Working Safely with 3D Printers

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Additive Manufacturing (AM), commonly referred to as 3D printing, is being increasingly adopted in Singapore as a cost effective industrial solution for fabrication of custom and precision components. In AM, 3D-printed objects are created from a digital file and a printer that lays down successive layers of material until the object is complete. Each layer is a thinly sliced horizontal cross-section of the actual object.

Figure 1: Example of a 3D printer in action (Image Source: Royalty free image from pixabay.com)

Application of 3D-printed products spans many industries – ranging from manufacturing, automotive, aerospace, marine, biomedical to construction. Examples of products that can be 3D-printed include:

- Tools, machine and vehicle parts
- Building and construction components
- Prosthetics, surgical implants and dental products
- Consumer goods (e.g. electronics, toys, jewellery)
- Food products (e.g. chocolate, candy, cake decorations)
- Pharmaceutical products (e.g. tablets)

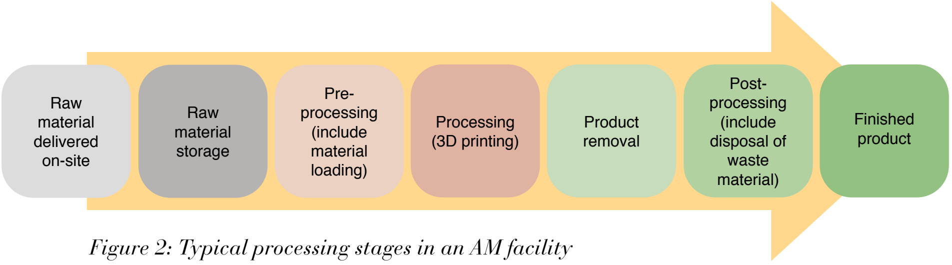

Figure 2: Typical processing stages in an AM facility

In the combat against COVID-19, Singapore designed and produced its own 3D-printed nasopharyngeal swabs in less than seven weeks. Millions of swabs have been printed to-date[1].

Advantages of 3D printing include greater design flexibility and complexity, opportunity for mass customisation, faster fabrication, less manpower intensive, and reduced waste per product versus traditional subtractive manufacturing methods.

In the manufacturing industry, common materials used in 3D printing include thermoplastics, metals/ metal alloys and ceramics. In the construction industry, 3D printing typically involves the use of special concrete mixtures.

Raw material for 3D printing may be in the form of a liquid; a solid filament, pellet, wire, film or sheet; granules or finely divided powder; or a colloid. Depending on the additive manufacturing process or technology employed, 3D printing may begin with the use of or result in the generation of fine/ ultra-fine powders. Fine particles (FP) typically handled in 3D printing are of average size 25 to 150 microns. Ultrafine particles (UFP), however, are in the nanoscale range (less than 0.1 micron or 100 nanometres in diameter).

Key hazards working with FP/ UFP include inhalation risk and combustible dust fire and/ or explosion. Fumes and/ or volatile organic compounds may also be emitted during 3D printing depending on the feedstock material(s) and processing method used.

This paper focuses on reducing powder inhalation risk to workers operating 3D printers. The human body cannot readily metabolise most of these powders, and build-up through exposure can quickly reach toxic levels.

Reducing Powder Inhalation

The health impact of long term exposure to FP/ UFP during 3D printing is, unfortunately, still a topic of research and not well understood. Potential health impact includes reduced lung function resulting from fine particulate deposition and adverse health effects arising from exposure to a hazardous substance (e.g. metals). Long term exposure undoubtedly poses occupational health risks and both employers and principals are required by law[2] to take reasonably practicable measures to eliminate or minimise this risk.

Figure 2 shows the typical stages which the raw material for 3D printing must undergo before the finished product is ready for delivery to the customer.

To reduce powder inhalation risk, exposure to FP/ UFP must be evaluated for each of the above stages and risk controls put in place so that worker exposure may be brought down to ideally negligible.

