Comparative study of selected indoor concentration from selective laser sintering process using virgin and recycled polyamide nylon (PA12)

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Abstract. Additive manufacturing (AM) stands out as one of the promising technologies that have huge potential towards manufacturing industry. The study on additive manufacturing impact on the environment and occupational exposure are attracting growing attention recently. However, most of the researcher focus on desktop and fused deposition modelling type and less attention given to the industrial type of AM. Usually, during the selective laser sintering process, recycle powder will be used again to reduce cost and waste. This article compares the PM 2.5, carbon dioxide (CO2) and total volatile organic compound (TVOC) concentration between virgin and recycled powder using polyamide-nylon (PA12) towards indoor concentration. Four phases of sampling involve during air sampling accordingly to the Industry Code of Practice on Indoor Air Quality 2010 by DOSH Malaysia. It was found that PM 2.5 and CO2 concentration are mainly generated during the pre-printing process. The recycle powder tended to appear higher compared to virgin powder in terms of PM 2.5, and CO2. The peak value of PM 2.5 is 1452 µg/m³ and CO2 is 1218 ppm are obtained during the pre-printing process during 8 hours of sampling. TVOC concentration from recycling powder is slightly higher during the post-printing phase where confirm the influence of the powder cake and PA12 temperature from the printing process. In summary, this work proves that elective laser sintering (SLS) machine operators are exposed to a significant amount of exposure during the SLS printing process. Mitigation strategies and personal protective equipment are suggested to reduce occupational exposure.
1. Introduction
Additive manufacturing (AM) technology introduced by Charles Hull in 1986 has grown significantly in the last three decades. In contrast to subtractive manufacturing, AM introduced an automated manufacturing technology that can build a prototype or product from CAD model data [1]. AM uses raw materials efficiently, unlike traditional manufacturing where waste materials are the main concern. This technology widely uses in various industries including aerospace, manufacturing, medical devices, and construction [1]. There is various type of AM technology and process present worldwide as illustrated in Figure 1. AM technology offers several benefits including less material waste, energy efficiency, time, and finishing [2]. It is expected that the growth of AM and 3D printing market from USD 5.31 Billion to USD 21.5 billion in 2025 [3].

Exposure from AM process towards indoor air quality and health address huge concern recently. Several researchers conduct an aerosol and chemical concentration assessment towards fused deposition modelling (FDM) type [4]–[8]. However, the study on emission from the selective laser sintering (SLS) 3D printing process still limited. Only Pal Graff et al., in 2017 investigates the exposure from SLS process using metal powder [9]. SLS use polymer or metal powder to build a prototype. In contrast to the other approaches, SLS does not require any object to support during the sintering process. SLS using laser power to sintered powder to become the product. The only powder which heated by the laser will crystallize, and others remain and turn to recycle powder which can be used again [10], [11]. Polyamide powder is typical material use in SLS printing process. Polyamide like nylons is semi-crystalline polymers that have high strength, fatigue resistance, high thermal stability and excellent surface resolution [11]. According to Bours et al., (2017), the industrial scale of AM likewise SLS give more impact to the occupational exposure compare to the desktop scale of AM [12]. Chemical concentration and particulate matter released from the AM process could affect the operators and surrounding air quality [13], [14]. Respirable dust such as PM 2.5 and total volatile organic compound (TVOC) may penetrate the human respiratory system and influence to the human and workers health [15], [16]. Therefore, this paper compares the exposure from SLS printing process using virgin and recycle polyamide- nylon (PA12) powder at an indoor environment. Several indoor concentration parameters selected in this study which could impact the indoor air quality and SLS operator’s health.

Figure 1: Additive manufacturing technology and process [17]–[19].
2. Methodology

(SLS) brand Farsoon model SS402P located at SLS Laboratory FTKMP Universiti Teknikal Malaysia Melaka is used in this experiment. The SLS machine has an external dimension size of 2660mm x 1540mm x 2150mm and weight of 3000 kg. The maximum build product in the SLS chamber is 400mm x 400mm x 450mm. CO$_2$ is used as a laser with 100W power while scanning speed is 12.7m/s. The laser wavelength is 0.3mm and 0.1mm thickness of powder layer for every rotating roller.

PA12 powder is collected from well-known powder supplier with bulk the density 0.4 g/cm$^3$, density of part 0.95 g/cm$^3$, melting point 183$^\circ$C and the powder is in white. Meanwhile, recycle PA12 powder was collected from the previous SLS printing process where have been heated at 193 $^\circ$C laser temperature, also from the same brand and properties.

Calibration block (143mm x 143 mm x 23mm) by manufacturer set to be print to investigates the concentration release from SLS process [13] as depicted in Figure 2 [20], [21]. The SLS laboratory is controlled by an air conditioning system and set to be 20 $^\circ$C with relative humidity around 60%. The sampling strategies such several sampling points, sample position, sampling period and sampling technique accordingly to Industry Code of Practice on Indoor Air Quality 2010, Department of Occupational Safety and Health (DOSH) Malaysia [22]. The environmental emission monitoring from SLS is divided into four phases, where a) background data; b) pre-processing (powder mixing), c) processing (SLS printing), and d) post-processing (powder cake break). Real-time monitoring was used to measure respirable particulate matter (PM2.5), the TVOC and CO$_2$ [23], [24]. The interval times for data measurement were 5 minutes. There are two rooms involve in this project with a dimension of 6 m length x 4 m width x 3 m height where 24 m$^2$ involves as depicted in Figure 3. Respirable particulate matter (PM2.5) in indoor air measured using Dustrak (DRX Aerosol monitor model8533, USA, TSI Inc.). Meanwhile, TVOC’s concentration was quantified using the ppbRAE monitor (ppbRAE 3000, USA, RAE System Inc. Meanwhile, CO$_2$ used Environmental monitor model EVM 7, the USA by 3M. The activity and task for every activity involve during SLS printing process are presented in Figure 4. Four different phases involve in whole SLS printing process where:

i. Background data (0 – 30 minutes)
ii. Pre-printing process (30 - 140 minutes) (Figure 4 (A), (B), (C) and (D))
iii. SLS printing process (140 - 360 minutes) Figure 4 (E)
iv. Post printing (360 – 480 minutes) Figure 4 (F), (G) and (H)

