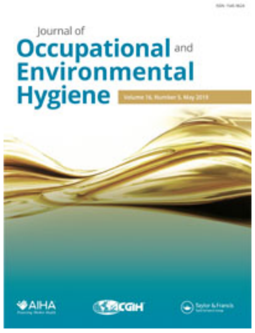

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COMMENTARY

Potential occupational hazards of additive manufacturing

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3-D printing; advanced manufacturing; nanotechnology; occupational health; occupational safety

Additive manufacturing (AM), often called 3-D printing, is becoming a prominent part of modern industry due to its usefulness in accelerating product development and prototyping, as well as producing complex and precision parts.[1] AM is a collection of processes for creating products by selectively joining small amounts of material based on a computer-aided design file.[2,3] This approach yields several advantages to industry: shortened production cycles, reduced tooling costs, reduced waste material, easier product customization, novel design options, and new possibilities in distribution and fulfilment.[3–7] AM has already impacted automotive, aerospace, medical device, and electronics manufacturing;[1,4] is expected to grow in biomedical applications;[8,9] and has found its way into construction,[10] offices, schools, and libraries.[11,12]

Despite dramatic growth in applications and adoption, there has been a relatively minimal amount of academic literature published on the potential implications of AM for worker safety and health. While many forms of AM share some similarities with existing technologies, changes in materials, instrumentation, applications, and work organization can create potential hazards that are either sufficiently distinct as to warrant renewed consideration, or are entirely new. The challenges may resemble those of nanotechnology, where the mixture of old and new processes, novel environments, and the pace of change made characterization of hazards and assessment of risk ongoing challenges.[13]

The challenge to academic researchers, industrial designers, and occupational safety and health personnel will be developing knowledge of AM potential hazards, exposure assessment methods, and controls; and to propagate that knowledge throughout the industry. Doing so will require foundational knowledge in the basic principles of AM processes and the context in which AM is conducted. Herein, those processes will be briefly described, various potential hazards identified, and several aspects of AM implementations discussed.

Overview of hazards

Addressing potential hazards of AM will require the development of a framework for hazard identification.[14] Such a framework may be provided by AM process categories. Based on international agreement, most methods fall into the following seven categories: material extrusion, powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination, and directed energy deposition.[2] Each process category is defined by its feedstock materials, the feedstock form (phase or state, such as liquid, solid, or powder), processes (the mechanical forces and energies used to bind the materials), and machine architecture. Holistic consideration of these characteristics and other, associated characteristics (such as pre-processing, post-processing, operating environments, and applications) can assist in the development and conduct of effective hazard analyses. A brief overview of these process categories and an examination of potentially emergent hazards is provided in the following sections. A brief summary of this section is presented in Table 1.

Material extrusion

Material extrusion processes use a nozzle that moves two-dimensionally (horizontally) to deposit a layer of

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Table 1. Related potential hazards by AM process category.

Category	Feedstock materials	Feedstock form	Binding/fusing	Most prominent potential hazards
Material extrusion	Thermoplastics (may include additives)	Spooled filament, pellet, or granulate	Electrical heating element-induced melting/cooling	Inhalation exposure to VOCs, particulate, additives; burns
Powder bed fusion	Metal, ceramic, or plastic	Powder	High-powered laser or electron beam heating	Inhalation/dermal exposure to powder, fume; explosion; laser/radiation exposure
Vat photopolymerization	Photopolymer	Liquid resin	Ultraviolet-laser induced curing	Inhalation of VOCs; dermal exposure to resins and solvents, ultraviolet exposure
Material jetting	Photopolymer or wax	Liquid ink	Ultraviolet-light induced curing	Inhalation of VOCs; dermal exposure to resins and solvents, ultraviolet exposure
Binder jetting	Metal, ceramic, plastic, or sand	Powder	Adhesive	Inhalation/dermal exposure to powder; explosion; inhalation of VOCs, dermal exposure to binders
Sheet lamination	Metal, ceramic, or plastic	Rolled film or sheet	Adhesive or ultrasonic welding	Inhalation of fumes, VOCs; shock, laser/radiation exposure

material (i.e., a cross-section) onto the "build platform;" this platform is then lowered or the nozzle raised to permit deposition of subsequent layers.[2] Post-processing may involve annealing to improve bonding, or surface treatments including polishing rough edges or painting. The most common materials used are thermoplastics, especially polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and polyamide (nylon); the materials are in the form of a filament that is melted by a heated nozzle. Additives such as engineered nanomaterials (ENMs) may be included to alter properties of the product.[15] Filaments may also include ceramic or metallic particles as precursors to creating pure parts of those materials.[16] Common monikers for material extrusion include "fused deposition modelling" (FDM™, Stratasys, Ltd, Eden Prairie, MN, U.S.A.), "fused filament fabrication" (FFF, open-source),[17] or simply 3-D printing (as this is the most publicly visible technique).

