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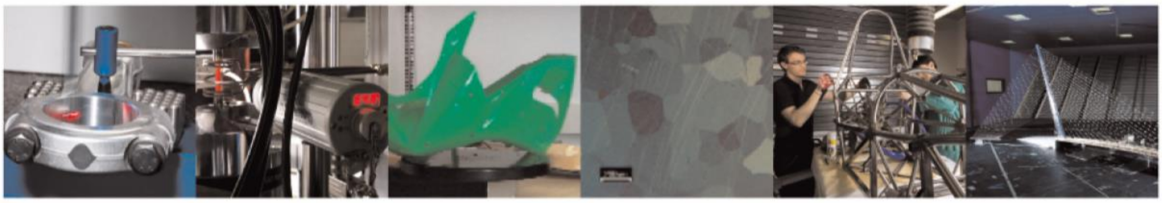

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Assessment of nanoparticle emission in additive manufacturing: Comparing wire and powder laser metal deposition processes

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ABSTRACT

Additive manufacturing (AM), often referred to as 3-D printing, is an emerging technology with a wide range of industrial applications and process typologies. Although the release of metal nanoparticles as by-products could occur, occupational exposure limits and cogent safety standards are not currently available due to the novelty of the technology. To support the definition of benchmarks, this study aims to provide a preliminary comparison between the nanoparticle release patterns of laser metal deposition, adopting different feedstocks, namely, metal wire and metal powder. The monitored device is a university research setup, and the work presents the results of two different processes with AISI 316L as a feedstock in powder and wired form, respectively. The monitoring confirmed the outcomes of previous studies, with a high release of nanoparticles from the powder head on the device (average 138,713 n/cm^3 during printing, with maximum values exceeding 10^6 n/cm^3). Moreover, the results show a significant concentration of nanoparticles with a wire head during the printing phase (average release of 628,156 n/cm^3 with a maximum of 1,114,987 n/cm^3) and during pauses (average of 32,633 n/cm^3 and a maximum of 733,779 n/cm^3). The monitored values during pauses are particularly relevant since no personal protection equipment was used in the wire processes and the operators could access the printing room during pauses for device interventions, thus being exposed to significant nanoparticle concentrations. This study presents a preliminary evaluation of the potential exposure during laser metal deposition while implementing different technologies and provides evidence for defining effective operational safety procedures for the operators.

Keywords: Additive manufacturing; Exposure assessment; Indoor air quality; Metal nanoparticle; Occupational health

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INTRODUCTION

Metal additive manufacturing and nanoparticle release

Additive manufacturing (AM) is a class of novel processes enabling the production of complex objects directly from a three-dimensional (3-D) model by depositing material layer by layer (ISO Standard 2021). The adoption of a metal feedstock in powder or wire form and the application of a laser or an electron beam to heat and melt the metallic feedstock makes it possible to manufacture components for several industrial sectors, from the automotive to biomedical and aerospace sectors (Vafadar et al. 2021). The variety of additive manufacturing devices and range of feedstock materials are continuously expanding, and the use of AM continues to grow. Consequently, the evaluation of potential risks associated with AM processes is fragmented, as no specific guidelines for standardized use are available. Recent toxicological studies (Vallabani et al. 2022) and in-the-field exposure monitoring (Gomes et al. 2019; Jensen et al. 2020; Pernetti et al. 2022) identified nanoparticle (NP) release of AM with metal as a potential risk factor for the operators (Ljunggren et al. 2019; Sousa et al. 2019). Nevertheless, only few studies have reported in-the-field measurement of emissions during AM operations, especially for the more innovative variants that have only recently experienced widespread use.

Laser Metal Deposition processes

Among AM innovative variants, laser metal deposition (LMD) processes can adopt different metal alloys as feedstock powders or wire (Ahn 2021). Powder LMD has been extensively studied because its predecessor is the laser cladding process, which has been in widespread industrial use since the 1960s. However, LMD processes utilizing wire as a feedstock are a more recent innovation that owe their success to new coaxial deposition heads, which improved the efficiency of the process (Li et al. 2022). The advantages of using wire as a feedstock include high deposition rates, ease of storage, zero material waste, lower material costs, and fewer safety hazards (e.g., elimination of handling of combustible dust) associated with the use of metal powders. Because the

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use of metal wire feedstock eliminates risks associated with the handling of combustible dust and potential exposure to powders, exposure hazards associated with the use of metal wire may often be unforeseen. Although previous studies have demonstrated the release of NPs in powder LMD processes (Bau et al. 2020), there is limited evidence of NP generation when using metal wire as an LMD feedstock. This study aims to provide preliminary data for comparing NP release during the powder and wire LMD processes and to propose considerations for including NP safety in risk management protocols for LMD operators.

