

Article

Towards Sustainable Manufacturing: Particle Emissions in Milling Post-Processing of 3D-Printed Titanium Alloy

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Abstract

Electron beam melting (EBM) is an additive manufacturing method that enables the manufacturing of metallic parts. EBM-printed parts require post-processing to meet the surface quality and dimensional accuracy requirements. Machining is one approach that is beneficial for achieving these requirements. However, during machining, particles are emitted and can affect the environment and the operator's health. This study aims to investigate the concentration of particles emitted during the milling of 3D-printed Ti6Al4V alloy produced by EBM. First, the influence of machining speed and cutting fluids, namely flood and minimum quantity lubricant (MQL), on particle emissions was statistically investigated. Then, the standby time required for the operator to safely open the machine door and interact with the machine within the machining area was studied. In this regard, two scenarios were proposed. In the first scenario, the machine door is open immediately after machining, and the operator waits until the particle concentration is acceptable. In the second, the machine door will be opened only when the particle concentration is acceptable. Statistical findings revealed that cutting fluids have a significant impact on particle emissions, exhibiting distinct patterns for both fine and coarse particles. Irrespective of the scenario, MQL results in higher particle concentration peaks and larger particle sizes, and the operator needs a longer standby time before interacting with the machine. For instance, the standby time in MQL is 328% more than that of the flood system. This study provides insight into sustainable manufacturing by taking into account social factors such as worker health and safety.

Keywords: EBM; 3D printing; machining; Ti6Al4V; particle emissions; operator's health; cutting fluids; MQL



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1. Introduction

Additive manufacturing (AM) is a manufacturing process that produces parts by adding material layer by layer. AM is a versatile fabrication technology that allows for the free-form production of complex designs on a variety of materials. Among AM processes, electron beam melting (EBM) is a metal powder-based system and one of the AM technologies that enables producing metallic parts with high design flexibility and customization. Engineering materials such as titanium alloy Ti6Al4V, which can be used in a wide range of applications, including medical, aerospace, and chemical fields, are widely produced by EBM [1]. Even with the capabilities of AM metallic processes, including EBM, there are still some flaws in the surface quality and dimensional accuracy of the produced parts

that necessitate post-processing to meet the final part's functionality [2,3]. The layer-by-layer printing mechanism and the agglomeration of partially melted particles in metal powder-based systems, including EBM, result in surface degradation [4]. Among other metallic AM processes, EBM-printed parts exhibit rougher surfaces [5]. The appearance of the parts is influenced by rougher surfaces, and their performance is diminished [4]. Generally, imperfections in 3D-printed parts may be addressed through pre-processing by optimizing the AM process and through post-processing techniques such as machining. However, concerns related to surface quality, including surface roughness, cannot be solely handled through EBM process optimization due to the inherent complexity of the EBM process [2]. Consequently, post-processing techniques remain a viable option for attaining the desired surface quality [1,6]. Among several post-processing techniques, machining can attain high-dimensional precision and enhanced surface quality, suggesting the need to integrate AM with machining for producing functional parts [1,3]. Surface roughness reduction during post-processing of EBM-printed components made from Ti6Al4V improved the integrity and uniformity of the mechanical properties [6]. Several studies have demonstrated that machining can improve the surface quality of EBM-printed Ti6Al4V alloy [3]. A surface roughness reduction of over 92% was achieved in [7].

During machining, aerosols in the form of solids and liquids are generated. Solid dust arises from the workpiece material and the cutting tool, while oil mist is attributed to the cutting fluid used during machining [8]. Solid particles are associated with both dry and wet machining, whereas liquid particles are correlated with wet machining, which involves the use of a cutting fluid. The emitted particles can contribute to environmental pollution [8] and pose a risk to the operator's health [9].

There is a growing interest in researching particle emission resulting from machining. A comprehensive review of particle emissions during machining is performed by [8]. Ullah et al. [9] studied the influence of machining parameters, including cutting speed, depth of cut, and feed, on the surface texture and integrity, as well as the particle emission during dry milling of TC4 titanium alloy. The results indicated that particle emissions were affected by the cutting parameters. The influence of the analyzed parameters on particle concentration was found to be dependent on aerodynamic diameter, with fine particles (0.5–2.5 μm) exhibiting distinct patterns compared to coarse particles (2.5–10 μm). Rodriguez et al. [10] proposed an evaluation cell to measure particle number and mass concentration, considering dry, MQL, and LCO2 cutting fluids when drilling CFRP/Ti6Al4V composite. Different airflow extraction scenarios were also considered. Among dry, MQL, and LCO2 methods, LCO2 demonstrated an enhanced tool life while avoiding the necessity for standby time for extracting particles. Higher oil mists are produced during MQL usage, necessitating increased standby time. When employing dry cutting with high air flow extraction, no standby time is required for particle evacuation; however, tool life is significantly reduced. Su et al. [11] studied the influence of different cutting fluids on the oil mist concentration of PM10 and PM2.5 during milling Ti6Al4V. The cutting fluids include MQL, electrostatic atomization lubrication (EAL), and nano-fluid EAL (NFEAL). The findings indicated a significant decrease in oil mist concentration for EAL and NFEAL compared to MQL. Khettabi et al. [12] demonstrated that the type of material, cutting speed, and tool geometry influence dust generation in the dry turning process. Kasim et al. [13] statistically examined the impact of cutting speed, feed rate, and cutting fluids on particulate matter (PM2.5) emissions during the milling of Inconel 718 and Aluminum alloy 6061. The cutting fluids were dry, chilled air, MQL, chilled MQL, flood coolant, and pulsating lubricant. Statistical analysis indicated that only fluid type significantly influenced PM2.5 emissions. The results indicated that MQL and chilled MQL produced higher PM2.5 concentrations, whereas the other methods exhibited acceptable levels.