Studies of material extrusion tools using thermoplastic filaments have observed release of VOCs and particulate matter, presenting the possibility of exposure to styrene or similar compounds.[18–20] Filament additives are also potential hazards, and some such as ENMs may not be fully characterized. In addition, there are safety concerns relating to processing and post-processing: heated surfaces and nozzles can reach temperatures high enough to melt thermoplastics and may be burn hazards; sanding, grinding, and polishing tools can create hazards of physical injury or inhalation exposure;[21,22] and other processes such as vapor polishing may involve volatile compounds such as acetone.[23]

Powder bed fusion

Powder bed fusion processes begin with a build platform covered in a layer of powdered material, which is fused by a heat source that scans the surface horizontally to create a cross section. The build platform is lowered and another layer of powder deposited, allowing the addition of successive layers. Variants of the process exist depending on the heat source: selective laser sintering (SLS) utilizes a laser to fuse almost any material; selective heat sintering uses a heating element to fuse thermoplastics, and electron beam melting utilizes an electron beam to fuse metal powder.[2,17] These processes may require heated chambers and either inert atmospheres (for lasers) or high vacuum (for electron beams).[24] Post-processing generally includes the removal of unfused powder and resurfacing.

Powdered feedstocks can pose a variety of hazards depending on the specific material and formulation. Fine powders can readily create inhalation and dermal exposures, and common materials can possess sensitizing or toxic properties.[25–28] Airborne powders can create a risk of fire and explosion,[29] and at least one case of an explosion related to AM of aluminium has been documented.[30] Post-process removal and reclamation of expensive build powders may add another significant source of exposure. ENMs and other additives are being explored to improve the sintering process,[31,32] raising the possibility of exposure to these materials. Heating sources may have varying hazards, including the production of ionizing radiation by electron beams.[33] Finished products may be hot enough to emit volatile compounds or also be burn hazards. Nitrogen or argon gas cylinders pose mechanical hazards in transport and asphyxiation hazards in closed spaces.[34]

Vat photopolymerization

Vat polymerization processes begin with a build platform coated in a thin layer of photopolymer resin within a larger vat of resin. Horizontal cross-sections of that layer are selectively cured with ultraviolet light exposure, and the build platform is then moved vertically to allow for successive layers of resin to be exposed. Post-processing may involve further curing, resurfacing, and the removal of support structures mechanically or by dissolution. Two prominent forms of this technique are stereolithography (in which polymerization is initiated with an ultraviolet scanning laser) and digital light projection (in which an ultraviolet light projector illuminates the entire cross-section simultaneously).[17]

Potential hazards in these processes emerge from the photopolymer resin itself, which may include volatile or toxic elements and compounds such as antimony, acrylates, and epoxies.[14] Exposures are possible in operation, support processes, and post-processing. Exposures to potentially hazardous chemicals in post processing, such as those used for dissolving support structures, is also possible. Ultraviolet light sources are potentially hazardous as well.[35]

Material jetting

Material jetting processes use an inkjet-style print head to print material onto the build platform, which moves vertically to allow deposition of successive layers. Typically two types of material are simultaneously used: a build material (usually a photopolymer); and a support material, which occupies the negative (empty) space in the final product and will be removed in post-processing.[17] Curing may occur during processing and/or in a separate post-process step. Additional post-processing may include resurfacing and the removal of support material.

Material jetting shares many of the potential hazards of photopolymerization due to the similarity in their materials, feedstock, and binding processes. This includes all concerns related to photopolymers and ultraviolet light.[14,35] However, differences in machine architecture between the two process categories may result in significant differences in associated risks.

Binder jetting

Binder jetting processes begin with a build platform covered in a layer of powdered material, which is then selectively cemented by an inkjet-style print head depositing an adhesive material (e.g., ethylene glycol). The build platform is then moved vertically and covered with more powder to allow printing successive layers.[17] Post-processing involves removal of unbound powder, resurfacing, or potentially other steps such as high-temperature annealing.

The most recognizable potential hazards associated with this technology relates to its use of powdered materials. As discussed in powder bed fusion, powders represent potential explosion hazards, [29] and possible inhalation and dermal exposures to toxic or sensitizing materials.[25–28] Additionally, liquid binders may have their own hazards, such as ethylene glycol being flammable, combustible and a potential irritant.[14,36] The feedstock may also be saturated with a chemical mix as a precursor to binding. Both that precursor and the binder add the possibility for exposure to VOCs. Post-processing creates additional exposure opportunities for previously described material-related hazards, and may include other potential hazards depending on the techniques used.