METHODS

Description of AM technology and experiments

LMD processes work through the deposition of a metal feedstock that is contemporaneously melted by a laser energy beam according to the design inputs. The monitoring campaign involves two tubular sample printing sessions, adopting the two deposition configurations. The first experiment deals with the powder deposition technology, while the second experiment exploits the wire deposition configuration. In the former experiment, a powder with a particle size ranging from 45–105 μm is fed with a mass flow rate of 9 g/min and melted with a laser power of 1 kW. In the latter experiment, a wire with a diameter of 1 mm is fed at a speed of 1250 mm/min and melted with a laser power varying between 1.25 and 1.5 kW. The robot’s travel speed is 600 mm/min and 1200 mm/min for the powder and wire experiments, respectively. Both powder and wire are made of stainless-steel alloy (AISI 316L), with the nominal chemical composition including chromium (16–18%), nickel (10–14%), molybdenum (2–3%), manganese (2%), and silica (1%) as the main metals declared in the safety sheet.

The monitored machine is an experimental setup used for research on process optimization in Politecnico di Milano, a polytechnic university located in Milan, Italy. It is an eight-axis system composed of an anthropomorphic six-axis robotic arm and a two-axis roto-tilting table to produce 3-D free-form elements. At the end of the mechanical arm, two different deposition heads can be

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installed: a powder head and a wire head. The manufacturing process occurs in a closed printing box (64 m^3) with an interlocked access door to provide protection against the laser beam, in accordance with standard CEI EN 60825-4 (IEC 2006). The machine utilizes a fiber laser source to melt the powder or the wire filler material for the AM process. The source generates a laser beam with a wavelength of 1070 nm and 3 kW of maximum power. The box is mechanically ventilated with a flow rate of 21 m^3/min, ensuring a complete air change every three minutes, while fumes, vapors, and metallic particulates are suctioned and filtered before being released outside the box.

Monitoring approach

The monitoring campaign focused on the measurement of real-time nanoparticle concentrations released during the powder and wire processes within the LMD box. The monitoring was performed using a Miniature Diffusion Size Classifier (DiSCMini – TESTO), based on the measurement of the induced unipolar charging of the particles flowing through two subsequent electrometer stages. The imparted charge on the particles is approximately proportional to the particle diameter and it is measured with two electrometers coupled in series with a diffusion stage and a filter that select particles per size. This enabled quantification of the particle concentration in the sampled air (n/cm^3, number of particles per air sample volume, measurement range in the order of 10^3 - 10^6 n/cm^3) and the average particle size (nm) within the range of 10–300 nm (Fierz et al. 2011). The DiSCMini carries out a sampling per second, directly providing the NP number and the average size for each measurement.

For the purposes of this study, the powder and wire LMD tests are divided in different phases:

- *Warmup (operator in the build room)*: preliminary activities for launching the build job, including charging of the feedstock and device general settings (Laser OFF).
- *Printing (operator out of the build room)*: when the laser is turned ON and LMD is ongoing.

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- *Pause (operator in the build room)*: time intervals with the laser off for interventions by the operator (Laser OFF).
- *Cleaning (operator in the build room)*: removal of the built object, cleaning of the printing plate with brushes, and vacuuming to remove small quantities of powder deposited in the mechanical gaps (Laser OFF).

The feedstock adopted influences the workflow, and in particular no cleaning phase is required for wire LMD processes.

RESULTS

The monitoring sessions took place during October–November 2021 and focused on three sample processes representing the usual operation of the device: one adopting powder (LMD-Powder) and two adopting wire (LMD-Wire).

