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Particle Levels in the User Operating Environment of Powder, Ink and Filament-based 3D Printers

Abstract

Purpose - On-site particle concentration levels due to emissions from a wide spectrum of additive manufacturing techniques were examined, including polymer-based material extrusion, metal and polymer-based powder bed fusion, directed energy deposition and ink-based material jetting.

Design/methodology/approach - Particle concentrations in the operating environments of users were measured using a combination of particle sizers including the TSI 3910 Nano SMPS (10-420 nm) and the TSI 3330 optical particle sizer (0.3-10 μm). Also, fumes from a material extrusion printer during printing were directly captured using laser imaging method.

Findings - The number and mass concentration of submicron particles emitted from a desktop open-type material extrusion printer for acrylonitrile-butadiene-styrene and polyvinyl alcohol, approached and significantly exceeded the nanoparticle reference limits, respectively. Through laser imaging, fumes were observed to originate from the printer nozzle and from newly deposited layers of the desktop material extrusion printer. On the other hand, caution should be taken in the pre-processing of metal and polymer powder. Specifically, one to ten micrometers of particles were observed during the sieving, loading and cleaning of powder, with transient mass concentrations ranging between 150 to 9000 $\mu\text{g}/\text{m}^3$ that significantly exceeded the threshold level suggested for indoor air quality.

Originality/value - Preliminary investigation into possible exposures to particle emissions from different 3D printing processes, which is useful for the sustainable development of the 3D printing industry. In addition, automatic processes that enables 'closed powder cycle' or 'powder free handling' should be adopted to prevent users from unnecessary particle exposure.

Keywords Material Extrusion, Powder Bed Fusion, Material Jetting, Directed Energy Deposition, Indoor Air Quality, Particle Emission

Paper type Research paper

1. Introduction

Additive manufacturing (also known as 3D printing) has been an active area of research for its extensive application in fields including engineering design, aerospace, construction and marine (Ali, Batai and Sarbassov, 2019). To achieve capabilities in printing complex structures of different materials, a variety of additive manufacturing techniques have been developed that include material extrusion (MEX), powder bed fusion (PBF), directed energy deposition (DED) and material jetting (MJT), etc. (Ivanova, Williams and Campbell, 2013; Chua and Leong, 2014; Boparai, Singh and Singh, 2016; Ngo *et al.*, 2018). It has long been acknowledged that 3D printing offers environmental benefits, such as less material wastage and higher energy efficiency as compared to conventional manufacturing methods (Rejeski, Zhao and Huang, 2018). However, emissions of particle and volatile organic compounds (VOCs) from 3D printing were recently reported and the spotlight was on desktop MEX printers (e.g., fused filament fabrication or also known as fused deposition modelling) due to its widespread adoption in product prototyping (Afshar-Mohajer *et al.*, 2015; Azimi *et al.*, 2016; Graff *et al.*, 2017; Du Preez *et al.*, 2018; Ding *et al.*, 2019). While most attention is focused on desktop MEX printers, particle emissions from other kinds of 3D printing techniques are also of concern to occupational health but have since been less explored.

In MEX, the filament is melted and extruded through a nozzle, which is then deposited on top of previously printed layers to create 3D objects. Unfortunately, due to the heating of the polymer filament, ultrafine particles (UFP, <100 nm) were generated and diffused into the air (Ding *et al.*, 2019). Particle number emission rates were reported to vary between 10^7 to 10^{12} #/min for different combinations of desktop MEX printers and filament types (Stabile *et al.*, 2017; Zhang *et al.*, 2017), which can have negative impacts on indoor air quality (Stephens *et al.*, 2013; Azimi *et al.*, 2016; Gu *et al.*, 2019). These UFP compose of high- and low-volatility compounds that evaporate almost completely at 200°C and 160°C for acrylonitrile-butadiene-

styrene (ABS) and polylactic acid (PLA), respectively (Mendes *et al.*, 2017).