Emitted particles during machining can remain suspended in the air for a long time [9]. Among the reported studies, only [10] studies the needed standby time to open the machine door after machining is finished, considering MQL and LCO2 when drilling CFRP/Ti6Al4V polymer composite. Thus, this research aims to investigate the duration for which the generated particles suspended in air are acceptable. The aforementioned literature demonstrates that particle emissions differ among various materials. A recent report [9] (published in 2025) indicated that titanium and its alloys are overlooked, despite the distinct manner in which chips are generated and particles are emitted from these materials compared to others. Moreover, there is no research conducted on 3D-printed titanium alloy, Ti6Al4V, produced by EBM, in which the material stock is powder. The only research that studied particle emissions using Ti6Al4V was [3], which employed dry milling. Dry machining, especially at high cutting speeds, can greatly increase surface roughness due to the rise in machining temperature [14]. Ti6Al4V alloy is a difficult-to-cut material due to its low thermal conductivity and its tendency to work harden at high temperatures [15]. It is typically machined in wet conditions by employing cutting fluids [1]. The cutting fluid plays a crucial role in reducing the machining temperature by dissipating heat from the machining zone [14]. Moreover, the range of machinable parameters, including cutting speed, can be limited when dry machining Ti6Al4V alloy. It can also lead to high tool wear. Thus, dry milling of Ti6Al4V is not economically feasible, as it also deteriorates the surface quality. Consequently, Ti6Al4V needs to be machined using cutting fluid to enhance machinability and economy. However, the use of fluids during milling can generate substantial emissions of oil particles, which may lead to respiratory and immune system diseases in workers [16]. In this regard, various cooling and lubrication strategies are typically employed to enhance the machinability of Ti6Al4V. It is evident from the previous literature that different cutting fluids have varying effects on particle emissions. The impact of cutting fluids on manufacturing sustainability, with regard to worker health and safety, needs to be taken into account [10]. In this regard, this study examined the influence of two cutting fluids, namely flood and MQL, on the particle emissions when machining Ti6Al4V.

This research aims to investigate the standby time required to open the machine door during machining of EBM-printed Ti6Al4V, considering different cutting fluids: flood and MQL. First, the influence of cutting speed and cutting fluids on particle emissions was statistically evaluated using a factorial design. Particle emissions were measured directly after machining was finished. Then, selected experiments were used to further investigate how long the particles remain suspended after machining is finished. Two scenarios were proposed, depending on when to open the machine door: either open the door and wait until the particle levels are acceptable, or wait and then open the door when the particle levels are acceptable. The aim is to enable the operator to interact safely with the machine within the machining zone. It is achieved by determining the scenario and the associated standby time when considering different cutting fluids, such as flood and MQL, which reduce the harmful effects of particles while also reducing waiting time.

2. Materials and Methods

2.1. Material Production and Characteristics

In this study, the feedstock material of titanium alloy (Ti6Al4V), in the form of powder, was used. The powder has a particle size ranging from 49 to 103 μm , with an average of 71 μm [17]. A scanning electron microscope (SEM) image of the Ti6Al4V powders obtained using a JEOL JCM-6000 Plus (Tokyo, Japan) is given in Figure 1a. The Ti6Al4V sample was 3D printed using the ARCAM A2, an EBM process, from ARCAM AB (Mölndal, Sweden); see Figure 1b. A rectangular sample of Ti6Al4V with dimensions of

35 mm × 35 mm × 10 mm was used in this study, as shown in Figure 1c. Figure 1d shows the surface morphology of the side face of the produced samples. It exhibits a rough surface with issues such as cracks, bare powder, and surface irregularities, suggesting the need for post-processing, such as machining. The chemical composition of the produced Ti6Al4V sample was evaluated using an energy-dispersive X-ray (EDX) from JEOL (JCM 6000 plus, Tokyo, Japan) and reported in Table 1.