The boxplot in Figure 1 presents an overview of the monitoring results of each phase. The box represents the particle concentration (Figure 1a and Figure 1b) and size (Figure 1c and Figure 1d), ranging between the 25th and 75th percentiles. The median is highlighted with a horizontal line, and the whiskers indicate the boundaries of the interquartile range multiplied by a factor of 1.5, identifying where the measured parameters are more scattered. For both processes, the average particle concentration during warmup was slightly lower than the background (LMD-Powder 1% and LMD-Wire 1.2%, see also Table S2), meaning that no nanoparticles were either generated or spread during the preliminary operations. Moreover, the cleaning phase of LMD-Powder did not entail a release of nanoparticles, as the average concentration was 15.7% lower than the background, and the peaks did not exceed 11,500 n/cm^3. The printing phase showed a significant generation of NPs for both processes: LMD-Powder had an average concentration of 138,713 n/cm^3, with peaks reaching 2.9 $\cdot 10^6$ n/cm^3, while the release by LMD-Wire was more constant during the laser activation, with an average value of 628,156 n/cm^3 and a maximum value of 1,114,987 n/cm^3. In terms of particle size, LMD-Powder had a larger interquartile range than LMD-Wire (54–

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72 nm and 71–81 nm, respectively), and several measured values exceeded the whiskers (>100 nm). Monitoring during the pauses, when the laser is OFF and the operators may enter the build box, showed a reduced increase with respect to the background for LMD-Powder (+31.7%), with a peak of 109,251 n/cm^3. Meanwhile, a significant concentration was measured for LMD-Wire, whose average was around 10 times higher than the background (32,115 n/cm^3), and there are several peaks exceeding 100,000 n/cm^3, with a maximum of 733,779 n/cm^3. As shown in the supplementary materials (Table S2 and Table S3), the worse production phase in term of particle release is printing, with median values higher by one or two order of magnitude that background ones. Interestingly, the ratio between background and printing median NP levels is particularly remarkable when wire is used, pointing out a 200-fold increase (Table S2). Moreover, a twofold increase in NP levels compared to background is present during the production pause only when wire is used (Table S2). Similar patterns are also shown comparing printing phase and warm-up phase levels (Table S3).

Figure 2 shows the time course of the patterns of particle concentration and size for LMD-powder. It is possible to observe a high release of nanoparticle at the beginning of the printing phase during the deposition of the initial layers, when the concentration exceeded $2.5 \cdot 10^6$ n/cm^3. This peak was also associated with the lowest particle size (<30 nm). After 30 minutes of printing, the release was reduced, and the pattern of concentration was regularly below 500,000 n/cm^3. During the pauses, when the laser is turned off and the operator enters the build box for intervention, there was a rapid drop of the concentration reaching the background value in 30–40 seconds, also corresponding to an increase in particle size (+20%). During the cleaning phase, no significant release events could be observed.

The monitoring also revealed a significant release of nanoparticles during the printing phase of LMD-Wire (Figure 3). The pattern was characterized by a rapid increase when the laser was activated, corresponding to a strong reduction in particle size (-72% from 76 nm towards 21 nm in job 1 and from 80 nm towards 22 nm in job 2). The size of the particles increased after the initial

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layers and was in the range of 60–110 nm for both processes. In printing job 1, the pattern of concentration indicated a slow regular increase during the second half of the process, reaching the highest value (1,114,987 n/cm^3) when the printing was concluded. For printing job 2, there was a correspondence between power reduction (-50 W corresponding to points b in Figure 3) and a decrease in concentration. For both processes, the concentration of particles decreased sharply when the laser was turned off, with values constantly below 20,000 n/cm^3 after a time interval of 1’30’’ after the end of build job 1 and 3’30’’ after build job 2. Nevertheless, a concentration higher than 100,000 n/cm^3 was observed from 30’’ to 1’53’’ after the laser deactivation for LMD-Wire. At these time intervals, the operators enter the printing box for maintenance procedures.

