# EARLY ADAPTATION OF ADDITIVE MANUFACTURING PROCESSES IN A TRADITIONAL MANUFACTURING LINE

Omnia Manufacturing


## Abstract

As 3D printing becomes more accepted throughout the design and manufacturing industries, small and large manufacturing companies will attempt to integrate additive manufacturing into their manufacturing lines. Challenges including supply chain management, certification requirements, industry regulations, pre and post processing, atmosphere control, thermal stresses, and testing are only some of the many companies must overcome.



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# Definitions

1. AM – Additive Manufacturing
2. MFG – Manufacturing
3. OEM – Original Equipment Manufacturer
4. DMLS – Direct Metal Laser Sintering
5. SLS – Selective Laser Sintering
6. SLM – Selective Laser Melting
7. CT Scanning – Computerized Tomography Scanning
8. SAE – Society of Automotive Engineers
9. Ra – Roughness Average
10. EDM: Electric Discharge Machine
11. PPM – Parts Per Million
12. FEM – Finite Element Methods
13. FEA – Finite Element Analysis
14. CAD – Computer Aided Design

# Introduction

Subtractive manufacturing implies the process of removing material from formed raw material in a controlled manor. Historically, subtractive manufacturing received its roots from carving and sharpening of wood, stone, and bone. Early and late history of ceramic and pottery forming as well as construction introduced new methods of manufacturing that relied on additive building. Additive manufacturing’s debut into modern history originated from blacksmithing, the art of cutting and forming metal into useable objects by treating the material with heat. Metal castings, an additive manufacturing technique developed by foundries, are created by melting metal into its molten form and pouring the resultant fluid into a formed mold. The most notable form of additive manufacturing is welding, primarily defined as the joining of two pieces of metal. Modern gas welding consists of using filler metal to combine two or more parts along a seam or joint, causing changes to the molecular structure in the heat affected zone as well as potentially introducing different elements.

Additive manufacturing as applied to 3D printing refers to the automated process of translating digital 3D modeling data into a physical 3D part layer-by-layer from dispensed material. Current metal 3D printing machines use SLS, SLM, and DMLS style printing. Each process is performed using a high powered and extremely accurate laser, 3D modeling data, and dispensed metal in the form of a very fine powder. As the metal powder is dispensed (either as a layer or selectively as the laser is operational) the laser either melts or sinters as dictated by the locations in the 3D model. Sintering metal powder will solidify the particles and “weld” the material together without welding, whereas melting will introduce different bead size, surface finish, and porosity within the finished product. The primary use-case of 3D printing additive manufacturing besides rapid prototyping is the development of designs and products that are ultimately impossible to build using traditional subtractive manufacturing methods or castings.

# I. Certification Retirements

Cost effective incorporation of additive manufacturing processes into a manufacturing line is variable on a job-to-job basis. Prototyping and proof of concept engineering requires different regulation and testing requirements compared with production part development. Depending on the position in the manufacturing line, different certifications must be present – whether for internal engineering testing prior to a traditionally manufactured part or for proof of product reliability and conformance requested by a customer.

Material certification is a two-step process stemming from the mill certification for the dispensed powder. The second process is a material testing certification post the printing process. This requirement will be contingent upon the test specimen being printed alongside and in the same production run as the part. It is vital that as an inspection protocol, the production part is incrementally tested using non-destructive testing methods along with destructive and nondestructive testing of the printed test specimen. The printing process for the production run should be vetted with destructive and nondestructive testing methods in order to reduce or remove discontinuities and porosity within the parts.

Nondestructive testing includes but is not limited to the following:

1. ***Ultrasonic testing*** – Utilizing the propagation of ultrasonic waves throughout a solid or fluid medium in order to detect internal flaws or discontinuities.
2. ***Magnetic particle inspection*** – A magnetic field in created in the test specimen and ferrous particles are applied to the surface. Magnetic flux will be stronger at surface discontinuity and will attract the particles.
3. ***Dye penetrant inspection*** – Applied penetrant will remain in surface breaks after excess is removed.
4. ***CT scanning*** – Internal and external representation of test specimen using x-rays.

Destructive testing includes but is not limited to the following:

1. ***Stress-strain testing*** – Applying forces to a test specimen in order to record the physical qualities of the material.
2. ***Hardness testing*** – Plastic deformation due to a force/load on an indenting machine.
3. ***Metallography testing*** – Visual microscopy testing on exterior and interior sections.

Further certification processes will be and are currently determined by industry regulations and customer requirements. Certifications include printer/material compatibility testing, safety certification, environmental regulations, and more.