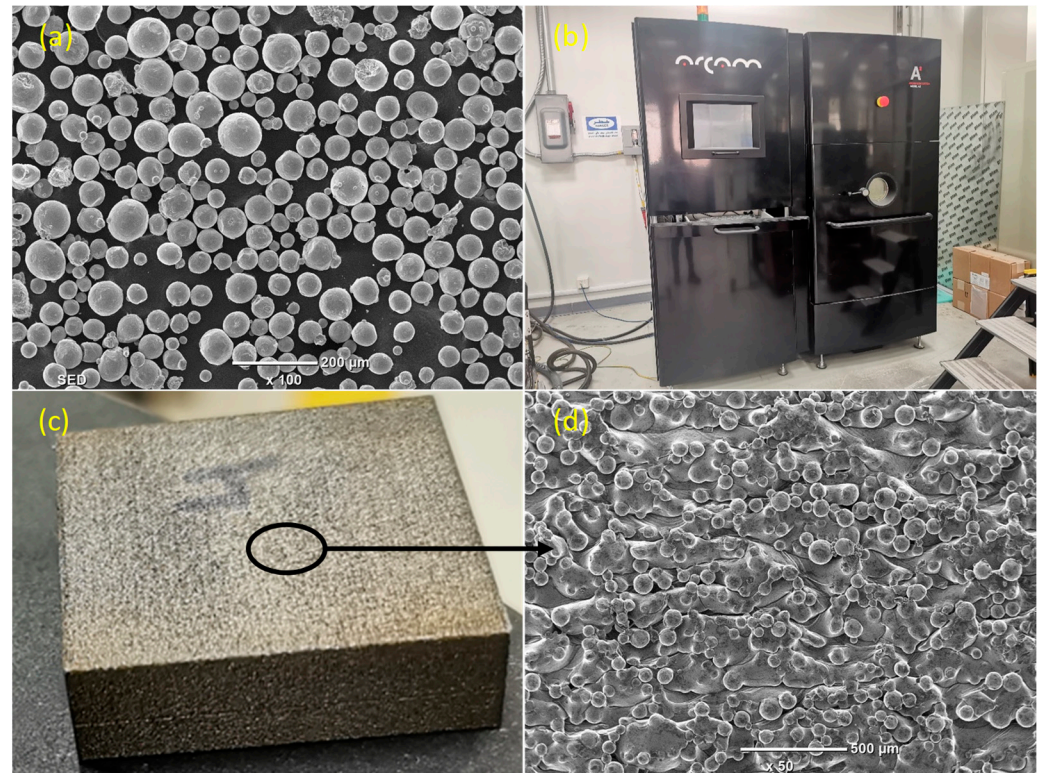


Figure 1. EBM printing and materials properties: (a) Ti6Al4V powder, (b) EBM ARCAM A2 Machine, (c) 3D-printed Ti6Al4V sample, and (d) SEM image showing surface morphology of the EBM-printed Ti6Al4V sample.

Table 1. Chemical composition of the EBM-printed Ti6Al4V sample.

Element	Ti	Al	V	F	K
Wt.%	88.24	7.02	4.28	0.34	0.11

2.2. Machining

The end milling experiments were performed using a three-axis CNC milling machine (DMC 635 V Ecoline, DMG MORI, Geretsried, Germany), as shown in Figure 2a. The milling machine is partly open from the top and has a length of 220 cm, a width of 190 cm, and a height of 230 cm. A tungsten carbide end mill from Snailmon EU, coated with TiAlN and having a 10 mm diameter and four flutes, was used (Figure 2b). Milling post-processing operations were performed at a constant feed (0.015 mm/tooth), depth of cut (0.4 mm), and radial depth (5 mm). Three machining speeds were used—40 m/min, 60 m/min, and 80 m/min—resulting in volumetric material removal rates (MRRs) of 0.152 cm³/min, 0.228 cm³/min, and 0.304 cm³/min, respectively. Two cutting fluids, namely flood and minimum quantity lubricant (MQL) were employed. The flood cooling used an emulsion prepared by mixing water and Fuchs ECOCOOL S-HL oil (Fuchs, Mannheim, Germany) in a 90:10 volume ratio. The emulsion is pumped to the machining zone through nozzles as depicted in Figure 2b. In MQL, sunflower vegetable oil (Alwafa, ZER Group, Gaziantep,

Turkey) was used at a flow rate of 180 mL/hr and a pressure of 6 bar. The setup of the MQL system is shown in Figure 2b.