In particular, two key stages where workers could come into contact with powder are:

<u>Pre-processing stage</u>

- Cleaning the filter module or changing the filters in the process gas circuit
- Loading, refilling or changing the powder reservoir
- Tooling or re-tooling the 3D printer
- Fitting or adjusting the printing platform and support structures

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Post-processing stage

- Residual powder evacuation off the printing platform and support structures
- Removing the printing platform and support structures from the process chamber
- Emptying the collecting duct and sieving the residual powder
- Cleaning the process chamber
- Cutting away printed residue off the printing platform
- Finishing the printed parts (e.g. grinding, polishing)

The principle of Hierarchy of Control[3] applies when deciding on the suitable risk controls to apply:

Figure 3: The Hierarchy of Control

Elimination

The idea behind elimination is to eliminate the hazard altogether or to eliminate exposure to the hazard wherever possible.

Safer manufacturing technology
Total hazard elimination is possible if, where feasible, 3D printing technology is entirely replaced with an alternative manufacturing technique that does not require the use of or result in the generation of FP/ UFP.

Closed system
If 3D printing and exposure to FP/ UFP is unavoidable, then it becomes important, from a Workplace Safety and Health (WSH) perspective, to select a printer system that is essentially operated in a closed system. Closed system manufacturing is inherently safer as it will ensure worker exposure is greatly minimised at each processing stage.

A 3D printer will be safer if it is specially designed such that the operator does not come into immediate contact with the powder even during pre- and post-processing. This can be achieved, for example, by designing the process chamber to be a fully-sealed enclosure and fitting it with a see-through integrated glove box. This will allow the operator to reach into the process chamber without contacting the powder. Powder leakage can be further minimised if the process chamber is kept under a slight negative pressure.

Reduced man-machine interaction
Exposure is directly correlated to man-machine interaction. Through automation and the use of robotics, several 3D printer operations can be designed to be performed automatically or remotely (e.g. powder loading, printer re-tooling, printing platform manipulation, powder evacuation, product removal) within the sealed process chamber. This limits the amount of time the operator spends in close proximity to the printer, thereby effectively reducing FP/ UFP inhalation risk.

Substitution

Substitution applies when we replace either the specific process or the materials used with a less hazardous alternative.

Less emissive printing method
Translated to 3D printing, substitution suggests that the printing method (e.g. powder bed fusion vs vat photo polymerisation vs material jetting) offering the least or no exposure to FP/ UFP be selected at the first instance.

Less emissive raw material
Another strategy would be to drastically reduce powder emissions by replacing high-emitter raw materials with low-emitter raw materials.

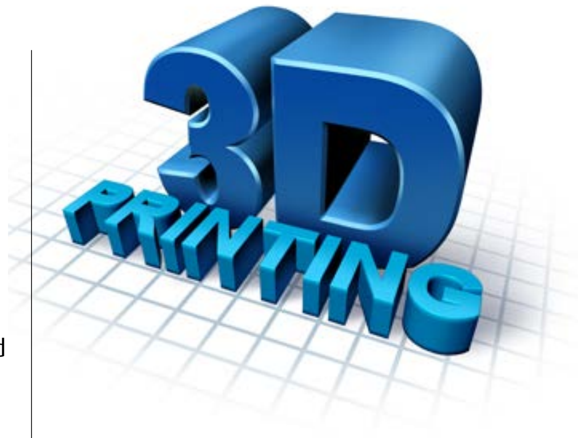
Engineering Controls

In general, engineering controls refer to hardware-based solutions that can be put in place to reduce worker exposure to a hazard. Engineering controls are typically far more effective than administrative controls as adherence to engineering controls is not human behaviour dependent.

Workplace ventilation
In 3D printing, the key engineering control solution for reducing inhalation exposure lies in providing a well-ventilated work environment. Good ventilation will reduce the quantities of FP/ UFP in the operator's breathing zone, thereby reducing the impact of 3D printer emissions.

There are two aspects of ventilation to look into:

Dilution ventilation
From a WSH perspective, general or dilution ventilation (effected through mechanical



ventilation) serves an important function – it reduces inhalation exposure to airborne contaminants (including FP/ UFP) in the work environment by diluting the contaminants to lower atmospheric concentrations.

