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Environmental Advantages in Additive Manufacturing

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ADDITIVE MANUFACTURING (AM) is a technology that uses a variety of methods to ultimately apply layers of material and create products (Ford & Despeisse, 2016; Ford, Mortara & Minshall, 2016). Although there has been an expansion in recent technology, AM has been used in manufacturing for a few decades (Ford, Mortara, et al., 2016). Since the late 1980s, AM has grown from simple product designs, with a focus on prototyping and customization, to modern times with billions of dollars in revenue and large-scale production of consumer and industrial products (Cotteleer, 2014). Forecasts showed a near $10 billion market by 2020, with automotive, aerospace and medical industries leading the way (Cotteleer, 2014).

Several AM technologies are available to manufacturers today and, although the end products of those technologies are similarly layered, the processes are much different. The International Organization for Standardization (ISO)/American Society for Testing and Materials (ASTM) standard 52900:2015 (ASTM F2793) categorizes AM processes into seven categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion (including several sintering methods), sheet lamination and vat photopolymerization (Table 1, p. 36). There is a great deal of diversity not only in machine and process technology, but also in material opportunities. Commonly used raw materials include various plastics and metals, but new developments are coming into the AM world using living tissues, glass and composites (Cotteleer, 2014).

In contrast to AM is the more common subtractive manufacturing, which simply entails material being removed from a larger supply to produce the commodity (Ford & Despeisse, 2016). Typical subtractive manufacturing involves using lathes, computer numerical control (CNC) machines, and drills or saws to remove material based on the specifications (Langnau, 2011). Subtractive manufacturing has been around even longer than AM and is a proven method of manufacturing based on quality, consistency and the capability to mass produce from raw material (Langnau, 2011). However, due to the fundamental nature of subtractive manufacturing, it produces more waste than AM (Ford & Despeisse, 2016).

Because of the nature of the process, it is theorized that AM promises to be a more sustainable process and will produce less waste than traditional manufacturing. The authors performed scholarly literature research and review into the environmental benefits of using AM over traditional manufacturing with emphasis on waste and energy reduction methods in AM. The technology review presented in this article details this research into the environmental benefits of AM, and contrasts it with the less sustainable subtractive manufacturing methods.