# II. Complying with Industry Regulations

Industry regulations derive from multiple organizations intervening at different stages in the additive manufacturing line. Local regulatory authorities will dictate requirements for the installation environment, raw materials used, handling and storage of equipment and materials, and handling of byproducts. Other regulations pertaining to product liability law and legal implications that tag along with these dictations must be built into the manufacturing line in order to verify whether risk will fall upon the original equipment manufacturer (OEM) or the product manufacturer.

Workplace safety regulations primarily pertain to machine safety features and operator proficiency. Currently only OEMs of additive manufacturing machinery provide operating and regulatory/safety training including the process, materials, and facility. All operators should follow manufacturer's guidelines and should only operate the equipment if they have received training from the OEM. The printing process should operate in a ventilated area and the operator should be trained to handle hazardous materials. Disposal of waste products should be performed by personnel trained to handle hazardous materials as well as an organization capable of removing such waste.

Due to the quick ascension of direct metal laser sintering printing, regulators and standardizing organizations have struggled to catch up. Currently there are few available tools to educate an individual or a company on current best practices and technology. Proprietary techniques are held tightly within manufacturing companies in order to create a competitive advantage in the newly forming additive manufacturing branch of the industry. SAE and American Makes – standardizing organizations – are currently working with their network and other regulatory organizations to create necessary specification documentation.

# III. Value of Additive Manufacturing

Additive manufacturing processes can provide value to nearly all aspects of a manufacturing line, whether allowing for the supply chain to be brought in-house or opening the manufacturing capabilities to include far more complex parts.

Diagram 1 illustrates a generalized manufacturing line that excludes specialized processes. The positioning of additive manufacturing is conditional upon a job-to-job basis propagating from cost effective product development. Product development is highly dependent on pre-processes, prototyping, and iterative testing. Product development methods apply to the early stages of the manufacturing line, providing a road-map in order to improve logistics and reduce time intensive processes in the MFG line. This stems from “processing and manufacturing plan” as well as “product analysis, modeling, MFG prep.” labeled in diagram 1, from which fixturing and tooling can be derived.

Additive manufacturing allows for re-visitation of previous assemblies and jobs, providing an infrastructure orbiting digital products/services, digital spare parts, customization and personalization, and flexible production volume and location based on time. Value-chain repositioning allows for the reinvention of the manufacturing line, creating a dynamic procurement system where AM can be placed to increase cost effectiveness and decrease design and build time.

Further value than simply cost-per-part analytical analysis can be extracted from additive manufacturing integration. Transitioning into a position where additive manufacturing as a service or substitution can be operational, multiple steps must be taken. Moving the supply chain in-house requires the ability to supply certifications of compliance documentation for material testing and all post-processing. Because AM is a newly adopted process, it is unclear to customers how post processing will affect the initial printing build. Once fully developed, the following transitioning steps should be taken: a) understanding AM – because there are few educational services available, the OEM must be contracted to provide ample training b) part selection – not all parts will benefit from AM, it is recommended to only consider AM if the part cannot be created using traditional manufacturing techniques c) re-/design for AM – all manufacturers and design teams should be prepared to re-design