In PBF, a laser selectively fuses regions of a powder bed to build a 3D part layer by layer. In DED, a laser beam is used to fuse metal powder or wire as they are being deposited through a nozzle in a process that is similar to welding (Yuan *et al.*, 2019). The pilot study by Graff *et al.* reported that operators were specifically exposed to particles during the handling of metal powder for selective laser melting (SLM) (Graff *et al.*, 2017). Another pilot study on selective laser sintering (SLS) found that PM_{2.5} exceeded acceptable limits during the pre-processing stages (Damanhuri *et al.*, 2019) but had no obvious increase in particle concentration levels outside its enclosure during printing. In fact, UFP was still being generated during printing through the thermal decomposition of polymers but was prevented from spreading beyond the printing enclosure. In MJT (e.g., aerosol jet printer), aerodynamic focusing is used to precisely and accurately deposit electronic inks onto substrates, for which the ink is a mixture of organic liquid and metal particles (Hong *et al.*, 2014). Emissions are likely to occur from the atomization of electronic inks that create a dense mist of material laden droplets and possibly from the rebounding of metal particles. Across the different printing techniques, Rejeski *et al.* reviewed the environmental implications of additive manufacturing and emphasised that research should be focused on MEX, PBF, and DED due to the health risks associated with nanoparticles emitted from filament-based printers and fine metal elements from powder-based printers (Rejeski, Zhao and Huang, 2018).

The process to comprehensively evaluate emissions from the diverse range of 3D printers and their environmental implications is complicated and expensive considering the large number of printing variables in additive manufacturing including material types (polymers, metals, ceramics, composites, and biological materials), material forms (filament, liquid and powder), printing processes (from filament extrusion to powder bed fusion to directed energy deposition), indoor environments (industrial facility, labs, offices, and home) and various pre-

possessing and post-processing options (Chua and Leong, 2014; Rejeski, Zhao and Huang, 2018; Stefaniak *et al.*, 2019). As such, in this study, these large number of variables are addressed through the investigation of particle emissions from different 3D printing processes that uses different materials and forms, starting from the pre-processing stage to printing and ending at post-processing, all conducted on-site to understand their effects on their operating environment. Specifically, particle concentration levels are evaluated within the operating environment of users resulting from the operation of six different 3D printers, namely, desktop filament-based MEX, industrial-grade filament-based MEX, metal powder-based PBF, polymer powder-based PBF, metal powder-based DED, and ink-based MJT. Furthermore, comparisons are made against air quality standards with recommendations to minimise users from unnecessary particle exposure.

2. Methods

2.1. On-site measurement of particle emissions from 3D printers

The experiments were conducted in an office and 3D printing laboratories within the Nanyang Technological University in Singapore and Singapore Centre for 3D Printing, respectively. In the office, a desktop MEX 3D printer (Crealiti Ender 3) was investigated as shown in Figure 1(a) using three different types of filaments (i.e., ABS, PLA and polyvinyl alcohol (PVA)) to evaluate their particle emission levels during printing and with measurements on each material repeated three times. The pre- and post-processing stages of MEX printing were unlikely to contribute to emissions due to the use of solid filaments. In order to assess the effectiveness of an enclosure during printing (Kwon *et al.*, 2017), emissions from an industrial-grade MEX printer (Fortus 450mc) in the 3D printing laboratory was also examined, as shown in Figure 1(b).

For PBF, both polymer and metal powder-based printers were investigated. In the former, the

polymer 3D printer considered was the EOX P396 (also known as SLS), while in the latter, the metal 3D printer was the SLM Solutions 280HL (SLM). For DED using metal powder, the DMG LaserTec 65 was adopted. For ink-based MJT 3D printing, the printer was the Optomec 5×system (also known as aerosol jet printer) that uses aerodynamic focusing to deposit electronic inks onto substrates (Goh *et al.*, 2016). For each printer, at least three repeated measurements were conducted. Among the printers adopted in this study, the SLS, DED, and aerosol jet printers were equipped with local exhaust ventilation that can extract internal gases from their printing enclosures, while the SLM had an internal gas circulation system with filtration capabilities. Detailed descriptions of the 3D printer-material combinations, internal gas circulation, main printing parameters, and facility conditions are shown in Table 1.