DISCUSSION

The key finding of this work is the identification of NP release during LMD-Wire processes. In this regard, NP generation is associated with the high laser power applied for melting the feedstock during the printing phase. In fact, the monitored data highlighted a positive trend between laser power and NP release. This can be deduced both by analyzing the LMD-Wire results (Figure 3), where a reduction in laser power is associated with a decrease in NP concentration, and by comparing the release of the two processes: LMD-Wire presents an average NP concentration 4.5 times higher than that of LMD-Powder when applying double laser power during the printing phase. In this regard, although DiSCMini can introduce an error rate up to ± 30% in terms of particle number and size, (Todea et al. 2017), the main outcomes of the study can be considered not affected by the precision of the measure. For all the processes, during the deposition of the initial layers, the particle size decreased strongly with respect to the background, meaning that the printing process is associated with the release of NPs with a reduced equivalent diameter. After the initial phase, the average diameter becomes larger due to the aggregation of NPs, as also detected in previous on-site studies (Bau et al. 2020).

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Since there are no standard safety procedures for NPs, during LMD-Wire processes, the operator is accustomed to entering the LMD box when the laser is off without personal protection equipment (PPE) and may be exposed to severe concentration peaks. In fact, LMD-Wire does not require a cleaning phase, and no specific PPE is currently adopted, as no powder is handled by the operator. In LMD-Powder, the operator wears PPE, namely, nitrile disposable gloves, a full-body protective suit, and a full-face respirator mask with aerosol and a class 3 particle filter according to EN 143:2021 (CEN 2021), during warmup and cleaning and when accessing the build room for interventions. It is also worth noting that pauses in the LMD-Wire process (when the operator is allowed to enter the printing box wearing no PPE) had mean NP concentrations of around 32,000 n/cm^3, which is about 11 times higher than the mean background level and exceeds the indoor reference values suggested by IFA (2008) and Seipenbusch (2008). These results are also higher than the values observed in Gomes et al. (2019) that highlighted a release of NPs during laser welding additive manufacturing in comparison to the background values by monitoring the environmental conditions of the operator's control position.

Moreover, the results show that there are no relevant differences in terms of operator exposure between the phases when the laser is turned off, according to the benchmarks available in the literature (Ljunggren et al. 2019; Pernetti et al. 2022).

Considered as a whole, the monitoring results showed several intervals exceeding the ceiling threshold, that is, five times the average values recommended for metal during the working shift, (i.e., 20,000 n/cm^3 for density higher than 6,000 kg/m^3 (Hendrikx and van Broekhuizen 2013; Pernetti et al. 2022)). Accordingly, a safe interval before entering the printing room for the monitored processes would be approximately two minutes after laser deactivation. However, the time needed for a decrease in particle concentration is strongly dependent on the efficiency of the extraction system (Sousa et al. 2021). Thus, to deduce safety intervals, more monitoring results based on different ventilation flow rates are necessary.

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CONCLUSION

Evaluating the exposure to metal NPs related to emerging technologies represents a challenge, requiring abundant monitoring data to define benchmarks and reference values for different processes. This study had several limitations related to dealing with a smaller number of monitored processes and measurement spots, which could undermine the representativeness of the results. Nevertheless, the measured data provide a preliminary overview of the potential exposure of operators during LMD processes, particularly when adopting wire as a feedstock material. The comparability of the NP release for LMD-Powder and LMD-Wire suggests the need to adopt specific design and safety measures in setting up both processes. In general, potential exposure is not critical in terms of average values during working shifts, but operators may be exposed to significant peaks during interventions right after laser deactivation. Therefore, effective ventilation and extraction system with filters for NPs, appropriate PPE for operators, and workflows that manage access within the printing box when the laser is turned off are key aspects to be considered to limit the potential NP exposure of operators.

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None.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, RP, upon reasonable request.

DISCLOSURE STATEMENT

No potential competing interest was reported by the authors.