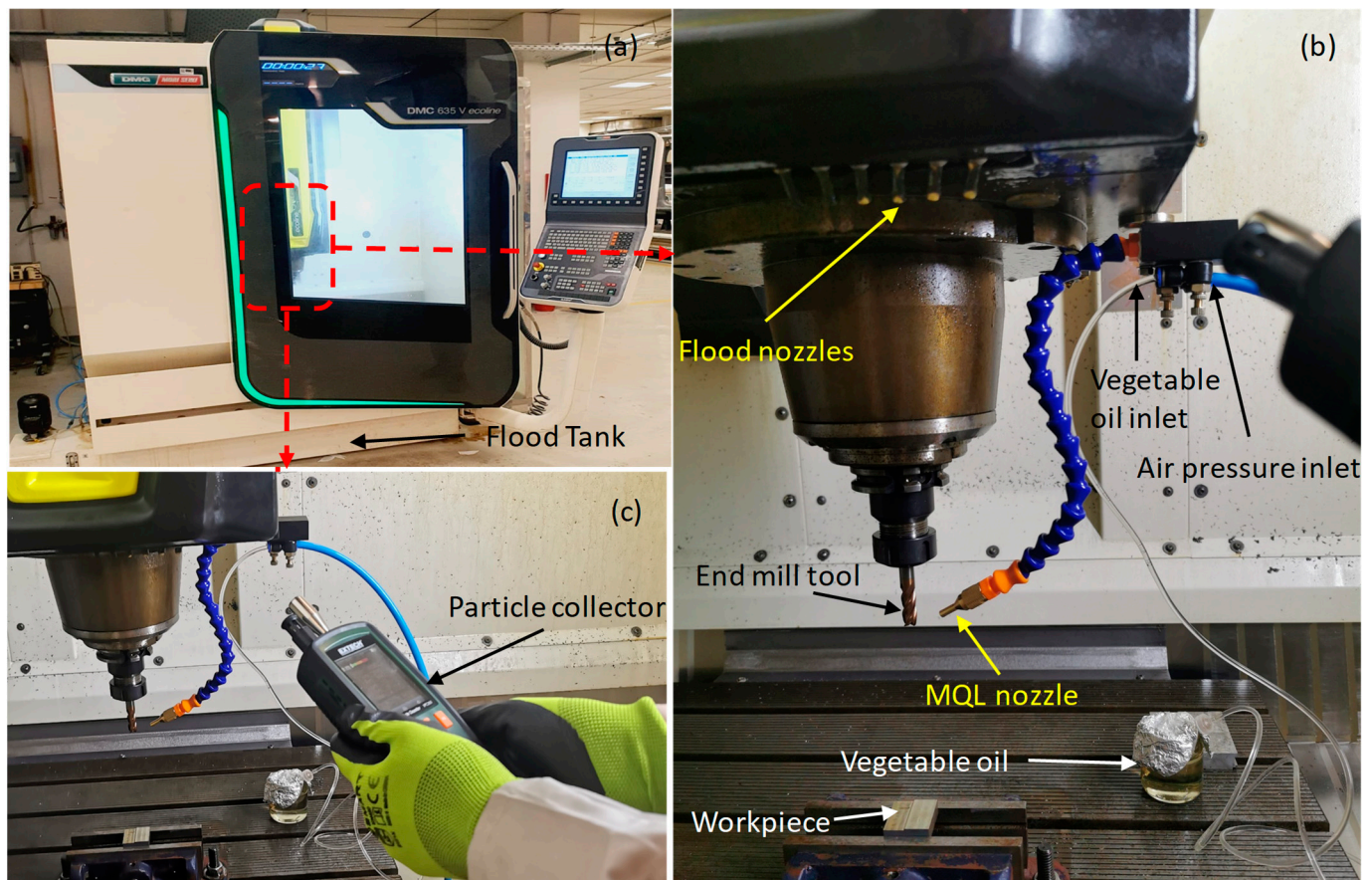


Figure 2. Machining and particle measurement experimental setup: (a) CNC milling machine, (b) machining setup showing the flood and MQL setups, and (c) particle measurement.

2.3. Particulate Matter Measurement

2.3.1. Measurement Equipment and Position

The particles were measured in the air within the machining zone inside the machine enclosure using the Extech VPC300 particle counter (Extech, Tokyo, Japan), as shown in Figure 2c. It has five particle size channels, including 0.3, 0.5, 1, 2.5, 5, and 10 μm . The equipment has an airflow rate of 2.83 L/min, and the sampling time was set to 40 s. Before machining, particle concentrations in the workshop (outside the machine) were measured and are referred to as “reference” in this work.

2.3.2. Measurement Time

The particle emissions were collected at different times (t), with $t = 0$ considered as the time at which the machining process was finished, i.e., when the feed, spindle speed, and cooling were turned off. Since the main objective of this research is to monitor the PM emissions and determine when the machine door should be opened to enhance the operator’s safety and health by suggesting when to open the machine door, different times were considered. The details regarding the times of measuring time (T_m) and machine door opening (T_o) are described in detail in the following section.

2.4. Experiment Design

Experiments were conducted in two stages as depicted in Figure 3. In the first stage, the influence of cutting speed and cutting fluids on the particle concentration was studied

statistically, considering a full factorial design. At this stage, particle concentrations were measured at a T_o of 0, i.e., directly after the machining operation was finished. Table 2 presents the considered milling variables and their respective levels. At this stage, a full factorial design was used, resulting in six experiments, each replicated three times, yielding a total of 18 experiments. The statistical analysis was conducted using Minitab 18.1.

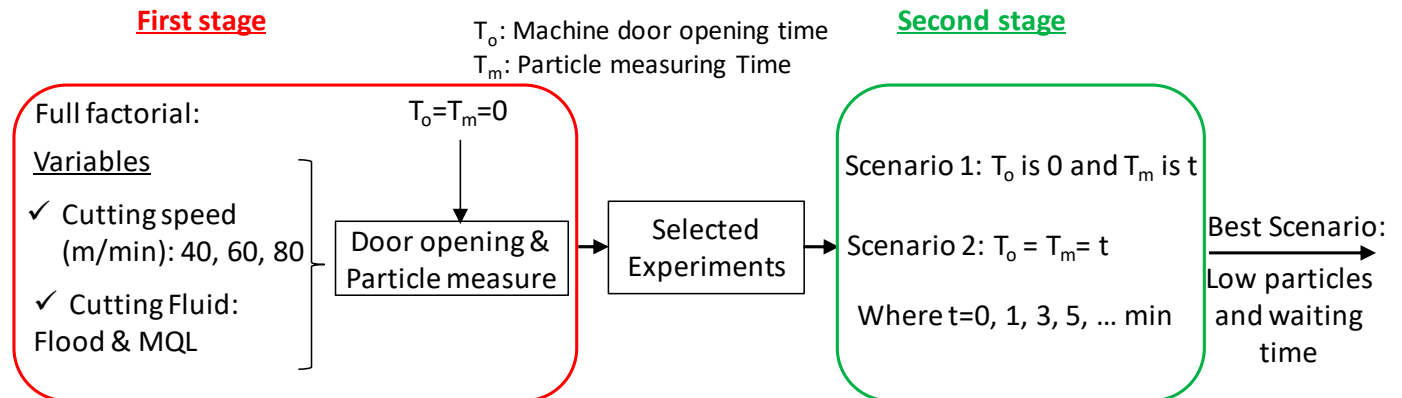


Figure 3. Schematic diagram of the study methodology illustrating the two experimental stages and the two proposed scenarios.

Table 2. Full factorial design variable settings.

Variable	Level 1	Level 2	Level 3
Cutting speed (S), m/min	40	60	80
Cutting fluid	Flood	MQL	-

In the second stage, selected experiments, based on the results of the first stage, were further performed at different T_o and T_m times; see Figure 3. In this stage, two scenarios were proposed. In the first scenario, the machine door is opened directly after machining is finished, i.e., T_o is 0, and then particle concentration was measured at different times, i.e., T_m is t . The process continues until the particle concentration level becomes normal and reaches the reference levels. In the second scenario, the door is opened at different times (t) and then particle concentration is measured at that time, i.e., $T_o = T_m = t$. Many experiments were performed with different t 's (e.g., $t = 1, 3, 5, 7, \dots$ min) until particle concentrations dropped to the reference levels. The scenario that results in lower particle concentration and a shorter waiting time will be selected. Figure 3 outlines the employed methodology.

These proposed scenarios can be applied in industrial settings using real-time particle monitoring and operational protocols. In Scenario 1, workers can be instructed through standard operating procedures and sensor-based indicators to wait until particle levels are safe. In Scenario 2, which is more beneficial in industries with stricter exposure limits, it may be safer to prevent door opening until the environment is confirmed safe. In this case, automated interlocks can be used to prevent the machine door from opening until the environment is safe. In both scenarios, particle sensors ensure workers interact safely with the machine.