Particle number concentrations were measured using a combination of particle sizers including the TSI 3910 Nano SMPS (for particles ranging 10-420 nm) and the TSI 3330 optical particle sizer (for particles ranging 0.3-10 µm), as shown in Figure 1. Apart from emission levels during printing, background particle concentration levels were also collected before the start of each printing process. In addition, measurements were taken during the pre-processing of printing materials as well as after printing when the enclosure doors were opened for the removal of printed parts. For the two PBF printers, during the pre-processing stages including ‘sieving powder’, ‘loading powder’ and ‘cleaning powder’, the two particle counters were made mobile to follow operators at a distance of approximately 0.5 m away. On the other hand, during printing, the positions of the particle counters were fixed and carefully chosen to be in the vicinity of the 3D printers with measurement distances as shown in Table 1. The doors to the printing enclosure must be closed and sealed for the industrial-grade MEX, PBF and DED printers during printing. On the contrary, the enclosure can be opened for the MJT printer, allowing particle concentration levels to be measured within the

135 printing enclosure at about ten centimeters away from the jet nozzle. Additional
136 measurements were also collected outside the enclosure when the doors were closed.

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(a) Desktop-grade MEX

(b) Industrial-grade MEX

(c) Metal-based PBF (SLM)

(d) DED

(e) Polymer-based PBF (SLS)

(f) MJT

Figure 1. Experimental setup for (a) desktop-grade material extrusion (MEX), (b) industrial-grade MEX, (c) metal-based powder bed fusion (PBF), (d) directed energy deposition (DED), (e) polymer-based powder bed fusion (PBF), and (f) ink-based material jetting (MJT) 3D printers. Particle number concentration was measured using a combination of TSI 3910 Nano SMPS and TSI 3330 OPS. Selective laser melting (SLM); Selective laser sintering (SLS). The front of each printer is in the X-Z plane, and Y axis points to the back of the printer. The dimensions of each printer can be approximated from their relative sizes to the SMPS in the images (45×23×39 cm).

2.2. Laser imaging method to visualise fumes from a desktop MEX printer

In addition to the measurement of particle concentration levels, laser imaging was also used to visualise particle emissions from the desktop MEX 3D printer, which otherwise would not be visible to the naked eye due to the small sizes of the particles (below one micro-meter). The laser imaging equipment comprised of a laser, optics, and a camera that were carefully positioned around the MEX printer as shown in Figure 2. A laser sheet (cross section: 1×8 cm) was generated by a solid state laser (DM20-527-DH, Photonics Industries International, Inc., USA) with pulse energy of 40 mJ at 1 kHz in addition to a volume optic to illuminate the particle fumes that were formed and diffused from the nozzle as well as surface of the printed object. A camera with 1920×1080 pixels was used to capture the formation and diffusion of the fumes.

Figure 2. Schematics of the laser imaging setup to visualise fumes from a desktop MEX 3D printer.

3. Results and Discussions

3.1. Particle emissions from filament-based 3D printers

For the desktop MEX 3D printer in an office, high concentrations of submicron particles were observed during printing with ABS and PVA filaments. However, there was no increase in particle concentration levels when printing with PLA filaments, as shown in Figure 3(a)-(c). The average number concentration of particles emitted for printing using ABS and PVA was one and two orders of magnitude above background concentration levels, respectively. In terms of particle sizes, PVA emitted particles in the range of 10-700 nm while ABS and PLA printing did not register particles in the range of 0.3-1 μm . On the other hand, for the industrial-grade MEX 3D printer with a sealed enclosure (i.e. Fortus 450mc), there was no observable increase in particle concentration during printing using ABS filaments.

(c) PVA

Figure 3. Nano-size particles measured for the MEX 3D printer by SMPS for (a) acrylonitrile-butadiene-styrene (ABS) filament (b) polylactic acid (PLA) filament and (c) polyvinyl alcohol (PVA) filament. The white dashed lines denote the range of printing.