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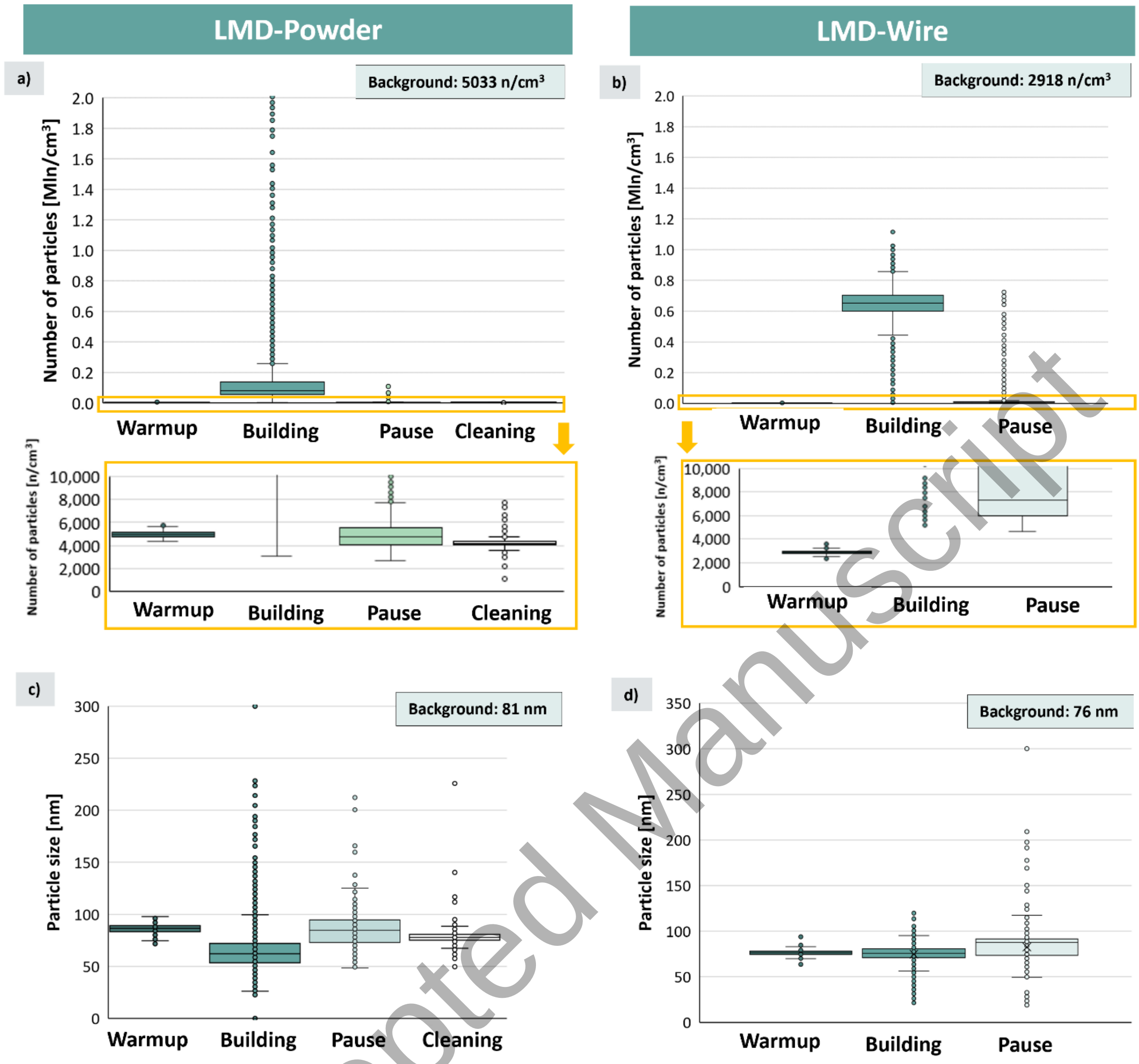

Figure 1. Particle concentration and size for the analyzed process phases. a) Number of particles LMD-Powder, b) Number of particles LMD-Wire, c) Size of particles LMD-Powder, d) Size of particles LMD-Wire.