3. Results

3.1. Stage 1: Statistical Effects of Cutting Speed and Fluids

Figure 4 shows the experimental results of the particle concentration at $T_o = T_m = 0$ based on the full factorial design. Results show the number of particles per cubic centimeter (particles/cm³) along with the variation among the three repeated experiments.

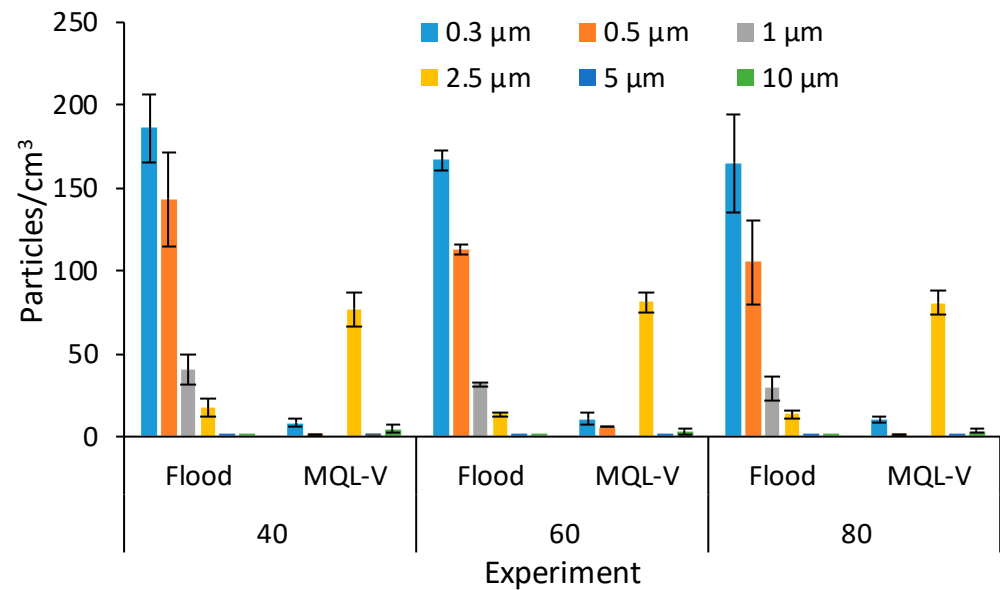


Figure 4. Particle concentration results of the full factorial experiments (stage one) at $T_o = T_m = 0$.

Table 3 presents the ANOVA tables showing the influence of cutting speed and fluid type on the particle concentration for different particle sizes. It should be noted that the residuals of all responses (i.e., particle sizes) follow a normal distribution, suggesting that the normality assumption is satisfied. It is worth remembering that this analysis is based on particle concentration collection directly after machining is finished, i.e., T_o and T_m are 0 min. It is evident from Table 3 (a–e) that the cutting fluid type is the most significant factor that influences the particle concentration. The cutting fluid contributes the majority of the variation in particle concentration. For instance, the contributions of the cutting fluid are 99.3%, 96.17%, 99.62%, 71.98%, and 93.88% of the total variation in particle concentration at 0.3 μm , 0.5 μm , 2.5 μm , 5 μm , and 10 μm particle sizes, respectively. Statistically, cutting speed shows no significant influence on any size of particles. However, its contribution was relatively high (18.98%) for the 5 μm particles, indicating that cutting speed influences their reduction. This is also evident in Figure 5d, where the particle concentration was lower at a cutting speed of 80 m/min.

Table 3. ANOVA analysis of particle concentration at $T_o = T_m = 0$: (a) 0.3 μm , (b) 0.5 μm , (c) 2.5 μm , (d) 5 μm , (e) 10 μm , and (f) R^2 .

(a)	Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	p-Value
	Model	3	39,861.6	99.57%	39,861.6	13,287.2	156	0.006
	Linear	3	39,861.6	99.57%	39,861.6	13,287.2	156	0.006
	Speed	2	109.1	0.27%	109.1	54.5	0.64	0.61
	Fluid	1	39,752.5	99.30%	39,752.5	39,752.5	466.73	0.002
	Error	2	170.3	0.43%	170.3	85.2		
	Total	5	40,031.9	100.00%				
(b)	Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	p-Value
	Model	3	21,323.3	97.92%	21,323.3	7107.8	31.45	0.031
	Linear	3	21,323.3	97.92%	21,323.3	7107.8	31.45	0.031
	Speed	2	381.5	1.75%	381.5	190.7	0.84	0.542
	Fluid	1	20,941.8	96.17%	20,941.8	20,941.8	92.66	0.011
	Error	2	452	2.08%	452	226		
	Total	5	21,775.3	100.00%				

Table 3. Cont.

(c)	Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	p-Value
	Model	3	6322.64	99.63%	6322.64	2107.55	177.57	0.006
	Linear	3	6322.64	99.63%	6322.64	2107.55	177.57	0.006
	Speed	2	0.15	0.00%	0.15	0.07	0.01	0.994
	Fluid	1	6322.5	99.62%	6322.5	6322.5	532.69	0.002
	Error	2	23.74	0.37%	23.74	11.87		
	Total	5	6346.38	100.00%				
(d)	Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	p-Value
	Model	3	0.020107	90.96%	0.020107	0.006702	6.71	0.132
	Linear	3	0.020107	90.96%	0.020107	0.006702	6.71	0.132
	Speed	2	0.004197	18.98%	0.004197	0.002098	2.1	0.323
	Fluid	1	0.01591	71.98%	0.01591	0.01591	15.92	0.057
	Error	2	0.001998	9.04%	0.001998	0.000999		
	Total	5	0.022105	100.00%				
(e)	Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	p-Value
	Model	1	15.587	93.88%	15.587	15.5872	61.37	0.001
	Linear	1	15.587	93.88%	15.587	15.5872	61.37	0.001
	Fluid	1	15.587	93.88%	15.587	15.5872	61.37	0.001
	Error	4	1.016	6.12%	1.016	0.254		
	Total	5	16.603	100.00%				
(f)	Response		0.3 μm	0.5 μm	2.5 μm	5 μm	10 μm	
	R ² (%)		99.57	97.92	99.63	90.96	93.88	

