TECHNICAL BRIEF

Metal Composition of Particles Emitted from 3D Printing

Introduction

Material extrusion, or fused filament fabrication (FFF), 3D printers, have been widely used in various indoor environments, but their unintended particle emissions could pose a health hazard to users and occupants. Chemical Insights Research Institute (CIRI) of UL Research Institutes has conducted a multi-year research initiative on 3D printer emissions and has found that 3D printing emits high levels of ultrafine particles (UFPs), smaller than 100 nm.[1] When inhaled, small particles tend to penetrate deep into the lungs and may enter the bloodstream, which is associated with an increased risk of respiratory and cardiovascular diseases. CIRI's study has shown that exposure to 3D print-emitted particles induces toxic responses according to in vivo, in vitro, and acellular assays.[2] Previous research has focused on particle emission characterizations. However, metals are an important component of the emissions associated with adverse health impacts, which are not well understood. In particular, metal-based additives are commonly used in plastics, and metal powder is an additive in emerging composite filament materials. These metals could be released during printing, increasing the health risks associated with exposure to 3D printing emissions.

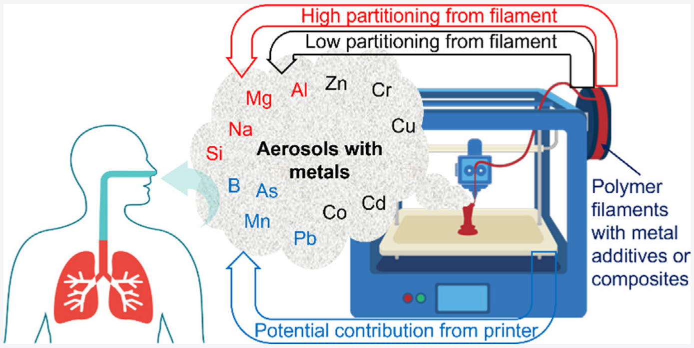

Figure 1: Graphic abstract of the published paper

This study analyzed the metal compositions of various raw filament materials and the particles emitted from using these filaments. Both particle and filament samples were analyzed using inductively coupled plasma-mass spectrometry (ICP-MS), and the concentration of each detected metal was calculated. Based on the measurement, the partitioning of metal from filament to particle was estimated, and the source of the metals was determined. Finally, the concentrations of potential exposure to 3D print-emitted particles and metals were estimated using an indoor exposure model and then compared to existing indoor air quality and health-based standard and regulation reference levels. This study has been published in Science of the Total Environment.[3]

Key Findings

METAL COMPOSITIONS

Chemical analysis showed that the metals specified in the filament formula were detected in the raw filaments. For example, copper and tin were detected with the highest concentrations from the bronze-added polylactic acid (PLA) composite filaments. The metal components of stainless steel (iron, chromium, nickel, and copper) were all detected with high concentrations from the metal composite filament. The mass fraction of metals (including metalloids) in polymer filaments was up to 1% by weight, while the metal composite filaments could contain up to 96% metals and metalloids by weight. In addition, unspecified metals, including sodium, magnesium, aluminum, potassium, and silicon, were also detected from the filaments, which were likely associated with additives in the materials.

Analysis of collected emission particle samples showed that the commonly detected metals with high levels included silicon, sodium, magnesium, calcium, and boron. Silicon was the highest detected metal of all particle samples, although not from all filament samples. In addition, boron was only detected in one filament but showed in nearly all particle samples. These results indicate that besides the filament additives, there are other sources of metals in particles emitted from operating 3D printers.

SOURCES OF METALS IN PARTICLES

Among the metals detected from both filaments and particles, silicon had the highest partition ratios, followed by sodium, magnesium, and aluminum. Most of these metals were not listed in the filament material safety data sheet, which indicates that unspecified metals associated with additive compounds were more likely to be transferred from filaments to particles. However, there were metals with high concentrations in filaments which were not detected in emitted particles. Specifically, the metal components associated with the metal powder in the composite filaments were found in low concentrations or not detected in particles. This indicates that the metal powder in filament materials was not likely to transfer from filaments to airborne particles. On the other hand, some metals detected in particles were not found in corresponding raw filaments. These metals, including boron, manganese, arsenic, and lead, could be attributed to a printer source. Calculations showed that some printers could contribute to over 80% of the detected metals in particles, depending on the brand.

ESTIMATED EXPOSURE TO METALS

Heavy metals that are potentially toxic to humans, such as cadmium, chromium, arsenic, selenium, cobalt, strontium, and lead, were detected in this study. Exposure to these toxic metals could increase health risks associated with exposure to 3D printing particle emissions. Exposure concentrations to the commonly detected heavy metals were estimated for residential, office, and school scenarios. Overall, the yields of heavy metals were low, ranging from 0.02 to 6 ng metals per gram of filament used. Therefore, exposure levels to these heavy metals in the residential scenario were low compared to those reported of indoor and outdoor fine particulate matter ($PM_{2.5}$) studies. In addition, all estimated heavy metal exposure levels were below the regulatory limits. It should be noted that metals only accounted for a small fraction of the total emitted particle mass; therefore, low exposure to metals does not necessarily mean low exposure to $PM_{2.5}$; in fact, some print conditions resulted in higher $PM_{2.5}$ exposure concentrations than the national ambient air quality standard.

Conclusions and Future Work

In this study, we quantified metal levels in 3D print-emitted particles and filaments. In addition, heavy metals associated with health risks were also detected in relatively lower concentrations. Both the filament and the printer can be sources of metals in the emitted particles. Metals associated with unspecified additive compounds seemed more likely to be released in particles, while metals associated with specified metal powder were unlikely to be released into airborne particles. In general, exposure to heavy metals in particles was low for typical indoor conditions, while exposure risks could increase for long-term operation or use in low-ventilated environments. In addition, exposure to overall particle emissions could exceed particulate matter standards. Therefore, best practices for safe operation should be used during 3D printing, especially in confined and poorly ventilated spaces.

CIRI will continue characterizing the emission properties associated with 3D printing to understand the potential health impacts of exposure to emissions. In addition, CIRI will evaluate the efficacy of various exposure mitigation strategies, including engineering control methods, for reducing exposure and potential health concerns.

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