For dilution ventilation to be effective, there is a need to:

- mix contaminated air with a large volume of fresh air;
- create air movement at all locations within the laboratory; and
- have sufficient air changes per hour to prevent contaminant build-up.

To effectively dilute airborne contaminants, single pass 100% fresh air should be provided. It is best not to re-circulate the air in a 3D printing work environment as this can result in contaminant accumulation within the work area and/ or distribution of contaminants throughout the building.

More details on dilution ventilation requirements and the formulas for determination of dilution ventilation rate can be found in *SS 567: 2011 Code of Practice for Factory Layout – Safety, Health and Welfare Considerations.*

Local exhaust ventilation (LEV)
A LEV device is designed to capture and remove airborne contaminants at or very near the source of emission. LEV devices provide spot ventilation to prevent the transmission of airborne contaminants from source to worker, thereby reducing inhalation exposure.

For 3D printers, the LEV device could be built-into the process chamber and interlocked to automatically turn on once the chamber is opened by the operator (e.g. to carry out printer maintenance or to troubleshoot a malfunction). Depending on the printer setup, LEV devices in the form of canopy hoods or flexible arm capture hoods may also be used.

For LEV to be effective, there is a need for the:

- hood to either enclose the contaminant source or be positioned as close to it as possible;
- capture velocity to be high enough to draw the contaminant into the hood from the furthest point where it is likely to be present; and
- direction of air movement to be designed such that contaminants are carried away from the worker's breathing zone.

More details on LEV requirements, the range of desired capture velocities for different contaminant dispersion scenarios, and the recommended duct velocities for proper conveyance through the exhaust system can be found in *SS658: 2020 Code of Practice for Design, Operation, Testing and Maintenance of Local Exhaust Ventilation Systems.*

For both dilution ventilation and LEV, the use of High Efficiency Performance Air (HEPA) filters is recommended. HEPA filters are at least 99.97% effective in trapping particles of diameter 0.3 micron and higher. Studies show that HEPA filtration is also effective for submicron and nanoparticulate matter removal.[4]

Administrative Controls

Administrative controls help to eliminate or reduce exposure to a hazard through adherence to a set of operating procedures or detailed instructions incorporating the control measures and safety precautions to be taken. Adherence to administrative controls, however, is highly dependent on human behaviour and should be used only as a supplement to engineering controls.

<u>Safe work procedures</u>
Safe Work Procedures (SWPs) provide a carefully planned step-by-step sequence of actions to be carried out to ensure that a particular work activity can be carried out safely. In the context of 3D printing, SWPs would need to be established, documented and implemented for each stage in Figure 2 as well as any adhoc or non-routine work activities like breakdown maintenance or emergency situations.

Adherence to SWP is key as performing the task incorrectly may lead to higher exposures arising from improper work methods. For example, when handling powder, slow & controlled movements are needed to minimise the creation of a powder cloud. An incorrect method of work may inadvertently increase inhalation risk.

For non-routine work activities like breakdown maintenance, companies may wish to consider incorporating the Permit-To-Work (PTW) system and Lockout Tagout (LOTO) procedures into the SWP.

With the SWP established and successfully rolled out, close supervision and regular audit becomes an important means to ensure that the SWP is strictly adhered to.

<u>Hazard communication</u>
Other than SWPs, workers may also be informed/ made aware of workplace hazards by the following means:

Safety data sheets
As 3D printing may involve the use of several raw materials, operators must be provided with easy access to the Safety Data Sheet (SDS) for each material used.

Under the WSH (General Provisions) Regulations, it is mandatory for the:

- occupier to obtain a SDS for each hazardous substance used, handled or stored in the workplace; and
- seller (or any agent of the seller) to provide the buyer with a SDS for the hazardous substance being procured.

The SDS is an important source of information from the seller (usually the manufacturer or the supplier) to the workplace occupier/ employer who purchases the chemical (raw material), and from the employer to employees who handle or use the chemical.