![Figure 2: Calibration block used for SLS printing process.](image-url)
3. Result and Discussion
The indoor sampling of PM 2.5, CO₂ and TVOC are presented hereafter. Figure 5 illustrates the indoor concentration between virgin and recycled powder. Background data shows an average of 21.8 µg/m³ of PM 2.5 concentration. However, a pre-printing process where powder activities are mainly involved shows the highest value of PM 2.5 at 1452 µg/m³. Recycle powder demonstrates a higher amount of PM 2.5 through the SLS process. These results are in line with those previous study where Pal Graff et al.,
in his paper found that recycle powder tended to be smaller from virgin and new powder [9]. It is observed that PM 2.5 relatively shows steady-state trend during SLS printing process due to SLS machine are fully closed. Contrary to the expectations, this study shows that post-printing activities did not influence much in PM 2.5 generation in indoor concentration.

CO₂ concentration as depicted in Figure 6 seems to be consistent with PM 2.5 generation during the pre-printing process. CO₂ generation significantly increases for both virgin and recycled powder during this phase and above DOSH Malaysia recommendation limit [22], [25]. However, the generation of CO₂ of recycles powder are much higher compared to the virgin powder at post-printing phase at 995 ppm.

Surprisingly, TVOC concentration during SLS printing process shows the highest during the post-printing process. Recycle powder significantly emit higher TVOC compare to the virgin powder. Pre-printing and SLS printing process did not show any huge difference in values. These results are consistent with the data obtained from the previous study that TVOC concentration is influenced by the temperature of the material during the SLS printing process [14], [23], [26]. Table 1 summarises all the data involves during four phases of SLS printing process. Average (avg), minimum (min), maximum (max) and standard deviation of data collected from this experiment.

![Figure 5: PM 2.5 concentration using virgin and recycle powder](image-url)
Figure 6: CO$_2$ concentration from SLS printing process using virgin and recycle powder

Figure 7: TVOC concentration using virgin and recycle powder
Table 1: Summary of data collection at SLS laboratory using virgin and recycle powder

|                  | Background data | Pre-printing (powder preparation) | SLS Printing | Post printing |
|------------------|----------------|-----------------------------------|--------------|--------------|
|                  | 0-30 minutes   | 30-140 minutes                    | 140-360 minutes | 360-480 minutes |
|                  | Virgin | Recycle | Virgin | Recycle | Virgin | Recycle | Virgin | Recycle |
| PM 2.5 (µg/m²)  | Avg    | 21.8    | 47.5  | 523.0   | 706.0  | 39.4    | 45.6  | 45.5    | 94.6     |
|                  | Min    | 15.0    | 37.0  | 158.0   | 221.0  | 26.0    | 21.0  | 31.0    | 36.0     |
|                  | Max    | 30.0    | 76.0  | 1070.0  | 1452.0 | 128.0   | 332.0 | 62.0    | 469.0    |
|                  | Std.Dev | 6.67    | 15.9  | 253.0   | 312.0  | 18.6    | 45.6  | 7.5     | 108.1    |
| TVOC (ppm)       | Avg    | 0.10    | 0.08  | 0.38    | 0.27   | 0.23    | 0.56  | 0.35    | 1.05     |
|                  | Min    | 0.00    | 0.00  | 0.30    | 0.1    | 0.1     | 0.4   | 0.2     | 0.6      |
|                  | Max    | 0.20    | 0.10  | 0.44    | 0.5    | 0.4     | 0.7   | 0.5     | 0.7      |
|                  | Std.Dev | 0.06    | 0.04  | 0.04    | 0.12   | 0.05    | 0.06  | 0.12    | 0.42     |
| CO₂ (ppm)        | Avg    | 725     | 749   | 954     | 914    | 613     | 577   | 757     | 869      |
|                  | Min    | 712     | 713   | 800     | 577    | 473     | 510   | 651     | 721      |
|                  | Max    | 749     | 851   | 1218    | 1211   | 892     | 758   | 833     | 995      |
|                  | Std.Dev | 13.03   | 52    | 73      | 224    | 118.9   | 58.0  | 52.8    | 74.3     |

4. Conclusion
In this investigation, the aim was to assess indoor concentration during SLS printing process. This study set out to explore the influence of virgin and recycle powder that impacts to the indoor concentration. This study has identified that recycle powder tended to be smaller than virgin powder and exceed the exposure limit by DOSH Malaysia. CO₂ and PM 2.5 generation are mainly exposed during the pre-printing process where powder preparation is being done. TVOC emission meanwhile are influenced by the temperature of powder cake from SLS printing process. This study has found that generally operators and workers are exposed to occupational hazard during SLS printing process. The evidence from this study suggests that efficient mitigation strategies such as ventilation could reduce the impact of powder on indoor air quality. Apart, suitable protective equipment (PPE) is needed to make sure operators and workers occupational exposure is reduced.

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