 categories of 3-D printing [3].**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Material Extrusion</th>
<th>Material Jetting</th>
<th>Binder Jetting</th>
<th>Vat Photopolymerization</th>
<th>Sheet Lamination</th>
<th>Powder Bed Fusion</th>
<th>Directed Energy Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymers and Polymer Blends</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Composites</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
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<tr>
<td>Metals</td>
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<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>Graded/hybrid metals</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Ceramics</td>
<td></td>
<td></td>
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<tr>
<td>Investment Casting Patterns</td>
<td>x</td>
<td>x</td>
<td></td>
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<td></td>
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<tr>
<td>Sand molds and cores</td>
<td></td>
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<tr>
<td>Paper</td>
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</tbody>
</table>

With the need for heat treatment, AM parts require the use of vacuum furnaces for a variety of processes: annealing, carburizing, nitriding, sintering, solution aging and stress relieving. These heat-treating systems must also be capable of meeting specific criteria such as heating uniformity and purity of atmosphere or vacuum level.

**Early Adopters of AM Technology**

Multiple markets have begun to adopt 3-D printing (i.e., additive manufacturing) over recent decades, and AM adoption is expected to continue to grow, as outlined in Fig. 1.

**Figure 1 – Timeline of 3-D printing adoption curves [4].**
Within the Automotive industry, one early adopter of AM technology is Ford Motor. Since the 1980s, the company has used this technology to develop prototype parts for test vehicles, including cylinder heads, brake rotors and rear axles. All of these prototype parts were created in less time than required by traditional manufacturing processes [5].

In addition to Ford Motor, all major automobile manufacturers use AM processes. BMW, for example, uses them to produce more than 100,000 parts per year for its vehicles. AM is also used by aerospace and defense manufacturers, such as Turbomeca who uses the process for its serial production of helicopter engine components. These engines are Turbomeca’s latest models and are claimed to be among the most advanced turboshafts ever designed [6].

**AM Technology & Current Industry Trends**

The current penetration of parts produced using AM methods represents around one percent of the total shipment values for the Automotive, Aerospace, Military and Tooling industries, reaching $5.165B in 2015 with a CAGR of 25.9 percent [7].

However, this number is rapidly increasing with the fast-growing adoption of AM technologies (as illustrated above). The largest AM technology penetration is currently within the Medical and Dental industries with, in some estimations, over 50 percent of dental implants being made with AM processes.

Additive manufacturing also complements others powder metallurgy (PM) technologies. These PM technologies – which include hot isostatic pressing (HIP), metal injection molding (MIM) and sintering – offer the ability to produce net-shape parts and each cover a different segment of the market and production requirements (Fig. 2). Net-shape parts manufactured using AM methods, though, could save up to 90 percent of the material versus the same part made through machining.

![Positioning of various PM technologies according to part weight or size and production series](image-url)
When it comes to the quality of AM parts, densities of 99.9 percent are achievable; however, the reality is that the majority of AM parts have less density than wrought parts. AM parts with less density often feature residual internal porosities, cracks, high surface roughness and impurities. Thus, while the mechanical properties of AM parts are usually superior to cast parts, they are inferior to wrought parts [9].

Experience has shown that AM technology efficiency improves with smaller and more complex components. Whereas, parts that need extensive machining after AM will rarely be competitive with traditional technology. Fig. 3 highlights the breakeven point for manufacturing according to a 2011 study conducted by Atzeni and Salmi [10].

![Image](image-url)

**Figure 3 – Breakeven point for subtractive manufacturing and 3-D printing (i.e., AM processes) [10].**

### Understanding the AM Challenges

Even though AM offers the opportunity to reproduce most parts currently manufactured by conventional technologies, such as milling and casting, it is only in some cases that the results are better or cheaper than the original part.

The heat treatment processes outlined in Table 2 are commonly used to modify the metallurgical properties of AM parts.

**Table 2.** Common heat treatment processes and the corresponding additive process for metal AM parts.

<table>
<thead>
<tr>
<th>Heat Treatment Process</th>
<th>Additive Process for Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sintering</td>
<td>Direct Deposit</td>
</tr>
<tr>
<td>Stress Relieving/Aging/SMHT</td>
<td><em>A process that utilizes an electron beam or laser to fuse material by melting as the material is being deposited.</em></td>
</tr>
<tr>
<td></td>
<td>Laser Metal Deposition (LMD or LMD-w)</td>
</tr>
</tbody>
</table>
| **HIP** | **Powder Bed Fusion**  
*A melting process that uses layers or electron beams to fuse each layer together.* |
| **Annealing/Aging** | **Direct Metal Laser Sintering (DMLS)** |
| **Stress Relieving** | **Electron Beam Melting (EBM)** |
| **Infiltration** | **Selective Laser Melting (SLM)** |
| **Curing at Low Temperature** | **Bidder Jetting**  
*A process in which a liquid binding agent is selectively deposited to join powder particles. Layers of material are then bonded to form an object.* |
| **Crucible Infiltration in Vacuum** | **Bidder Jet Process (BJP)** |

And while AM has great potential, it also has several significant challenges. To start, the mechanical properties of AM parts lack the same mechanical and metallurgical properties as wrought material.