Sheet lamination

Sheet lamination processes, or reel-to-reel manufacturing, roll sheets of material across a build platform, where the desired cross-section is cut with blades or a laser, and then bonded to preceding layers with adhesive or ultrasonic welding.[17] Build materials can vary widely for this process category, although metals are common.

Potential hazards in such processes include mechanical injury from the process itself, exposure to noise, and inhalation of welding fumes or volatiles from adhesives.[36,37]

Directed energy deposition

Directed energy deposition processes operate by placing a wire or powder at a desired location on an object, and then fusing that material with a laser, electron beam, or plasma arc.[2,17] This process can add metal continuously rather than step-wise, unlike many other process categories.

Potential hazards of directed energy deposition processes are dependent on both their feedstock material, forms, and the binding mechanism. Metals may be toxic or sensitizing,[25–28] and dermal contact or inhalation of powders might occur. Each of the three prominent binding strategies (laser, electron beam, or plasma arc) represents a potential burn hazard, and may present unique hazards (such as vision damage, exposure to ionizing radiation, or electrical shock).

Other hazards

More generalizable potential hazards may originate from the use of electrical machinery itself. Shock or mechanical injury during maintenance and malfunction is conceivable, as is noise exposure during routine operation. Ergonomic hazards while loading, unloading, and maintaining AM tools is possible, depending on machine architecture and the mass of feedstocks or other consumables.

Workplace environment

AM processes are often dependent on phase changes or chemical reactions that are sensitive to temperature, humidity, or other conditions. Tools may place constraints on their operating environment, and may affect the workplace by generating heat, fumes, or airborne particulate. Facility design will need to consider both the requirements and external impact AM tools to ensure a safe and healthy workplace.

Take-home exposures

Workers may inadvertently transport materials beyond the workplace on their shoes, garments, and body. This is especially likely for powdered material and semi- or non-VOCs. Such exposure may be unanticipated and uncontrolled and represent an increased secondary exposure risk for the worker and collocated members of the public (such as family members). Mitigating this risk will serve to protect both the worker and the general public.

Robotics and automated systems

Automated systems are essential in AM, manifesting in computer-aided design and partially autonomous fabrication processes. Additional autonomous systems may be further incorporated for support processes (such as loading consumables), unloading products, transporting consumables and products, and in post-processes. Such systems may create or mitigate potential hazards related to their particular operations. For instance, a robotic system assists removing and transporting a product may reduce ergonomic stress on the worker, but may increase the risk of impact by the robot or a falling object (the product). Similarly, the ability to use robotics or operate remotely may lower exposures to hazards at the AM tool itself (such as inhaled powder or VOCs), but may indirectly raise other hazards by adding a source of impact, crushing injury, or user error to the workplace.

Fatigue and psychological stress

Several factors may cause AM to be atypically fatiguing or stressful. As tool time is highly valuable and skilled workers are in short supply, instrument faults need immediate action from a small group of workers; this combination may result in scheduling late, irregular, or long shifts, or on-call hours. Additionally, the pace of innovation means fewer routine processes and a perpetual demand for change and adaptation. Moreover, this rapid advance combined with trends of automation can cause stress relating to feelings of job security. These stresses may resemble those emerging from the changing organization of work in other areas.

Bioprinting

Bioprinting is the deposition of biological molecules, materials, and organisms (cells). Several techniques for bioprinting are quite similar to AM process categories, including inkjet bioprinting (material jetting), micro-extrusion bioprinting (material extrusion), and laser-assisted biprinting (directed energy deposition).[38] The similarities of some of these techniques and the research and biomedical opportunities that could arise from their combination make it conceivable that they will be used in tandem, or that single instruments will be capable of fabricating both biological and nonbiological materials. These bioprinting processes may have their own potential hazards, some of which may resemble nonbiological AM (the emission of particulate matter, the use of polymers and related chemistry, the use of lasers or heat sources). Other hazards may relate to the biological nature of these processes (chemicals needed for sterilization or conjugation protocols, activity of biomolecules or living cells).

Risk management considerations

Hazard, exposure, and risk characterization

The potential hazards of AM include those that are well-understood, those that are completely novel, and those that are a blend of old and new. Partially or completely new hazards will likely pose greater challenges for hazard characterization, exposure assessment, and consequently risk analysis. Addressing these challenges will require developments in multiple areas including toxicological study, exposure assessment method development, and standards creation.

