Emerging Health and Safety Issues in Makerspaces

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INTRODUCTION

Makerspaces have embraced a new generation of tools, such as 3-D printers and laser cutters, which greatly expand shop capabilities and increase interest and participation in fabrication. However, their small size, easy availability, and placement in many non-traditional locations such as libraries, meeting rooms, community centers, homes, and dormitories emphasize the need for evaluating and controlling their potential hazards.

One approach commonly used to control exposures is to follow a hierarchy of controls [1]. Implementation of controls in this order can help ensure inherently safer systems [2,3]:

- Elimination
- Substitution
- Engineering controls
- Administrative controls
- Personal protective equipment (PPE).

This paper reviews health and safety hazards posed by two common makerspace tools - 3D printers and compact laser cutters - and uses the hierarchy of controls framework to present recommendations to minimize effects of these hazards.

3D PRINTERS

Since emerging as a new technology in the 1980's, the term "3D printing" has grown to encompass many additive manufacturing technologies. Though the cost, availability, and user-friendliness of modern 3D printers makes them common in academic makerspaces, they can pose a number of unique hazards. For example, stereolithography (SLA) printers use liquid resin solutions whose health hazards and disposal issues have not been fully characterized, and any operation involving laser sintering not only has laser hazards but also inhalation hazards from the use of small particle size powders (plastic, metal, ceramic etc.) as well as handling concerns associated with combustible dusts. Potential generation of particulates or odors is relevant to many types of 3D printing, and the technology which has been evaluated most thoroughly for these emissions is the one most frequently in use in academic makerspaces: fused deposition modeling.

Fused Deposition Modeling (FDM) involves heating a thermoplastic polymer (often acrylonitrile-butadiene-styrene (ABS) or polylactic acid (PLA)) to at least its softening point and extruding that polymer through a fine-orifice nozzle which is moving in the xy plane. Such a process is inherently prone to potential aerosol generation, and indeed emission of particulates has been identified during FDM 3D printing [4,5]. The vast majority of these are ultrafine particulates (UFPs) [6], meaning their diameter is <100 nm. These particles are potentially hazardous if inhaled as they will deposit in all regions of the respiratory tract and, due to their small size, can pass directly through cell walls from the respiratory system to the circulatory system [7]. Considerable research into the potential health effects of UFPs is underway.

Humans have long been exposed to ultrafine particulates in the form of soot and other products of fuel combustion as well as such common activities as cooking or burning candles [8], and more recently from the use of computer laser printers [9]. It is unclear how much concern should be attributed to data showing emission rates from 3D printing that are comparable to these other commonly-accepted sources in the absence of toxicological studies or regulatory exposure limits.

Although work to-date on emissions of UFPs during 3D printing is limited and has not been uniform in terms of the part manufactured or placement of monitoring devices, the results suggest some general trends. ABS systems appear to emit more particulates than PLA, perhaps due to the higher temperature needed to soften ABS. Some data also suggest that enclosed printers emit lower levels of particulates, that multiple printers running simultaneously increase emissions, and that colored feedstock may emit more UFPs than uncolored feedstock. The heating of thermoplastics also emits volatile organic compounds (VOCs)[4], including the chemical styrene when ABS feedstock is used.

Given the available data, UFP generation is a potential hazard of 3D printing. One immediate way to control this hazard is to substitute PLA for ABS whenever possible to reduce overall emissions. Enclosure of 3D printers is a simple engineering control which can also limit exposure, either by purchase of an enclosed printer or by providing an enclosure post-purchase. It is also important to ensure adequate general ventilation, especially where multiple printers will be used. Monitoring can be performed to indicate if specialized local exhaust ventilation may be needed to further reduce exposure to UFPs. Exposures can also be limited by educating users to minimize the time spent directly in front of 3D printers.

FDM 3D printers can present ancillary hazards as well. 3D-printing processes that require use of a support resin require removal of this support material after printing. This is often accomplished using a caustic surfactant parts washer bath.