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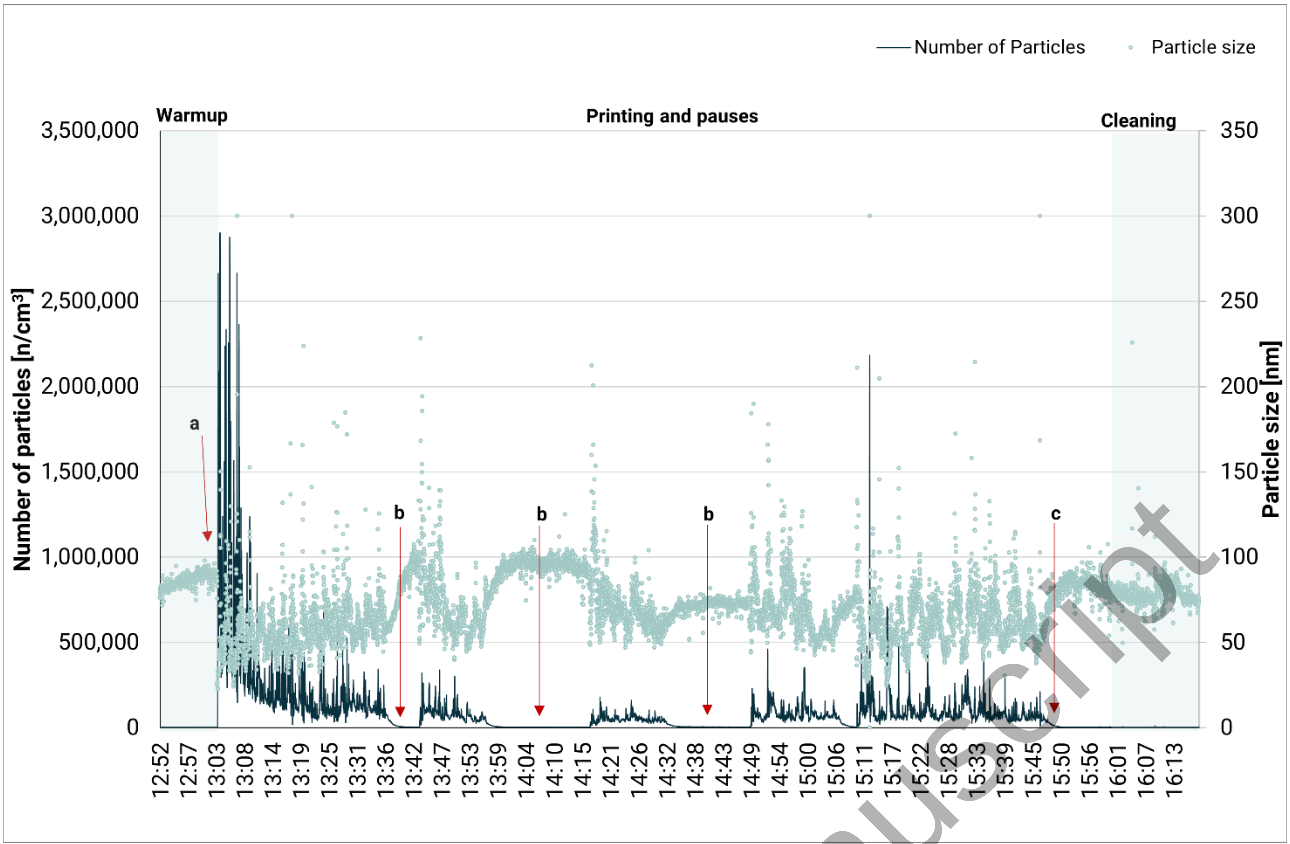

Figure 2. LMD-Powder: Number and size of the particles detected as a function of time and operational phase. a) Laser ON, b) Laser OFF (Pause and intervention of the operator), c) end of printing.