Nanotechnology safety and health may be a useful model for addressing these concerns in AM. Both share the traits of a large and expanding variety of materials and processes, a mixture of familiar and new hazards, and evolving technologies and applications. Attention was drawn to specific issues in nanotechnology which received concerted effort,[13] resulting in rapid and concurrent advances in material hazards and toxicology,[39–41] development of new exposure assessment methods and tools,[42,43] and risk-assessment and risk-management frameworks to handle even substantial uncertainties or data gaps.[44,45] AM may benefit from a similar coordinated and concerted approach on creating generalizable knowledge on hazards, exposure assessment methods, and finally risk-assessment and risk-management paradigms that are adaptable in the face of incomplete information.

Engineering controls

For many potential hazards of AM, appropriate and generally accepted practices and controls already exist. Control of particulate emissions (including ultrafine) has been well validated using local exhaust ventilation and HEPA filtration.[46] Consensus standards on laser safety such as ANSI Z136 will remain applicable in AM systems.[47] Use of these and other existing guidance, methods, and standards should be considered in the context of initially addressing potential hazards. Challenges are more likely to arise in the context of novel and partially novel hazards. Addressing such concerns will require a holistic approach, considering the hazards both individually and in tandem.

Additional constraints may also originate by the process itself or related economic concerns. One example is the economic incentive to reclaiming unused, high-value materials, such as superalloy powders. Control methods that maximize recovery while also preventing worker exposure will be of significant interest to any manager, while those that sacrifice recovery for protection will have less appeal to management. While effective solutions may exist for some processes, a substantial opportunity exists for advancing safety practices and tools in others.

Safety culture

As manufacturers leverage the advantages provided by AM, product development, supply chains, and small businesses may change in significant ways. These implications can create unique challenges for the safety culture in related workplaces, and occupational safety and health professionals will have the opportunity to meet these challenges.

Accelerated pace of innovation

Direct use of digital design, near real-time process adjustments, and reduced re-tooling requirements will accelerate the development cycle. This change may pose a challenge to the occupational safety and health professional, as new materials and processes rapidly transition into and out of use in the workplace. Maintaining pace will require continuing education about the technology and early insights into potential changes that new products may bring to the process and materials used. Solving this effectively may require the integration of safety professionals and other personnel in decision-making at the design stage, as advocated in Prevention through Design (PtD) strategies.[48]

Distributed production, supply chain, and workforce

Because complex parts can be fabricated on a single AM tool, businesses have new options with respect to production and supply chain networks. Companies may choose to abandon central factory models, in favor of distributed models: manufacturing products at individual point-of-sale locations, satellite manufacturing locations, or third-party contractors (service bureaus).[3,49] Products may be produced just-in-time, rather than stockpiled.[49] Additionally, more tasks might be amenable to remote management as reliability improves.

These changes may create both challenges and opportunities. Decentralization of production might reduce locally specialized occupational safety and health expertise, and safety information will need to be communicated effectively to partners that may be continually in flux or not authorized access to all proprietary information. Innovation in communication approaches and standards may be needed for the transmission of necessary safety information between distant locations and different companies.

Small operators

The decline in price for AM tools and their usefulness in prototyping will also encourage adoption by small businesses, which may be fluid in their processes and products.[5,31] In addition to challenges related to the accelerated pace of innovation and the distributed supply chain and workforce, a small business may have significant resource constraints or lack institutional knowledge of occupational safety and health practices.[50] Occupational safety and health professionals will have the opportunity to develop new protective strategies that are comprehensible and economical for effective for small firms, and to shape the safety culture of a still-developing and highly-important industry.

Conclusions

AM is making its way into more workplaces as businesses eagerly seize the opportunities it offers in prototyping and production. However, AM also presents unique potential occupational health and safety challenges due to the variety of processes, the increasing use of novel materials and processes, and characteristics particular to places and purposes for which it is used. AM process categories can act as a framework to aid in hazard identification, with additional hazards arising from organization of the workplace, workforce, and related technologies.

For a subset of hazards, appropriate characterization data, exposure assessment techniques, and controls already exist; others will require development. There are significant knowledge gaps which affect the ability to assess risks and prioritize resources. Outside of thermoplastic extrusion, there is a minimal amount of peer-reviewed, scientific literature on the emissions of AM processes. Similarly, there are few published field studies of AM emissions or worker exposures to hazards. There is also a limited understanding of how the typical AM user receives and implements potential safety data, much less their use of controls. Controls will also need to be studied to validate their effectiveness against AM hazards. The development of the nanotechnology occupational safety and health field may be a model for such development in AM. Much like in nanotechnology, the ability to develop generalizable fundamental knowledge will be crucial to an approach that can track the moving target that will be state-of-the-art AM.

If AM is the leading edge of a new industrial revolution, the opportunity for the occupational safety and health profession is to make it a far safer revolution for the worker than any prior. Delivering that safe industrial revolution demands academic researchers, industrial designers, and occupational safety and health experts become informed about AM and prioritize development of knowledge and techniques that will enhance health and safety in this vital field.

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