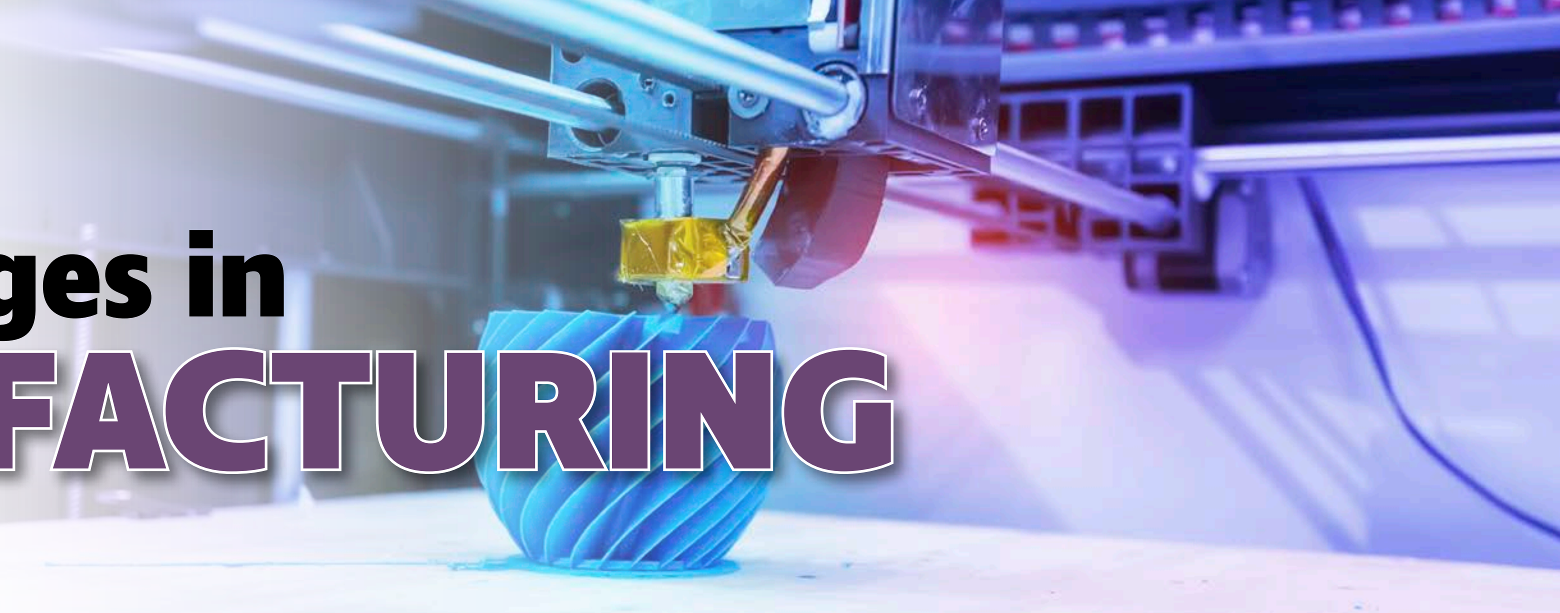
KEY TAKEAWAYS

- **Additive manufacturing has been advancing in technology since the late 1980s and is forecasted to take large strides in the manufacturing market.**
- **The environmental advantages of additive manufacturing must be considered to strategize for improving manufacturing sustainability.**
- **Research is proving that additive processes are more efficient and reduce the environmental impact of waste products than conventional manufacturing. This article details several of the advantages and challenges to additive manufacturing.**

Environmental Waste & Energy Reduction Findings

AM has four general environmental advantages over conventional or subtractive manufacturing: material efficiency, resource efficiency, production flexibility and part flexibility. Unlike subtractive manufacturing in which waste material is removed to reveal a product, AM only creates what is needed for the product with minimal support structure (Huang, Liu, Mokasdar, et al., 2013). Resource efficiencies refer to how generally simplistic AM machines are. Conventional machinery often requires auxiliary tools, equipment and coolants, which utilize energy and generate emissions and waste (Faludi, Bayley, Bhogal, et al., 2015). Because AM has less need for ancillary equipment than do conventional machines, AM requires fewer resources, and therefore has fewer energy needs (Huang, et al., 2013). Also, because these ancillary tools and equipment are not needed for production, parts can be made by smaller manufacturers located closer to users, thus reducing transportation costs and related emissions (Ford & Despeisse, 2016; Huang, et al., 2013). Part flexibility is a major waste reduction aspect of AM. The ability to make on-demand products reduces inventory and other wastes (Huang, et al., 2013). Finally, production flexibility, or the ability to quickly switch between different products without costly or time-consuming setup, allows a more streamlined supply chain and economical production batches to meet customer needs (Huang, et al., 2013).

One significant way that AM reduces waste in the manufacturing industry is by the inherent made-to-order technology. Inventory waste reduction and fewer unsold products can be taken advantage of due to small-batch orders and only producing as many items as are requested



(Ford & Despeisse, 2016). Companies have capitalized on making spare parts with the made-to-order technology, and can generate less high-value waste (Ford & Despeisse, 2016). In fact, it is estimated that up to $370 billion in savings will occur by 2025 from the reduction of input material and a shorter supply chain (Ford & Despeisse, 2016). Similar to on-demand AM technology, product and material life cycles have an environmental impact as well. Repairs to certain parts can be completed using AM technology, which essentially extends the life cycle of an original part. Waste is reduced as fewer product replacements are required (Ford & Despeisse, 2016).

Energy consumption is greatly reduced with this on-demand manufacturing capability and machine utilization is key (Ford & Despeisse, 2016). AM technology requires both a warm-up and a cool-down procedure, which consumes some energy while the machine is not generating a product; as such, optimal machine utilization planning can minimize energy use (Baumers, Dickens, Tuck, et al., 2016; Faludi, et al., 2015). In recent studies, CNC machines were compared to two polymer printing machines with results mostly depending on utilization (Faludi, et al., 2015). When the 3-D printers were idling, they consumed higher amounts of electricity; however, CNC machines produced large amounts of material waste and consumed cutting fluid on par with the 3-D printers' electricity use (Faludi, et al., 2015). Overall, the results showed that some 3-D printers, when used at higher utilization rates, had lower energy consumption, and produced the least amount of material waste (Faludi, et al., 2015). Furthermore, having more detailed parts to print is a significant energy advantage because the consumption remains constant no matter how simple or complex the part design (Böckin & Tillman, 2019). AM can produce a wide variety of detailed parts for the aerospace and automotive industries. Examples of these parts include engine turbine parts and components for rocket engines (Böckin & Tillman, 2019).