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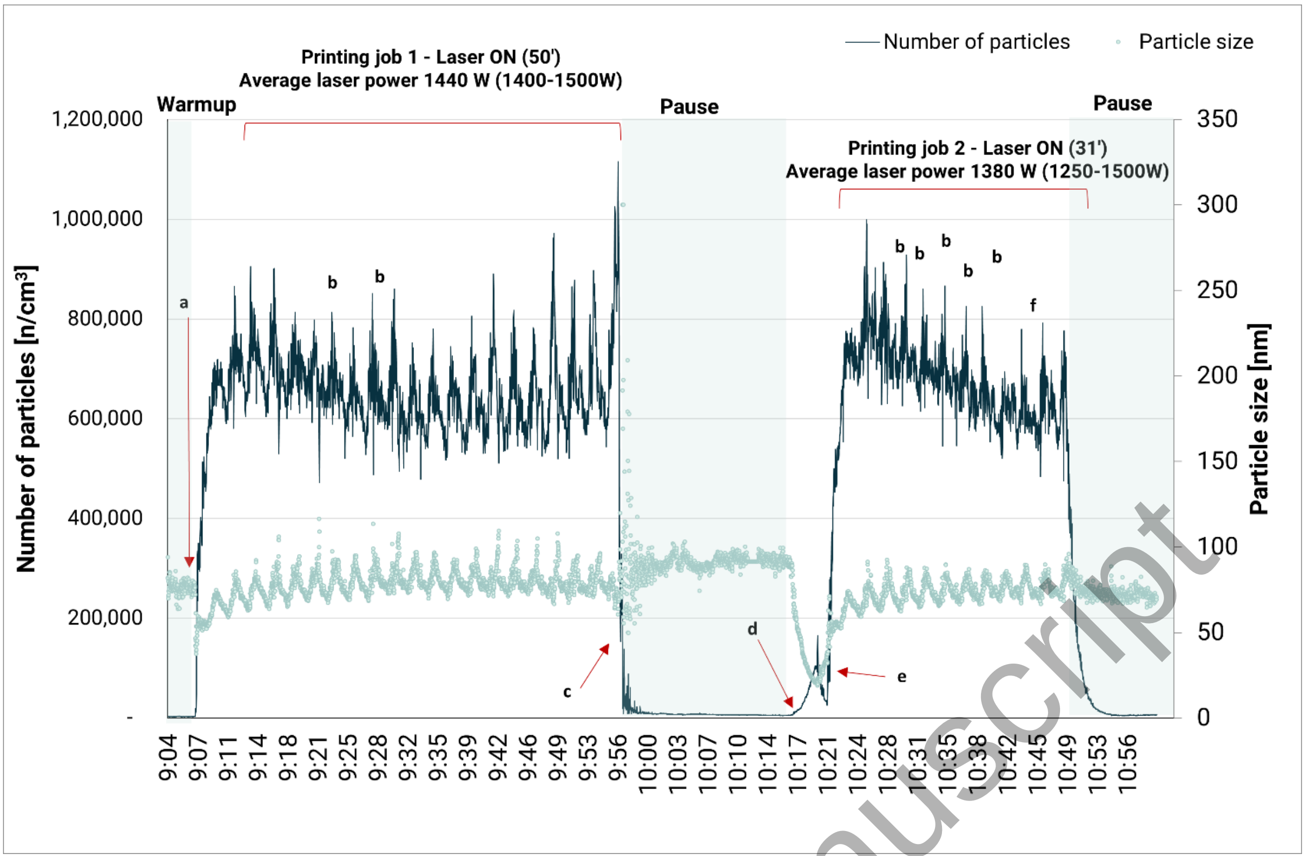

Figure 3. LMD-Wire: Number and size of the particles detected as a function of time and operational phase. a) Laser ON, b) Decrease of laser power (–50W), c) End of printing job 1, d) Laser activation e) Start printing job 2, f) Increase of laser power (+50W).

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TABLE 1. OVERVIEW OF ENVIRONMENTAL MONITORING RESULTS.

	LMD-Powder - Number of particles				LMD-Wire - Number of particles		
	Warmup (Laser OFF)	**Printing (Laser ON)**	**Pause (Laser OFF)**	**Cleaning (Laser OFF)**	**Warmup (Laser OFF)**	**Printing (Laser ON)**	**Pause (Laser OFF)**
Min	4,410	3,089	2,709	1,144	2,350	5,186	4,608
Max	6,114	2,902,042	109,251	11,255	3,635	1,114,987	733,779
Average	4,975	138,713	6,626	4,243	2,890	628,156	32,633
Standard dev.	252	217,568	8,252	500	180	157,232	86,835
Median	4,952	81,235	4,738	4,194	2,879	651,777	7,267
25th percent	4,788	56,370	4,118	4,045	2,787	599,131	5,990
75th percent	5,158	137,544	5,596	4,334	2,967	702,658	10,998
	LMD-Powder - Size of particles				**LMD-Wire - Size of particles**		
	Warmup (Laser OFF)	**Printing (Laser ON)**	**Pause (Laser OFF)**	**Cleaning (Laser OFF)**	**Warmup (Laser OFF)**	**Printing (Laser ON)**	**Pause (Laser OFF)**
Min	72	10	49	50	64	21	19
Max	98	300	212	226	94	120	300
Average	86	64	84	78	76	75	83
Standard dev.	4	18	12	7	4	11	19
Median	86	62	85	78	76	76	88
25th percent	83	54	73	75	75	71	73
75th percent	89	72	95	81	78	81	92

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