Printer operators will be able to obtain the following material-specific details from an SDS:

- Substance information and identified hazards
- Precautionary measures for storage, handling and exposure control
- First aid and emergency response
- Disposal considerations

More information on SDS may be found in *SS 586: 2008 (2014) Specification for Hazard Communication for Hazardous Chemicals and Dangerous Goods – Part 3: Preparation of Safety Data Sheets (SDS).*

Visual communication
The use of hazard signs, labels and stickers are ways in which workers can be visually reminded of the hazards present and/ or the personal protective equipment that must be put on prior to work commencement. If installed at strategic locations (e.g. on doors, on the printer, on raw material containers), such visuals may be effective to alert workers on what they will be encountering and serve as a "last minute" trigger to adopt the necessary precautionary measures.

For guidance on the creation of hazard signs, refer to *SS 508: Graphical Symbols – Safety Colours and Safety Signs Parts 1-5. With regard to the use of hazard pictograms on labels and stickers for container labelling, see SS 586: 2014 Specification for Hazard Communication for Hazardous Chemicals and Dangerous Goods – Part 2: Globally Harmonised System of Classification and Labelling of Chemicals – Singapore's Adaptations.*

<u>Worker training</u>
Provide workers* with training on the specific 3D printer being used. The training should include familiarization with the printing technology, on-site hazard identification, SWPs, understanding the risk controls in place, personal protection requirements, knowing when PTW and/ or LOTO should be applied, and how to use the information in an SDS.

* *This includes the printer operator and any personnel interfacing with the printer.*

<u>Authorised access</u>
Security measures should be implemented to prohibit unauthorised persons from entering 3D printing facilities unless they have undergone a WSH briefing, are equipped with suitable protective attire, and escorted by an authorised staff member. This is an administrative measure to protect persons unfamiliar with 3D printing to FP/ UFP exposure and other hazards present in the printing facility.

Personal Protective Equipment

This should be used only as a last resort, after all other controls higher up in the Hierarchy of Controls (Figure 3) have been implemented, or as a short term contingency during maintenance and repair, emergency, or as a temporary measure until controls higher up in the hierarchy can be implemented. Effectiveness of this risk control measure largely depends on the protective equipment being selected and fitted correctly, worn at all times while in the work environment, and properly maintained.

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Respiratory protection
To reduce powder inhalation risk, the use of personal respirators is essential once the process chamber is opened. Start by selecting the correct respirator type for the task:

Half-face particulate respirator
A very popular half-face respirator is in the N95 mask filter. N95 masks can filter 95% of airborne particles ≥ 0.3 microns. As such, N95 masks may be useful in 3D printing applications involving FPs of size ≥ 0.3 microns.

Note that the 'N' in N95 stands for "non-oil" applications. For applications involving oil-based aerosols, P95 masks should be used as these are designed to be strongly resistant to oil. For greater filtration effectiveness, there are also N99 and P99 masks companies may consider. N100 and P100 masks (able to filter 99.97% of airborne particles ≥ 0.3 microns) may also be used but users may experience breathing difficulty.

Full-face powered air purifying respirator (PAPR)
For 3D printing applications involving UFPs < 0.3 microns, the use of a full-face PAPR with HEPA filter is recommended. Being a powered air-flow device, operators will find using a PAPR more comfortable than the N95 mask. The use of a HEPA filter is important as studies have shown HEPA filtration to be effective for submicron and nanoparticulate matter removal[4].

For added protection, companies may wish to replace the HEPA filter with a Ultra Low Particulate Air (ULPA) filter. An ULPA filter can remove at least 99.999% of airborne particles with a minimum particle size of 0.1 microns (100 nanometres) and is particularly suited for UFP removal.

Concluding Remarks

While this paper focuses on possible strategies to reduce powder inhalation in 3D printing facilities, there are other WSH concerns (e.g. skin or eye contact with powder or chemicals, contact with sharp or hot objects, fire and explosion risk, machine safety, laser safety, exposure to inert gases, electric shock, ergonomic concerns, fatigue) that need to be looked into via a holistic risk assessment so that workplace accidents and injuries can be prevented.