The caustic solution's high pH (often 12 or above) is hazardous to the skin and eyes, and the resulting mix of resin suspended in surfactant solution may not be lawful or safe to dispose down a regular drain. Caustic baths can be eliminated entirely if the part can be printed without such a support. If a less hazardous parts-washing material is available, substitution should be considered, but in many cases this is either not practical or introduces other hazards (e.g., d-limonene can be used to dissolve HIPS as a support material, but it is flammable, an inhalation hazard, and a sensitizer). Administrative controls such as user awareness of the hazard and training on a documented procedure for appropriate parts washer bath use are critical. This is of special interest if the location of the 3D printer and bath is not one where chemical use has been common or typical; users of the parts washer bath in such an area may not have needed chemical hygiene training previously. PPE such as safety glasses or goggles and appropriate gloves in the sizes and length to safely do this work must be available. A review of parts washer bath waste must be discussed in advance to ensure to appropriate management and disposal.

COMPACT LASER CUTTER SYSTEMS

Technological improvements and a rapidly growing marketplace over the past two decades have helped transform laser cutting from a largely industrial process to one well-suited for smaller venues such as makerspaces. These improvements have resulted in a proliferation of powerful and increasingly affordable compact laser cutter systems, many of which are small enough to fit on a desk or benchtop. These systems can process a wide variety of organic and soft metal substrates and excel in smooth cutting, engraving, and marking. With easy-to-use design and driver software, compact laser cutters operate much like a traditional printer, making them common tools in many makerspaces. As widespread as compact laser cutter systems have become, they are not without hazards.

Laser Hazards

The use of any laser can pose hazards to operators and others working nearby from beam and non-beam hazards. Beam hazards can result in thermal injuries to the eyes and skin from direct or reflected light; non-beam hazards include fires, electrical shocks, and laser-generated air contaminants.

Beam hazards are determined by wavelength, power, mode and speed (pulsed or continuous wave), and human contact. The American National Standards Institute [10] categorizes lasers into Classes. Class 1 are the least harmful and pose no potential hazard under normal operating conditions, while Class 4 are the highest hazard, capable of causing serious burns to eyes and skin. Most compact laser systems use gas tube CO_2 lasers in the 30 - 50 W range (larger units can exceed 100 W), making them Class 4 lasers. However, due to a combination of enclosures, shielded access covers, and beam interlocks, the overall system classification is generally Class 1.

Laser-Generated Air Contaminants

Highly concentrated beam energy transfer at the substrate interface results in localized melting, evaporation, volatilization, and spattering, which in turn generates primary and secondary aerosolized particulates, gases, and chemical vapors. These products are derived from a combination of the substrate itself (e.g., monomer release from PMMA), pyrolysis, and interactions with the cutting atmosphere. Laser-generated emissions are specific to the substrate material (composition and thickness), process performed (through-cutting, engraving, marking), processing / cutting speed, laser pulse rate, and laser wavelength and power. Information about laser-generated air contaminants comes largely from laboratory experiments with industrial lasers as well as (non-laser) substrate thermal degradation studies.

Several investigators have used enclosed chambers with controlled, monitored exhaust ventilation to evaluate emissions from laser cutting. For example, Pilot et al. [11] measured total particulate (aerosol), nitrogen oxides, and ozone emissions from plasma arc and laser (CO_2) cutting of mild and stainless steel in air. They found that laser cutting produces negligible levels of nitrogen oxides and ozone, and significantly less particulate aerosol, than plasma arc cutting. Subsequent work [12] demonstrated that laser cutting is also "cleaner" than grinding or circular metal saw cutting, that air-assist cutting produces lower emissions than non-air assist cutting, and reconfirmed that lasers generate fewer aerosols than plasma torches. Regardless of substrate, laser-generated aerosols tended to have multi-modal size distributions, centered around a particle diameter of about 0.45 µm, well within the respirable range of particulate matter. The authors further evaluated electrostatic precipitation as a means to reduce downstream particulate concentrations, documenting removal efficiencies > 85% for particulate matter only but not addressing methods to filter or adsorb gases and chemical vapors.