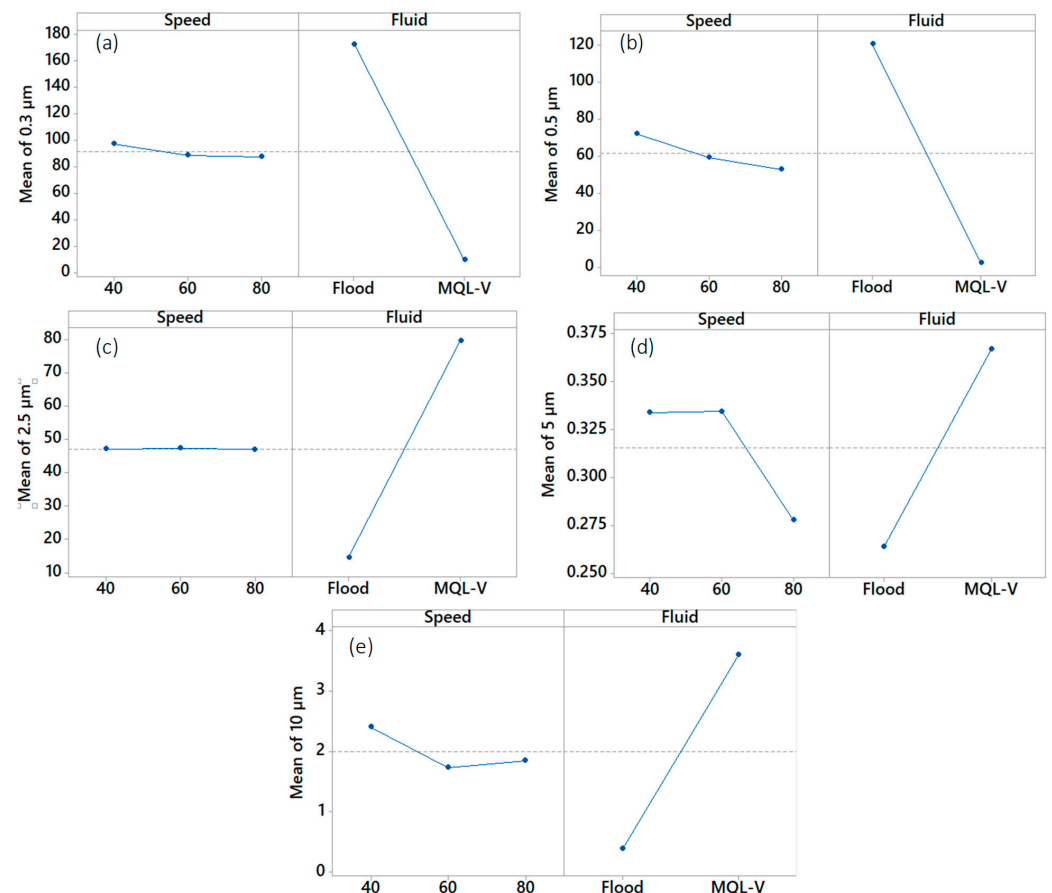


Figure 5. Main effect plots of particle concentration at $T_o = T_m = 0$: (a) 0.3 μm , (b) 0.5 μm , (c) 2.5 μm , (d) 5 μm , and (e) 10 μm .

The influence direction of cutting speed and cutting fluid on the particle concentration is shown in Figure 5. In general, the particle concentration is slightly decreased as the cutting speed increases. When T_o and T_m are 0, the effect of cutting fluid shows different patterns depending on the particle size. For instance, at lower particle sizes, namely 0.3 μm and 0.5 μm , the flood type results in considerably higher particle concentrations. On the other hand, MQL cutting fluid shows considerably higher particle concentrations at higher particle sizes (2.5 μm , 5 μm , and 10 μm). It should be noted that this variation in particle concentration patterns at different sizes, considering flood and MQL, is limited to measurements taken immediately after machining is finished. It is evident from the next section (Section 3.2) that, when varying T_o and T_m , the peak concentration of MQL constantly exceeds that of the flood system. Accordingly, the following section (Section 3.2) assesses the particle concentration at various points after machining to guarantee that their levels are safely acceptable.

3.2. Stage 2: Analysis of Door Opening Time

To investigate the development of particle emissions with time, further experiments were performed based on the results obtained from Stage 1, Section 3.1. As it was evident that cutting fluid shows considerable influence on the particle concentration, both types of cutting fluids were considered to investigate the development of particle concentration with time. Since the cutting speed shows no significant impact and exhibits lower particle concentration at higher cutting speeds (80 m/min), the cutting speed of 80 m/min was selected for the second-stage experiments.