The fumes emitted from the desktop MEX printer were captured through laser imaging during the printing of a cube using ABS and PVA filaments, as demonstrated in Figure 4. It was observed that emissions were formed and released from the printer nozzle, whose main role is in the melting and extruding of filaments (Ding *et al.*, 2019). Another source of fumes was from the newly deposited layer on the top of the printed cube (i.e. still in molten state). Through the visual aids, emission was most abundant for PVA as compared to ABS, while no visible fumes were captured for PLA. This was also in agreement with the trends observed from particle concentration measurements in Figure 3.

(a) ABS

(b) PVA

Figure 4. Laser imaging to capture fumes that were formed and diffused from the nozzle of a desktop MEX printer and from newly printed layers during the printing of a cube for (a) ABS with nozzle temperature at 260°C, and (b) PVA at 220°C. Two videos (ABS-260°C-printing and PVA-220°C-printing) are accessible online as supporting information.

3.2. Particle emissions from powder- and ink-based 3D printers

During the operation of PBF 3D printers (i.e. SLM and SLS) with air-sealed enclosures, there was no increase in submicron or ultrafine particles above background levels outside their enclosures. Graff *et al.* also reported that the generation of nano-size particles smaller than 300 nm was very limited in the external environment for SLM (Graff *et al.*, 2017). However, caution should be taken in the pre-processing and handling of metal or polymer powder. Specifically, noticeable traces of micron-size particles (1-10 µm) were observed during the powder sieving and loading processes for the SLM and SLS printers, respectively, as shown in Figure 5(a)-(b). Micron-size particles were also observed during the post-processing stage of ‘cleaning powder’, where operators brushed remaining powder inside the printer enclosure after printing for SLS. In fact, powder that was dispersed into the air during the pre- and post-processing stages eventually settled across surfaces over the lab (e.g. on furniture and the floor), which was particularly evident with polymer powder.

Another observation was the difference in powder sizes between those measured (1-10 µm) during pre-processing and the dimensions provided by the powder manufacturer (e.g. 10-45 µm). A possible reason is that virgin powder can contain a small proportion of particles below 10 µm (Damanhuri *et al.*, 2019), which are easily airborne (Xie *et al.*, 2009). For post-processing, there was insignificant increase in particle concentration levels when doors to the enclosures of both SLM and SLS printers were opened ‘after printing’. This was partly due to their internal exhaust systems that had removed air-borne particles during printing. After the printed parts were removed from the enclosure, leftover powder on part surfaces were cleaned

via compressed air in a sealed cleaning facility with no observable increase in particle concentration levels in the external environment.

For DED, due to the enclosed system with air extraction, there was no significant increase in particle concentration from background levels outside the printer during operation. As for MJT, the number concentration of particles between 10 to 420 nm increased two to five times when sampling was performed inside the printer enclosure during printing, as demonstrated in Figure 5(c). However, outside the printer enclosure with doors closed, there was no increase in particle concentration levels, which can partially be attributed to the internal air extraction system within the enclosure.

As a recommendation, operators should not open enclosure doors immediately after printing and to leave sufficient time for the printer to extract particle-laden air out of the enclosure. Additionally, personal protective equipment such as masks should be worn at all times during the printing, pre- and post-processing stages to minimise exposure to micron-size particles (Chen *et al.*, 2017; Graff *et al.*, 2017). To fully isolate operators from powder exposure, automated facilities for sieving and powder loading should be developed and adopted across the wide spectrum of powder-based 3D printers. It is worth noting that the exploration of nanoparticle exposure in 3D printing will need to be extended to concrete printing using powder with nanoclay and nucleation seeds additives (Panda, Mohamed and Tan, 2019; Panda *et al.*, 2020).

(a) Metal-based PBF (SLM)

(b) Polymer-based PBF (SLS)

(c) MJT

Figure 5. Micron-size particles measured for (a) metal-based powder bed fusion (PBF), and (b) polymer-based PBF. (c) Nano-sized particles measured for material jetting (MJT) 3D printer. Note that ‘printing range 1’ and ‘printing range 2’ for MJT denote sampling inside and outside the printing enclosure, respectively.