Haferkamp et al. [13] evaluated CO_2 laser cutting emissions from thermoplastics: polyamide (PA), polyethylene (PE), polycarbonate (PC), polymethylmethacrylate (PMMA), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). Aerosol particle size distributions generally had diameters between 0.03 and 0.50 µm, also well within the respirable range. With the exception of PMMA, each of the materials emitted in excess of the (German) occupational exposure limit for total aerosols, with PA, PC, PE, and PP emitting the highest levels. The relatively low aerosol emissions from PMMA and PS, however, were made up for by very high concentrations of gaseous and vapor emissions. Laser cutting of plastics also generated elevated levels of specific hazardous compounds, including hydrogen chloride, benzene, dioxins/furans, and PCBs from PVC; methylmethacrylate monomer from PMMA; styrene and 1,3-butadiene from PS; and polynuclear aromatic hydrocarbons (PAHs) from all materials.

In a non-controlled work environment, concerns about possible occupational over-exposures to emissions from CO_2 laser cutting operations at a manufacturing site led the US National Institute for Occupational Safety and Health to perform a health hazard assessment [14]. Personal and area air samples collected during laser cutting of several materials, including acrylic plastics, generated airborne levels of ethyl acrylate up to 6 times the permissible exposure limit.

A valuable tool for evaluating laser emissions was identified from the Laser Zentrum Hannover (LZH), a research institute in Hannover, Germany [15]. This resource consists of a searchable on-line database for emissions reference data generated from LZH applied research on different laser operations, laser types, and substrates.

In a different context, Pierce et al. [16] reviewed occupational hazards from medical laser procedures, including Nd:YAG and CO_2 systems. Laser- and electrosurgical-generated smoke plumes constitute a significant hazard to which 500,000 healthcare workers per year may be exposed [17]. In addition to hazardous chemicals, medically-generated smoke can also contain viable cellular matter as well as potentially infectious material such as viruses, viral DNA or RNA, and bacteria. While not relevant in most makerspaces, these findings have implications for laser use in biomechanical engineering, biopolymers and films, and related disciplines.

A brief summary of commonly-recognized laser cutting emissions by substrate material appears in Table 1. It is based upon references noted here, from substrate composition, and other (non-laser) thermal degradation studies [e.g., 18].

Table 1. Common laser cutter emissions, by substrate[1]

Metals	Potential heavy metals
Wood (incl. MDF and plywood)	Soot, benzene, formaldehyde, acrolein, PAHs
Polyamide (Nylon®)	Cyanide, nitrogen oxides
Polycarbonate	Benzene, toluene, xylene, cresol, PAHs
Polymethylmethacrylate	MMA and ethyl acrylate, acetone, formaldehyde, phenol, PAHs
Polyoxymethylene (Delrin®)	Formaldehyde
Polystyrene	Styrene monomer
Polytetrafluoroethylene (Teflon®)	Fluorocarbons, HF
Polyvinylchloride	HCl, possible phosgene, benzene, trace dioxins/furans and PCBs

[1] In addition to substrate particulate aerosols

Controlling Laser Cutter Hazards

User Training

The control of any hazard begins with good user training, onboarding, and the development of a culture of safety. Appropriate levels of supervision are critical until new users can demonstrate proficiency in the proper and safe use of any tool. Due to the CNC nature of modern compact laser cutting systems, the "barriers to use" are often low.

Factory-Supplied Safety Features

Compact laser cutters should be purchased as part of a factory-supplied system, including a complete enclosure, beam-interlocked access lid or door, shaded view panel, and a means to provide contaminant exhaust. The device should also carry an electrical safety listing from a recognized organization.

Although the laser hazards of most compact cutting systems are effectively controlled by a combination of features, some institutions still require internal registration for all high power lasers - purchasers should consult their environmental health and safety office. Users and supervisors should also regularly inspect the enclosure and lid, noting any cracking, crazing, or discoloration. If any component is found damaged or broken, the laser cutter should be removed from service, locked out, or otherwise disabled from use, and repaired or replaced.