Post-treatment processing must also be considered when calculating energy consumption (Kellens, Mertens, Paraskevas, et al., 2017). Often, post-treatment processing is needed to remove the manufactured part from the build plate or support structures, and these processes also use energy. However, although the printers used in AM mainly consume electricity, their comparatively reduced levels of consumption have frequently categorized their machines as "green" (Peng, Kellens, Tang, et al., 2018). Many studies have shown that although lower than conventional manufacturing, energy consumption is still an apprehension for AM, but that many other environmental advantages balance any energy consumption concerns (Huang, et al., 2013).

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AM reduces resource use in many ways. AM techniques are estimated to be as much as 97% material efficient, whereas subtractive technology can generate as much as 90% waste (Achillas, Aidonis, Iakovou, et al., 2015; Peng, et al., 2018; Verhoef, Budde, Chockalingam, et al., 2018). Often, the AM design process can lead to lighter-weight products with the same functionality as those produced using conventional manufacturing processes (Huang, et al., 2013). For industries such as aviation, producing lighter-weight parts through AM can reduce both resource and fuel use (Verhoef, et al., 2015).

Resource use reduction can be improved when unused powder from the AM process can be reused or recycled. However, in some cases, such as laser sintering AM processes where metal powder is used, a significant amount of powder waste may be generated (Samant & Lewis, 2017). As each build is completed, the unused metal powder is removed and typically would be disposed of due to degradation of the powder (Samant & Lewis, 2017). However, more recent methods allow for recycling of the spent powder. Methods such as blending used powder with new, virgin powder have increased the availability to recycle in applications where the blended powder still meets specifications (Samant & Lewis, 2017). Some metal powders such as certain titanium alloys do not lend to blending as well due to the introduction of oxygen, and are not always feasible recycling methods (Samant & Lewis, 2017). Another method to reuse the metal powder is by an induction plasma process that heats and solidifies the powder, then vaporizes impurities to provide a better, recycled product (Samant & Lewis, 2017). These processes will be helpful for future AM, since recycling raw material is a huge advantage over subtractive manufacturing.

Similar to metal powder, polymer powder in printing processes also has recycling potential. Research has shown that certain plastics such as acrylonitrile butadiene styrene and high-density polyethylene can be converted from waste products into usable filament product for 3-D printing (Mohammed, Mohan, Das, et al., 2017). One study used empty, shredded milk cartons to granulate and be further extruded into the correct diameter filaments (Mohammed, et al., 2017). Although it took some trials to generate the appropriate mixture of plastic and the correct heating requirements, eventually an adequate fila-

TABLE 1

SEVEN CATEGORIES OF ADDITIVE MANUFACTURING

Category	Alternate names/examples	Description
Binder jetting	3-D inkjet	Uses liquid materials printed onto thin layers of powder, building layer by layer, "gluing" the particles together.
Directed energy deposition	•Laser metal deposition •Laser-engineered net shaping •Direct metal deposition •Electron beam •Plasma arc melting	Focuses thermal energy to melt metal and metal-based materials during deposition.
Material extrusion	•Fused filament fabrication •Fused deposition modeling •Fused layer modeling	Polymer or composite material is pushed through a nozzle.
Material jetting	•Smooth curvatures printing •Multi-jet modeling •Direct ink writing	Droplets of material are selectively deposited—can include polymers, composites and biological materials.
Powder bed fusion	•Selective laser sintering •Selective laser melting •Direct metal laser sintering •Electron beam melting •Selective heat sintering •Multi-jet fusion	High-power thermal energy selectively fuses regions of a powder bed of material.
Sheet lamination	•Laminated object manufacture •Selective deposition lamination •Ultrasonic/ultrasound additive manufacturing	Sheets of material are bonded to form a part.
Vat photopolymerization	•Stereolithography •Digital light processing •Scan, spin and selectively photocure •Continuous liquid interface production	Liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Note. Adapted from "Additive Manufacturing: Scientific & Technological Challenges, Market Uptake & Opportunities," by S.A.M. Tofail, E.P. Koumoulos, A. Bandyopadhyay, et al., 2018, *Materials Today, 21*(1), pp. 22-37; and "7 Families of Additive Manufacturing," by Hybrid Manufacturing Technologies, 2015.

ment was generated (Mohammed, et al., 2017). These filaments became successful 3-D-printed objects to further prove that plastic waste could be reused and printed into new products for consumers or industrial applications (Mohammed, et al., 2017).