3.3. Analysis of on-site particle concentration levels

In Figure 6(a) and (c), the total number concentration of ABS (statistical median: 3.3×10^4 #/cm³) or PVA (statistical median: 3.0×10^5 #/cm³) during printing approached or significantly exceeded the lightweight nanoparticle reference value of 4×10^4 #/cm³, respectively (Van

Broekhuizen *et al.*, 2012). In order to further analyse particle concentration levels from the emissions, particle mass was calculated using the TSI multi-instrument manager software with corresponding bulk density of powder or filament used by the respective printers. This was then used to compare with the National Ambient Air Quality Standards (NAAQS) by the U.S. Environmental Protection Agency (EPA) for PM_{2.5} or PM₁₀, both averaged over 24-hours (Esworthy, 2013). These standards were developed for outdoor air quality, but they are also applicable for indoor air contaminant levels (Charles *et al.*, 2005; Abdul-Wahab *et al.*, 2015). To the best of the author's knowledge, there is currently no available industrial standard for short-term exposures to 3D printing related powder and hence, general inhalable dust standard was adopted here. It was more reasonable to evaluate particle emission levels of MEX 3D printers using PM_{2.5} (total mass concentration below 2.5 µm) considering the health risks associated with fine particles. On the other hand, PM₁₀ (total mass concentration below 10 µm) was used to assess exposure levels of the PBF printers for which the particles were in the micron-size from the pre- and post-processing stages.

In Figure 6(a) and (c), PM_{2.5} levels from the desktop MEX printer using ABS (statistical median: 12.5 µg/m³) approached the unhealthy limit of 35 µg/m³ while PVA (statistical median: 215 µg/m³) significantly exceeded the very unhealthy limit of 150 µg/m³ defined by NAAQS. Stricter industrial standards will need to be developed considering the elevated health risks associated with ultrafine particles. For SLM or SLS, PM₁₀ levels during sieving or powder loading significantly exceeded the NAAQS PM₁₀ limit of 150 µg/m³ by 10-50 times, as shown in Figure 6(b).

(a) Desktop MEX

(b) PBF

(c) Summary

Figure 6. Time-resolved total particle number and mass concentrations (a) from 10 nm to 2.5 µm for the desktop MEX printer using three materials, (b) from 10 nm to 10 µm for metal-based PBF and polymer-based PBF. (c) Statistical results for repeated tests. Boxes indicate the inter-quartile range with median (50%) in between. The top and bottom of whiskers represent 5th and 95th percentile. ^aNAAQS PM_{2.5} standard limit. ^bNAAQS PM₁₀ standard limit. Acrylonitrile-butadiene-styrene (ABS); Polyvinyl alcohol (PVA); Polylactic acid (PLA).

4. Conclusions

This study comprehensively investigated particle emissions from a wide spectrum of 3D printing techniques and their resulting impact on number or mass concentration levels in the operating environment of users. The printers include desktop and industrial MEX 3D printers, PBF, DED, and MJT. Ultrafine particles form the bulk of emissions from MEX printers, while micron-sized particles were observed during the pre-processing of PBF printers (i.e.

SLM and SLS). For desktop MEX, the ultrafine particles diffused into the air from the printer nozzle and newly deposited layers. When printing with ABS and PLA, PM_{2.5} mass concentrations and total number concentrations were below recommended thresholds, whereas for PVA, both mass and number concentration limits were violated. For the industrial MEX with enclosure and air extraction, no significant increase in particle concentration levels was observed outside the printer.

For powder-based 3D printers (SLM, SLS and DED) and ink-based MJT printer with sealed enclosures and internal air extraction, particle concentration levels outside the printers remained relatively constant throughout the duration of printing. However, for powder-based 3D printers, operators can be exposed to polymer or metal powder during pre-processing stages of sieving, loading and cleaning, with particle concentration levels significantly exceeding the PM₁₀ limit by 10-50 times. Developing and adopting automatic powder-handling equipment is hence needed to achieve ‘closed powder cycle’ or ‘powder-free handling’ operations. Internal gas ventilation, mechanical ventilation for working stations, and personal protective mask are also recommended during the powder handling and operation of powder-based printers. This study serves as a preliminary investigation into possible exposures to particle emissions from different 3D printing processes, which highlights the need for more studies to be conducted to ensure occupational safety and for intervention measures.

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