Fire

Fires are serious and real hazards since small ones (usually self-extinguishing) occur frequently during cutting. Users must remain with the laser cutter during active cutting and shortly thereafter. The air assist feature significantly reduces the risk of larger fires by removing debris from the cut, and some new systems now come with integral high temperature alarms and / or automatic shutdowns.

In addition to a room that meets applicable building and life safety code requirements, every space with a laser cutter should also have at least one portable fire extinguisher close by. Multi-class ABC dry chemical fire extinguishers are common, inexpensive, and effective; however, their fine dry chemical powder will damage sensitive electronics and optics. Carbon dioxide or other clean media extinguishers are strongly recommended instead. Consult the institutional fire marshal or environmental health and safety office for assistance, including fire extinguisher use training as required. Integral fire suppression systems are now also available as an option for some laser cutter systems.

Laser-Generated Air Contaminants

Particulate aerosols, gases, and vapors emitted during laser cutting must be controlled through a blend of careful material selection, proper settings and feed rates, and the application of appropriate ventilation. Makerspace managers are encouraged to carefully review the materials permitted for use, and consider limiting or banning those with the "worst" emission profiles. Since many different materials actually look alike, some organizations have established procedures to ensure that only locally-sourced, approved materials are used.

The containment and removal of laser-generated air contaminants is critical, even for small compact laser cutters. True local exhaust ventilation that meets good engineering practices [19] and ultimately discharges outdoors is the most reliable, effective, and safe method for handling potentially hazardous airborne contaminants. These systems require a thimble-style connection to the laser cutter exhaust port (to avoid back-pressures or excessive suction), ductwork, a fan, and discharge from a high point on the building to ensure good mixing and avoid re-entrainment indoors. Unfortunately, new ventilation systems of this type are generally expensive, and even connecting to an existing system can be costly. In some cases, through-the-wall or -window discharge can be safely accommodated, with certain additional restrictions or pre-treatment controls. Consult the environmental health and safety or facilities engineering department for guidance.

Many suppliers offer recirculating filtration units for laser cutters, offering quick and self-contained solutions for managing exhaust emissions. Users are strongly urged to be aware of the capabilities - and limitations - of these devices, and to consult colleagues and environmental health and safety professionals for experiences with specific brands and models before purchase. These devices rely upon multiple filters to trap and remove particulates, generally followed by one or more canisters of activated charcoal and/or other specialty adsorbents for the removal of chemical vapors and some gases. While particulates can be readily captured by HEPA filters, gases and chemical vapors as well as ultrafine particles require adsorption, neutralization, scrubbing, or other means for removal. Filters improve in efficiency over time, but once the active sites on these other kinds of air cleaners reach saturation, a continuous steady-state release of contaminants will occur back into the room. Self-contained filtration units also require regular maintenance, including periodic replacement of costly filters and canisters; depending upon the adsorption media and contaminants, some of these components may require special handling and disposal as hazardous waste.

CONCLUSIONS

Laser cutters and 3D printers are used in many academic makerspaces to create sophisticated items quickly, easily, and affordably. However, these technologies present some under-appreciated hazards regarding the generation of air contaminants (particulates/aerosols, VOCs) and waste management. Makerspace managers are encouraged to become aware of these potential hazards and implement exposure minimization strategies by following the safety hierarchy of controls.

Although research into potential health hazards of 3D printers and laser cutters continues, there is a decided paucity of data at present. Collaboration between environmental health and safety professionals and academic makerspace managers to gather data on these and other new devices under standardized conditions is recommended. Azimi et al. [4] provide one example of a standardized "test artifact" as designed by NIST [20]. The authors are interested in hearing from others who have conducted studies on these tools or would be interested in collaborating in the future. 3D printers and laser cutters will only grow more ubiquitous with time, and a fuller understanding of appropriate controls for their unique hazards will serve to enhance the safe operation of academic makerspaces.

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