3.2.1. Scenario 1: $T_o = 0$ and $T_m = t$

Figure 6 depicts the particle concentrations measured at different times (T_m is t) immediately following the end of machining (T_o is 0 min). In other words, the machine door is open directly after machining is finished, and then particle concentrations are measured at different times. The patterns of particle development over time inside the machine differ substantially for both flood (Figure 7a) and MQL (Figure 7b). Figure 6a shows that the particle concentration of the flood type is higher at $t = 0$ and decreases rapidly over time. In other words, the peak concentration occurs directly after machining is completed. Furthermore, the particle concentration caused by the flood becomes close to the reference levels in about 7 min after machining is finished. Regarding the MQL as illustrated in Figure 6b, the particle concentration shows different patterns depending on the particle size. For instance, when the particle size is less than 2.5 μm (0.3 μm , 0.5 μm , and 1 μm), the particle concentrations start low and significantly increase, reaching their maximum concentration after about 5 min of machining finishing and opening the door. For the larger particles (10 μm), the concentration at 0 is higher, and it decreases with time. The particle concentration peak from MQL is comparable to that of the flood at 0.3 μm size, but it is significantly higher than the flood for all other sizes (i.e., 0.5 μm , 1 μm , 2.5 μm , 5 μm , and 10 μm). Moreover, the particle concentration caused by MQL cutting fluid takes longer to drop to reference levels than flood. For instance, even 30 min after the completion of machining and the subsequent opening of the door, the particle concentration associated with MQL remains slightly higher. In contrast, the particle concentration generated under flood cooling conditions returns to a reference level within about 7 min after machining is completed.

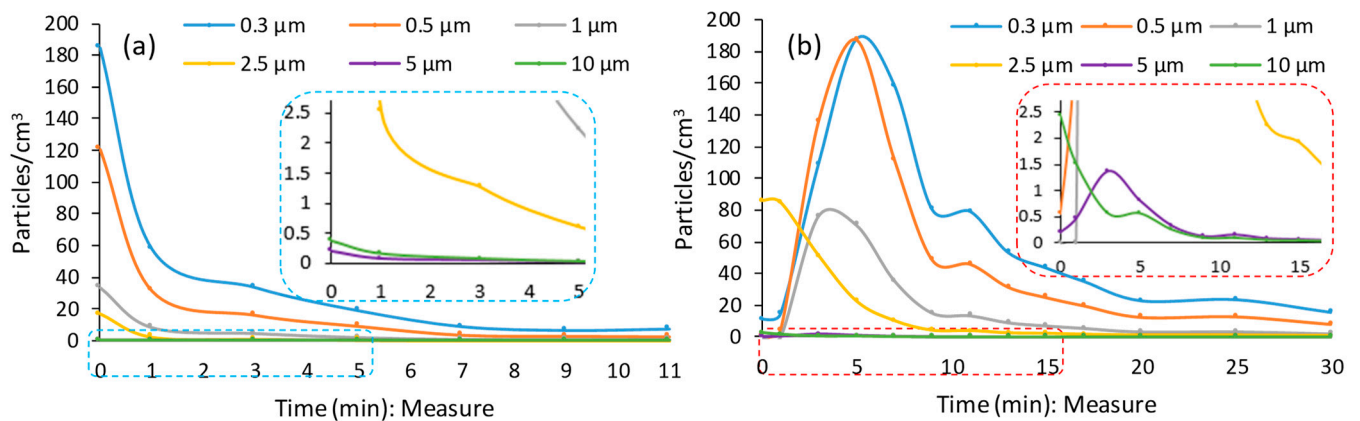


Figure 6. Particle concentrations under scenario 1, in which the door is opened when t is 0 ($T_o = 0$) and particles are measured at different times t when cutting speed is 80 m/min: (a) flood system and (b) MQL system.