Second, if companies are to manufacture AM parts on a large scale, they need to be able to 3-D print in metal faster and from less costly powder alloys. The AM process also induces defects, stresses and anisotropic mechanical properties due to the columnar grain structures on the parts. These imperfections negatively influence the mechanical properties of the material, especially the fatigue behavior [11].

Thus, to achieve the necessary metallurgical specifications – such as surface quality, geometrical accuracy and mechanical properties – AM parts must be post-processed by machining, electrical discharge machining (EDM), grinding, polishing, heat treatment and HIP [12]. It is also important that heat-treated AM parts do not have surface or internal oxidation, decarburization or a discolored surface from water vapor, oxygen or alloy evaporation.

Powder particle size also has a direct influence on the final part density, dimensional accuracy and surface roughness. The result is the smaller the particle, the better the final AM part quality. However, non-weldable alloys cannot be processed by AM, and challenging-to-weld alloys, such as aluminum, require an individual approach [13].

As such, the current challenge facing the heat treatment industry is developing heat treatment processes that are both suitable for AM parts and cost effective. Even more specifically, the question facing the AM industry is how to apply existing coating processes to eliminate surface imperfections and improve corrosion resistance.
Improving Surface Coating & Heat Treatment Costs for AM Parts

One of the growing methods to eliminate surface imperfections and improve metal corrosion is aluminum ion vapor deposition (IVD).

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**Ion Vapor Deposition (IVD)**

A physical vapor deposition process for applying pure aluminum coating to various parts, mainly for corrosion protection and improving surface quality.

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Aluminum IVD coatings offer several process advantages when it comes to mitigating surface imperfections. To start, aluminum IVD can be used at temperatures up to 925 °F (496 °C), as well on titanium without creating solid metal embrittlement concerns. Other advantages include:

- Can be used for space applications
- Can be polished to a mirror-like finish
- Is superior to cadmium and tin-plating for electromagnetic interference (EMI) uses

The largest use of aluminum IVD is for corrosion protection of ferrous alloy parts. The aluminum IVD coating process can also be used on all small parts, such as trunnions, cylinders, retainers, caps, retainer rings, spacers, strikers, springs, bolts, brackets, standoffs, links, flap tracks, rings, outboard actuators, strut terminals, blower impellers, stops, screw assembly ballnuts, plates, housings leg bolts, fasteners, nuts, covers, housings, etc. There are also applications for non-ferrous parts – such as copper alloy bushings – that are coated for dissimilar metal protection.

A type of IVD system for small parts is a barrel coater. These are designed to handle large volumes of small parts – making it more cost-effective to process a single load – and are typically used for coating small cylindrical net-shape parts such as fasteners, bolts, pins, nuts, rivets, etc.

Operating the equipment is also very simple. Once the coating cycle starts, the operator addresses a menu to input the operating parameter to coat the parts. Depending on the application, aluminum IVD coatings are applied in the range of 0.0003 to 0.002 inches. The menu is then retained for future use with similar parts. Throughout the process, the necessary steps – including pumpdown, glow discharge cleaning,
aluminum IVD coating, cooling of parts (when required) and venting of the coater to atmosphere pressure – are completed automatically.

Yet to be successful, parts that undergo the aluminum IVD coating process must meet certain important properties as illustrated in Table 3.

Table 3. Important properties the aluminum IVD coating process must meet to be successful [15].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Brief Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion</td>
<td>The coating will not show separation from the base metal at the interface when examined at a minimum magnification of approximately four diameters. The interface between the aluminum and the base metal is the surface of the base metal before coating.</td>
</tr>
<tr>
<td>Appearance</td>
<td>The high-purity aluminum coating is smooth, fine-grained, adherent, uniform in appearance, free from staining, pitting and other defects. The coating has no indication of contamination or improper operation of equipment used to produce the deposit, such as excessively powdered or darkened coatings.</td>
</tr>
<tr>
<td>Composition</td>
<td>The composition of the aluminum coating is less than 99 percent aluminum.</td>
</tr>
<tr>
<td>Corrosion Resistance</td>
<td>Test samples have no evidence of corrosion of the base metal after testing.</td>
</tr>
<tr>
<td>Coverage</td>
<td>The coating completely covers all visible surfaces, including roots of threads and sharp corners.</td>
</tr>
<tr>
<td>Substrate Integrity</td>
<td>The process used to deposit the coating will not cause a temperature rise in the parts that could cause adverse reaction between the coating and the substrate or adversely affect the substrate.</td>
</tr>
<tr>
<td>Thickness</td>
<td>The thickness of the coating should be sufficient for its intended use. Class 3 coatings are typically 0.0003 to 0.0005 inches thick. Class 3 coatings are used where corrosion protection and/or dissimilar metal compatibility is needed for close tolerance or threaded parts. Class 1 (0.001-inch minimum) and Class 2 (typically 0.0005 to 0.00099 inches) are used where corrosion protection and/or dissimilar metal compatibility are needed for structural and functional ferrous and non-ferrous alloy parts. Class 2 coatings are generally specified when Class 1 coatings exceed dimensional tolerance requirements.</td>
</tr>
</tbody>
</table>