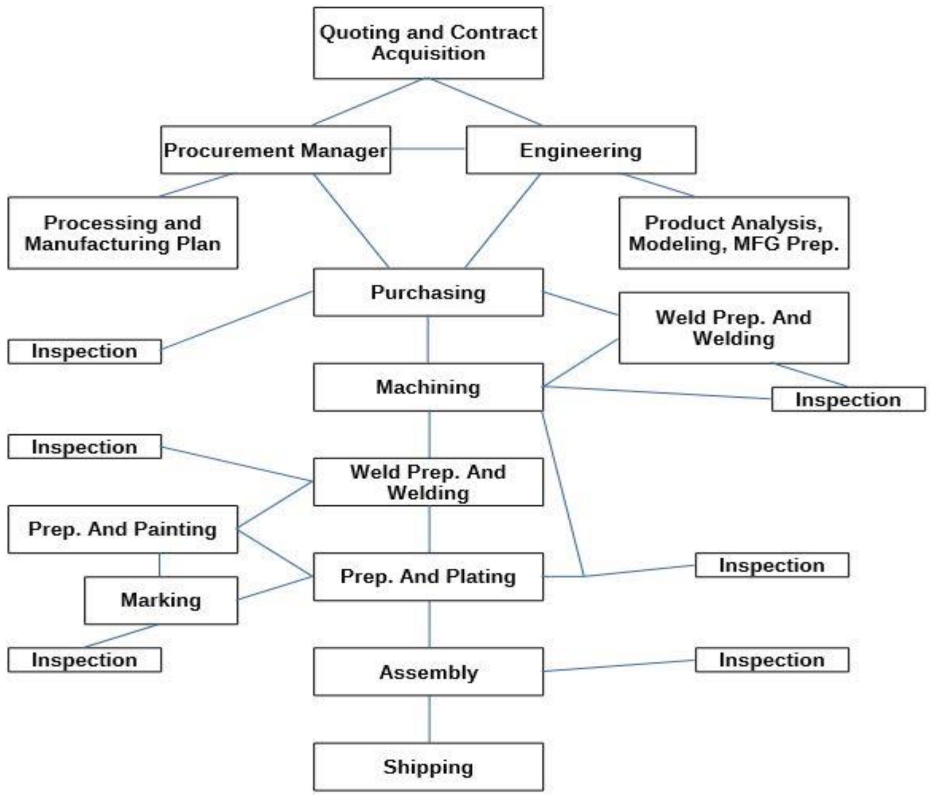


*Diagram 1: The Randolph and Baldwin, Inc. manufacturing line*

for AM processes or design from the start for AM d) process and material optimization – striving towards the optimization of DMLS printing by altering orientation and support structure should be performed prior to every new production run e) fast production implementation f) optimization for production – implement a process to quickly move from the AM process through to post processing and subtractive manufacturing.

# IV. Additive Manufacturing Supply Chain

Economy of scale in a traditional manufacturing industry relies on the development of tooling and fixtures along with adequate demand for the production. Additive manufacturing removes the necessity to revolve around economies of scale for any product and provides a scenario where low-volume parts can be produced for the same cost as high volume parts. For certain jobs, the supply chain can be brought completely in-house, removing the reliance on supplier time-lines and allowing procurement to guarantee delivery dates for internal and outbound products.

By understanding and vetting the complete manufacturing line on a job-to-job basis, manufacturing can be translated from a fragmented webbed framework into an internal and predictable operation. The question – how quickly and how costly is the consideration of additive manufacturing for a specific job? – is the first of many when considering the cost impacts of AM within a manufacturing line. By bringing the supply chain in-house, it is important to consider the removal of powder, removal of part, and removal of bi-products while designing a production build. In order to prove the effectiveness of additive manufacturing and any new process, the benefits must outweigh the negatives. Therefore, AM must remove or combine processes, reduce effective build time, broaden design capabilities, or increase reliability at a scale that qualifies the burdens of bringing parts of the supply chain in-house.

# V. Hybrid Manufacturing Processes

The designation of additive manufacturing as a component in a manufacturing line removes the assumption of an "all-in-one" manufacturing unit. The current state of AM forces design attention to areas that are not necessarily reasonable for the use-case of the production part. For example, certain piping designs, turbine designs, and piston designs may require surface finish of 32 Ra on critical surfaces, but a much more lenient finish on less critical features. Therefore, from the onset of manufacturing line design and component design, it is important to determine the end-product specification requirements prior to considering AM's cost effectiveness. The hybrid manufacturing process will incorporate AM and machining/finishing processes to accurately print production parts with complex or required intricate interior features and adequate external surface finishes and feature design.

The end-to-end additive manufacturing environment includes the below example number tree and their respective sub-processes.

**1.** Materials

- Determine the appropriate material for the end product specification requirements. How well will this material react to post process treatment? Will there be potential complications in the printing process for certain material makeups? 3D printable metal powder has been engineered to be comparable to currently available extrusion standards, although due to a scattered marketplace, many products are proprietary to the inventing company.

**2.** Setup

- The setup time required to move from a completed design to a fairly optimized printing process that will output material shape with expected physical properties can take a reasonable amount of time. Using AM as a process for a custom designed product for a customer, it is likely that customer will require certification of compliance documentation for material make-up and functionality per physical specification requirements. Including cleanup and transitions, this process may involve: prototyping on a smaller scale, material testing, and orientation/support structure design.

**3.** Build

- The build process is straight forward, although it should be monitored by a machine operator at least through the first product run. A test specimen shall be printed alongside each printing process and testing using nondestructive and/or destructive testing methods.

**4.** Breakout

- The part must then be removed from the base plate using a horizontal or vertical saw or EDM machine. This process will also require the breaking and removal of support structures (if applicable) and the removal of any excess metal powder inside hollowed sections.

**5.** Post processes

- Machining to complete part formation, heat treatment to bring the part up to its expected physical properties, bead blasting and polishing to bring the surface finish into compliance, additional welding to repair or complete sections of part. In the desired order, these are some potential post processes necessary in order to move the part from freshly printed into a completed product.

**6.** Facility management

- Keeping the AM machine clean and separate from machining, grinding, and other post processing that will create potential contamination is important in order to maintain consistent quality. The base plate must be chosen correctly for the material used during the printing process and must be resurfaced between printing processes.

**7.** Disposal of waste

- Although the printing process will be self-contained, excess powder should be sifted and reused for future printing processes. Waste metal powder and other byproducts should be disposed of in a manor applicable to regulatory organizations and government.