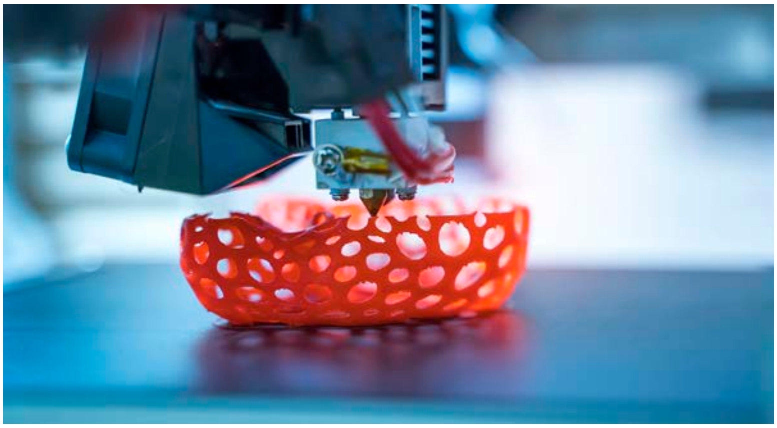
Furthermore, resource efficiency involves advances in the various types of raw material used in AM. Biodegradable plastic is another way that AM contributes to reducing wasted products (Newman, 2014). Research companies are finding ways to make suitable biodegradable plastics and other green materials that are appropriate for manufacturing needs and produce less nondegrading plastic in the world (Newman, 2014). More research and testing must be completed before these materials are fully in the market, but the advancements are showing clear progress toward the success of green materials (Newman, 2014).

Hybrid manufacturing processes may also be a solution to the environmental benefits of both additive and subtractive manufacturing. In this newer method, the product is first manufactured with additive technology, then further processed with subtractive methods (Manogharan, Wysk & Harrysson, 2016). Hybrid manufacturing is gaining attention in many industries where the concepts stem from the need to remanufacture existing parts or to reuse a part (Liu, Wang & Wang, 2017). This is where most environmental advantages would arise, as the need to reproduce new parts diminishes. Economic studies have been used to evaluate not only the production times of this hybrid system, but also the energy costs for using both additive and subtractive methods (Manogharan, Wysk & Harrysson, 2016). Results from these studies indicate that traditional CNC-only processes begin as more efficient for initial batch sizes, but that hybrid AM was able to produce near-net production rates over time (Manogharan, Wysk & Harrysson, 2016). Costs for AM materials still greatly exceed those of subtractive methods, and for the current market will minimize the production and energy benefits of traditional manufacturing (Manogharan, Wysk, & Harrysson, 2016).

Powder waste reduction, plastic waste reduction, machining and part life cycles, and reduced energy usage are some of the ways that AM is currently a more sustainable manufacturing technology than subtractive manufacturing. AM is the more sustainable, less wasteful and typically more efficient manufacturing process. As recent forecasts in the technology show, AM is continuing to rise in major industrial sectors and will be making large strides in reducing the amount of waste produced to the environment (Ford & Despeisse, 2016). AM presents several efficiency opportunities, and large-scale production efforts are being recognized for their economic impacts and environmental sustainability achievements (Ford & Despeisse, 2016). Despite the many environmental advantages to using AM technology, a few challenges may discourage its use for some applications (Cotteleer, 2014).

Environmental Challenges in Additive Manufacturing

Several challenges in AM make the technology costly, less efficient and consequently less sustainable than conventional or subtractive manufacturing. The technology is relatively immature as compared to conventional man-



Remarkable progress has been made in the advancements of AM over the past 3 decades, and the environmental benefits have been demonstrated as more efficient, less wasteful and more sustainable than conventional subtractive manufacturing.

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ufacturing, with decades less research and application (Cotteleer, 2014). Quality consistency, size limitations, material and supply chain limitations, and higher costs are some examples of AM challenges (Cotteleer, 2014). High costs of industrial AM applications are a difficult sell in many business cases (Cotteleer, 2014). Not only are the up-front costs of a printer high, but the cost of raw material is also challenging for the market. Recycling efforts may offset the costs, but much more research is required before waste recycling supports the higher costs of AM (Cotteleer, 2014).

One challenge in AM is the limited speed at which production occurs (Ford & Despeisse, 2016). Conventional manufacturing produces products at much higher rates and, thus, can demonstrate less energy consumption to product for some applications (Ford & Despeisse, 2016). Quality is another significant challenge in AM. Metal printing has issues with dimensional accuracy during the print process, and with compliance in aspects of tensile and defects (Cotteleer, 2014; Ford & Despeisse, 2016). Size limitations are due in part to the printer bed capabilities, which are much smaller than traditional manufacturing capabilities (Cotteleer, 2014).