AM Requirements for Heat-Treating Systems
According to a metal powder manufacturer, for vacuum furnaces to meet the requirements of AM processes they must possess certain features [16]. For example, the AM process necessitates …

- A multi-purpose vacuum furnace that features, for example, excellent low and high-temperature uniformity, forced convection, high vacuum and precise, controllable pressure gas quenching.
- Ability to perform stress relieving, annealing and age annealing at relatively low temperatures (<1,472 °F [<800 °C]).

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1 See MIL-DTL-83488 for a more detailed explanation.
• Ability to perform hardening, annealing and solution annealing at high temperatures of up to approximately 2,372 °F (1,300 °C).
• Forced convection in heating (<1,472 °F [<800 °C], mostly nitrogen atmosphere)
• High vacuum for clean, non-contaminated surfaces. For example, Titanium TiAl6V4 is a very standard material for which heat treatment is beneficial in enhancing its mechanical properties.
• Precise pressure gas cooling for quench hardening when necessary, such as with tool steels, stainless steels, etc.
• Options for nitriding and carburizing.
• Multi-zone temperature controls with work (load) thermocouples attached, or close, to the part’s surface.

Figure 4 – Ipsen vacuum furnaces at the GE AM facility in Pittsburgh, Pennsylvania [17].

Five Methods for Improving Heat Treatment Costs of AM Parts
If, in addition to refining heat treatment processes for AM parts, the goal is to improve heat treatment costs, there are several methods for doing so:

1. Increase the load density.
   Since AM parts are usually very light with thin walls and complicated shapes, you want to fit as many parts as possible on a single base. Once you have optimized the available surface space, load these bases into a vacuum furnace to maximize use of the hot zone. It is also possible to computerize load configurations according to the hot zone’s usable dimensions. More parts per base (and bases per load) will lower the cost of heat treatment and improve furnace hot zone usage.

   In addition, on average, 60 percent of energy is wasted via heat loss, and only around 28 percent of heat is used to bring the part to the required temperature and keep it at the holding temperature. These energy losses are independent of load size, meaning the operational cost decreases as the load/weight ratio increases.
2. **Use lightweight fixtures.**
   The parts’ thin walls dictate the load support and fixture design. With the help of fixtures, the load should be designed in vertical orientations and use only a minimal number of part supports. Lightweight fixtures, such as coated CFC grids, are highly recommended.

3. **Optimize heat cycles for different parts.**
   Relatively low wall thickness increases the efficiency of heating up, but it also creates challenges for the heat treatment process. Cycle parameters, such as heat-up rate and cooling speed, should be very precise when they are set up so as to not adversely affect the parts.

4. **Follow specific load techniques for tall parts with thin walls.**
   Components should be loaded vertically with 20 mm spacing between parts to minimize distortion. Typically, Z-level layers increase the total cycle production time. In comparison, increasing the X-Y complexity of each layer has much less of an effect on cycle time. For this reason, the height of the parts is typically limited to an 8:1 ratio [18].

   For alloy materials, such as titanium, nickel, cobalt, tungsten and cobalt-chrome-molybdenum, a metal hot zone with modified molybdenum heating elements is required. For high-temperature applications above 2,552 °F (1,400 °C), tungsten could be used. Finally, for tool steel – and if the carburizing process is necessary – a graphite hot zone is acceptable.

5. **Have gas flow controllability.**
   The vacuum furnace you use should be capable of cooling with a different gas according to alloy requirements and the part’s physical geometry. The flow and pressure should also be adjustable via computer and changeable according to alloy, process type, part geometry and the ratio for the part’s total surface to weight.

**Results**

It has been found that IVD aluminum can be applied to copper and stainless steel alloys to provide corrosion compatibility with aluminum structures. IVD aluminum is also acceptable for use on titanium parts, which are coated to prevent galvanic corrosion of dissimilar parts.

By coating the titanium part with IVD aluminum, one is able to eliminate the galvanic cell due to dissimilar metal contact. This is essential for titanium structural or threaded parts that come in contact with aluminum alloys.

**Conclusion**

The IVD process provides a solution to one of the common challenges facing the AM industry: how to apply existing coating processes to eliminate surface imperfections and improve corrosion resistance. Overall, aluminum IVD coatings offer several process advantages when it comes to mitigating surface imperfections.

For many manufacturers, finding new methods of refining heat treatment processes (while also minimizing costs) for AM parts is an essential and necessary step. Additive manufacturing is still in its infancy, yet its projected growth and the benefits it could bring to multiple industries is staggering.
Resources


[18] Janusz Kowalewski, Ipsen USA, Private discussion with metal powder manufacturer VVT.