# VI. Designing for Additive Manufacturing DMLS

Re-designing a component or an assembly to incorporate additive manufacturing requires complete overhauling of the features for better and for worse in order to comply with the short-list of AM design requirements. This process will involve the original design engineers as well as a design engineer unfamiliar with the part's manufacturing history or design history. New perspective with AM in mind opens design considerations.

Designing a part from scratch with the understanding of an AM machine's printing process, supporting features and orientation, and physical properties and features that can be printed using DMLS will greatly reduce the frustration and barriers of outdated specifications and manufacturing requirements. The orientation of a printed part will determine the necessary external and internal support structure patterns and density. Bridging gaps, overhangs, angled walls, internal features should be kept in mind while determining a proper orientation method. Support structure and orientation will be a determining factor in whether a printed part will hold expected physical test properties.

Accompanied design software with AM machines will provide feedback and recommendations regarding the orientation and physical details of a 3D model. The recommendations and automated support structures will not always be the best option. Manually designing support structures into a design or re-designing/re-orienting in order to benefit from more self-supporting features may be better options. Support structures are meant to anchor the printed part to the base plate securely throughout the processes. It is important to design the supports with factors such as thermal expansion in mind in order to potentially reduce the effects of stress buildup. The rule of thumb for thin walled features is a 40:1 height to wall thickness ratio. This is an important consideration when designing internal support structures that will not breakdown overtime or due to stresses.

Self-supporting features will reduce printing time and reduce post processing requirements. Angled walls and overhangs can be considered fully self-supported when under a 45-degree angle from vertical. Bridge overhangs and gaps can be considered fully supported if smaller than .08 inches. This said, completely hollow internal gaps should be designed in order to not collapse within itself by incorporating internal supports to a potentially fully supported feature. These features should be designed with drainage holes for residual byproducts and excess metal powder.

## VII. Open and Closed Atmosphere Additive Manufacturing

The primary contaminant observed during a printing cycle is an overabundance of oxygen. An open atmosphere AM machine contains no atmosphere control and relies on the air quality of the manufacturing facility. In order to reduce oxygen levels, argon or a substitute shielding gas is added in the immediate working area. Steel, nickel, cobalt, bronze, and tungsten are recommended to be printed in open or closed systems. Closed atmosphere AM machines are capable of creating a vacuum atmosphere controlled printing chamber with oxygen levels around 25 PPM. Titanium, aluminum, and magnesium are recommended to be printed in closed systems. Material selection as well as working in either an open or closed atmosphere machine will require redesigning of the printing process and laser power. The laser power will affect the surface finish as well as the bead size laid down, in turn affecting required post processing and machining time as well as porosity within the material.

## VIII. Thermal Stresses

The most influential force that will affect the outcome of a printed part is thermal stress buildup. Residual stresses from cooling areas of parts and the stationary base plate will cause stresses that must be overcome by support structures. Research is being conducted with aspirations of scientifically predicting thermal stresses using FEM (FEA) in association with 3D CAD models and software. Current AM software provides predictive printing visualization by slicing the 3D model into layers which are representative of the printing process and offers basic thermal stress warnings. Non-scientific predictive models use algorithmic interpolation methods to vaguely indicate potentially high stress areas.

American Makes, a national accelerator for additive manufacturing and 3D printing, is currently engaging in research sponsorship through colleges and universities in order to further the understanding of AM processes. Test results for scientifically based thermal stress simulations on 3D printed parts were promising, with an 8% observed error from live tests. Simulations for a disk test specimen before and after being cut from the substrate showed a bowl effect upwards. Simulations for a rectangular bar before and after removal from the substrate showed warped edges. Testing both scientifically and algorithmically, the plasticity and elasticity in the formed metal should be observed.

# IX. Continuous Metallurgy Monitoring

Taking predictability of thermal stresses and the printing process a step further, continuous metallurgy monitoring is the primary goal for AM software and EOMs. The ability **to** accurately monitor the internal physical properties and external physical properties of a printed part while monitoring the machine parameters will provide runway to produce modular and dynamic printing programs. Modular programs will automatically recognize patterns between one printing job and another printing job and based on sensor data will be able to recommend machine parameters and post processing for certain areas of the production part. Dynamic programs will be able to automatically change machine parameters throughout the printing process in order to optimize the printing based on the support structures needed, the orientation, necessary post processing, and the physical property requirements.

Current methods of continuous monitoring systems are non-scientific and will only provide a basic understanding of what is or what will occur during the printing process. Ultimately, continuous metallurgy monitoring will provide feedback for strain, surface finish (on external and internal faces), porosity, chemical analysis, and information regarding the physical properties of internal support structures.