Wasted powder is also a major environmental impact of AM, but, as noted, recycling efforts are increasing. Besides the powder waste, AM processes may use compressed air, gases such as argon and nitrogen, and electricity for various applications (Kellens, et al., 2017). Energy is also needed to manufacture the powder material used in the AM process (Paris, Mokhtarian, Coatanéa, et al., 2016). However, the overall environmental impact of AM processes holds many advantages in reducing energy and material consumption.

Although there are several advantages to recycling polymer materials, obstacles in the economics of reusing the waste products has demonstrated no net gains (Cruz Sanchez, Boudaoud, Hoppe, et al., 2017). In the mechanical recycling processes for polymer materials, several technological disadvantages arise. Those disadvantages include degradation of the material, quality characteristics and logistical considerations (Cruz Sanchez, et al., 2017). Two main improvements are needed for recycling efforts to be cost effective: reduced price differences between reclaimed polymer feedstocks of the higher cost virgin materials, and improved efficiencies in the methods of recycling, thereby reducing the costs and increasing productivity (Hopewell, Dvorak & Kosior, 2009).

Safety & Health Issues With Additive Manufacturing

Because of the wide variety of processes and materials used, potential safety and health concerns vary based on the technology and base materials used. Many of the relatively inexpensive and commonly found desktop 3-D printers utilize material extrusion techniques called fused filament fabrication (FFF) or fused deposition modeling (FDM) (Azimi, Zhao, Pouzet, et al., 2016; Tofail, Koumoulos, Bandyopadhyay, et al., 2018). Several studies have shown that these desktop 3-D FFF/FDM printers can emit ultrafine/nanosize particles (UFPs), which are particles less than 100 nm in size (Azimi, et al., 2016; Floyd, Wang & Regens, 2017). FFF/FDM printers can also emit potentially hazardous volatile organic compounds (VOCs) such as styrene, ethylbenzene, methyl styrene, acetaldehyde, ethanol, acetone, isopropyl alcohol, methl methacrylate and caprolactam (Azimi, et al., 2016; Floyd, et al., 2017; Gu, Wensing, Uhde, et al., 2019; Wojtyła, Klama & Baran, 2017). UFP and VOC emissions and rates are dependent on the type of thermoplastic filament used, and the stage of the printing process (Floyd, et al., 2017; Gu, et al., 2019; Stephens, Azimi, El Orch, et al., 2013; Wojtyła, et al., 2017). Potential airborne exposures will vary depending on the type of printing process and the base materials used.

Another commonly used 3-D-printing process is stereolithography, which involves curing by light-activated polymerization, often with ultraviolet (UV) light or UV lasers (Tofail, et al., 2018). Selective laser sintering (SLS) also uses a laser, but instead of a photosensitive resin, it uses a polymer in the form of a fine powder and the laser fuses the particles together (Formlabs, 2017). SLS printers can, and often do, use Class 4 laser systems, which can cause not only direct radiation hazards, but indirect (scattered) radiation hazards. Clearly, an organization should carefully monitor such devices, evaluate them for safety hazards, establish appropriate controls and limit use to properly trained personnel.

One potential benefit of the use of AM versus subtractive manufacturing processes such as lathes, milling or drilling machines is the potential for reduction in sound levels in the workplace. While 3-D printing can still generate noise, many manufacturers are intentionally enclosing the process, which can also reduce potential particulate and VOC exposures (Quinn, 2018). Although the actual sound level measurements are proprietary, measurements conducted by the authors in AM production areas have revealed levels much lower than in areas where CNC lathes and mills are used for subtractive manufacturing. Of course, the number, types and locations of sound generating equipment will vary, as will the presence or absence of enclosures or insulating materials. In general, however, AM processes have the potential to be much quieter options than traditional production equipment.

Conclusion

Remarkable progress has been made in the advancements of AM over the past 3 decades, and the environmental benefits have been demonstrated as more efficient, less wasteful and more sustainable than conventional subtractive manufacturing (Cotteleer, 2014). Reducing the environmental impact of manufacturing is essential to further advance global sustainability and waste reduction efforts. Companies should be looking to these processes to increase material and resource efficiencies, and to provide flexibility with production and parts (Huang, et al., 2013). Studies prove that AM is indeed the more sustainable, less wasteful and typically more efficient manufacturing process. **PSJ**

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