With relatively new technology like 3D printing, there are often gaps in the information available on WSH implications and it is always better to err on the side of caution by implementing risk controls and best practices that are grounded in reasonableness.

The long-term success and wider adoption of 3D printing technology heavily depends on addressing its unique health and safety issues. The collaborative efforts of industry and standards development organizations are necessary to help ensure the continued development and evolution of appropriate local standards and WSH guidelines to address new and emerging WSH challenges in 3D printing.

Further Information

- Workplace Safety and Health Act
- Workplace Safety and Health (Risk Management) Regulations
- Workplace Safety and Health (General Provisions) Regulations
- Code of Practice on Workplace Safety and Health Risk Management
- WSH Guidelines on Management of Hazardous Chemicals Programme
- WSH Guidelines for Laboratories Handling Chemicals
- WSH Guidelines on Flammable Materials
- WSH Guidelines on Safe Use of Machinery
- SS 508: Graphical Symbols – Safety Colours and Safety Signs Parts 1-5
- SS 567: 2011 Code of Practice for Factory Layout – Safety, Health and Welfare Considerations
- SS 586: 2014 Specification for Hazard Communication for Hazardous Chemicals and Dangerous Goods – Part 2: Globally Harmonised System of Classification and Labelling of Chemicals – Singapore's Adaptations
- SS 586: 2008 (2014) Specification for Hazard Communication for Hazardous Chemicals and Dangerous Goods – Part 3: Preparation of Safety Data Sheets (SDS)
- SS658: 2020 Code of Practice for Design, Operation, Testing and Maintenance of Local Exhaust Ventilation Systems
- SS ISO 17296: 2016 Additive Manufacturing - General Principles (Parts 2 to 4)
- TR 70: 2019 Guidelines on the Selection Criteria for Metal Additive Manufacturing Processes
- TR 87: 2021 on Safety of Additive Manufacturing Facilities
- ISO/ASTM 52907: 2019 Additive Manufacturing — Feedstock Materials — Methods to characterize metal powders
- ISO/ASTM 52910: 2018 Additive Manufacturing — Design — Requirements, guidelines and recommendations
- UL 3400 Outline of Investigation for Additive Manufacturing Facility Safety Management ©2017
- "3D Printing with Metal Powders: Health and Safety Questions to Ask" by Glassford E, Dunn KL, Dunn KH, Hammond D, Tyrawski J. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH Publication No. 2020-114
- "3D Printing with Filaments: Health and Safety Questions to ask" by Glassford E, Dunn KL, Dunn KH, Hammond D, Tyrawski J. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH Publication No. 2020-115
- "Potential occupational hazards of additive manufacturing" by Gary A. Roth, Charles L. Geracia, Aleksandr Stefaniak, Vladimir Murashov, John Howard; J Occup Environ Hyg. 2019 May; 16(5): 321–328. doi:10.1080/15459624.2019.1591627.
- NASA Technical Memorandum on Submicron and Nanoparticulate Matter Removal by HEPA-Rated Media Filters and Packed Beds of Granular Materials (May 2016)

Under Development (as at 1Q 2021)
- ISO/ASTM CD 52931: Additive Manufacturing — Environmental Health and Safety — Standard guideline for use of metallic materials
- ISO/ASTM WD 52933: Additive Manufacturing — Environment, Health and Safety — Consideration for the reduction of hazardous substances emitted during the operation of the non-industrial ME type 3D printer in workplaces, and corresponding test method
- ISO/ASTM AWI 52938-1: Additive Manufacturing of Metals — Environment, Health and Safety — Part 1: Safety requirements for PBF-LB machines

Reference

[1]Speech by MOS Low Yen Ling at the NAMIC Global Additive Manufacturing Virtual Summit (21 Oct 2020)

[2]Workplace Safety and Health (Risk Management) Regulations

[3]WSH Council's Code of Practice on Workplace Safety and Health Risk Management

[4]NASA Technical Memorandum on Submicron and Nanoparticulate Matter Removal by HEPA-Rated Media Filters and Packed Beds of Granular Materials (May 2016)