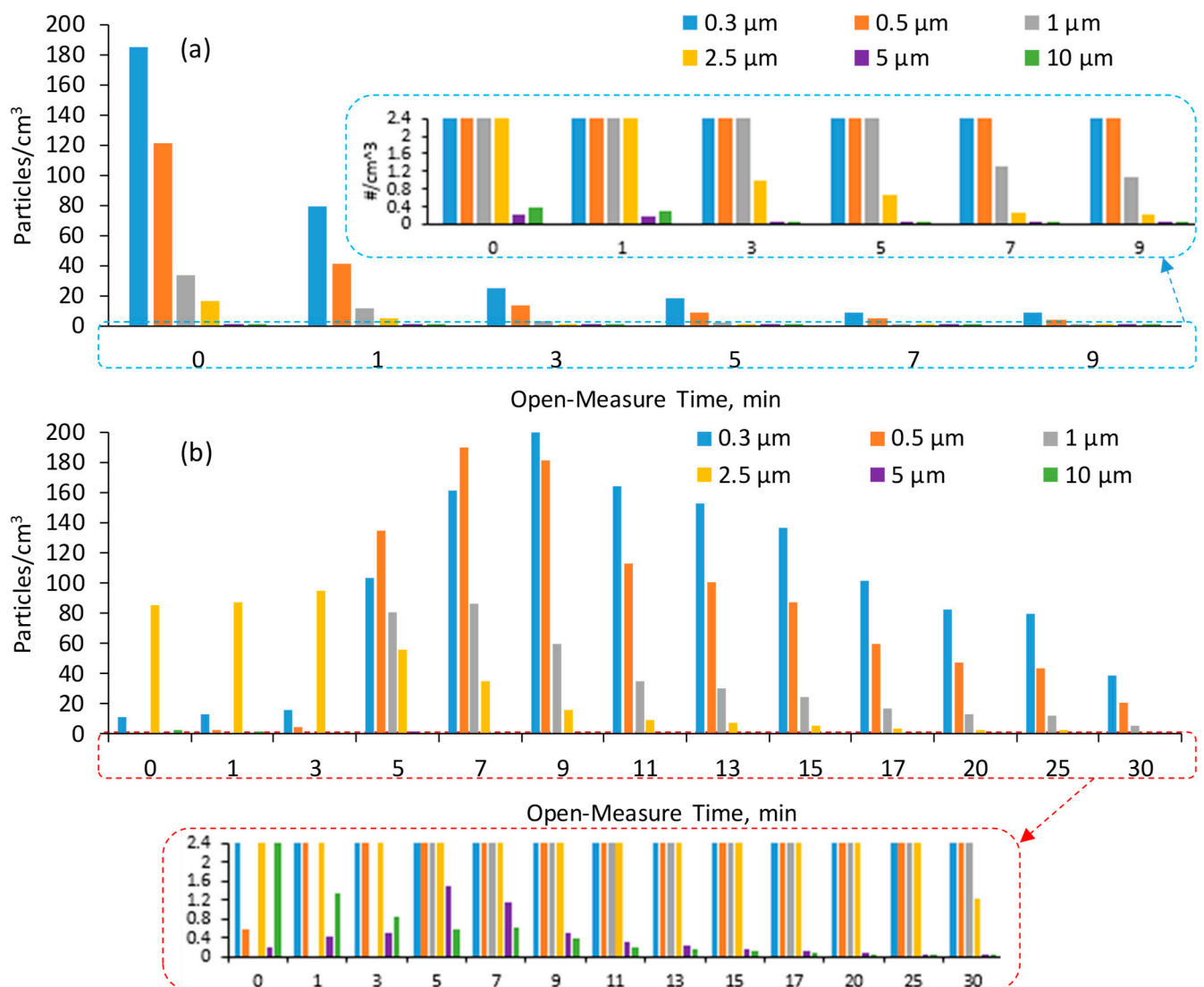


Figure 7. Particle concentrations under scenario 2, in which the door is opened at t and particles are measured at time t ($T_o = T_m = t$) when cutting speed is 80 m/min: (a) flood system and (b) MQL system.

3.2.2. Scenario 2: $T_o = T_m = t$

Figure 7 shows the particle concentration when the door was opened at time t after machining was finished ($T_o = t$ min). The particle concentration was then measured at that same time ($T_m = t$). It is worth noting that numerous experiments were conducted in this scenario. For instance, six experiments were performed using flood cutting fluid at 80 m/min cutting speed to achieve the workshop's reference particle concentration, as shown in Figure 7a. In contrast, more experiments (13 experiments) were needed for the flood cutting fluid, as shown in Figure 7b. Figure 7a clearly shows that the particle concentration decreases rapidly with increasing door opening time (t), reaching the reference level after about 7 min under flood cutting fluid conditions. However, particle concentration generally starts low and then increases to the maximum, followed by a drop in the case of MQL, as shown in Figure 7b. Figure 7a illustrates that even when the machine door is opened after 30 min, the particle concentration remains higher.

4. Discussion

A summary of the particle concentration peaks associated with both flood and MQL for the two proposed scenarios is presented in Table 4.

Table 4. Particle concentration peaks for flood and MQL at scenarios 1 and 2.

Scenario	Fluid	Particle Concentration (Particles/cm ³)					
		0.3 μm	0.5 μm	1 μm	2.5 μm	5 μm	10 μm
1	Flood	187.694	187.403	76.290	85.722	1.371	2.438
	MQL	184.854	121.050	33.799	16.647	0.209	0.382
	Difference (%)	1.54	54.81	125.72	414.94	555.98	538.22
2	Flood	199.973	189.462	86.636	95.079	1.481	2.438
	MQL	184.854	121.050	33.799	16.647	0.209	0.382
	Difference (%)	8.18	56.52	156.33	471.15	608.61	538.22

Table 4 highlights that MQL produces substantially higher particle concentrations and larger particles than flood cooling. This is evident from Table 4, where the variation (%) in concentration peaks between the MQL and flood increases significantly, from 8.18% at a particle size of 0.3 μm to 538.22% at 10 μm , suggesting that MQL produces higher peak concentrations and larger particles. The higher concentration peaks and the larger particle sizes observed with MQL could be attributed to its atomization process.

Table 5 compares the particle concentrations of both flood and MQL after 7 min and 30 min, respectively, for the two scenarios, scenario 1 and scenario 2. It is evident that, for both scenarios, the particle concentrations resulting from using flood cutting fluid are close to the reference levels within about 7 min. However, for the MQL, the particle concentrations remain higher even after 30 min of finishing machining for both scenarios, with scenario 2 being significantly far from the reference levels. These findings are consistent with [10], which found that MQL resulted in prolonged standby times. Given that both scenarios yield similar standby times—7 min for flood and 30 min for MQL—it is advisable to adopt the second scenario, as it is more probable that the particles will not be distributed outside the machine during the standby time.

Research is being conducted to develop methods for reducing particle emission concentration, their associated sizes, and standby time. For instance, Su et al. [11] proposed employing electrostatic atomization to break down the liquid into fine charged droplets, thereby diminishing the size and concentration of the particles associated with MQL. A second report [10] demonstrated that a high-capacity extraction system, coupled with the

reduction in oil in MQL, effectively reduces particle concentrations and minimizes the standby time required to safely open and interact with the machine.

Table 5. Comparison of minimum particle concentration levels for flood and MQL systems under Scenarios 1 and 2 with the reference level.

Scenario	Fluid	T _o (min.)	T _m (min.)	Particle Concentration (Particles/cm ³)					
				0.3 µm	0.5 µm	1 µm	2.5 µm	5 µm	10 µm
1	Flood	0	7	8.8321	3.7542	0.9640	0.2447	0.0132	0.0090
	MQL	0	30	15.7638	8.3146	2.2823	0.5291	0.0180	0.0127
2	Flood	7	7	9.1229	4.5599	1.3231	0.2664	0.0079	0.0085
	MQL	30	30	38.5371	21.0784	5.2659	1.2246	0.0376	0.0217
Reference levels				7.2893	3.5085	0.8656	0.1875	0.0051	0.0049

The presented analysis indicates that the proposed scenarios in machining processes can help production managers establish conditions for safe and healthy work while reducing environmental pollution. Air pollution is recognized for its harmful effects on the lungs and airways, and it can also adversely affect other organ systems, including the bones, eyes, liver, kidneys, cardiovascular system, and skin [18]. It also highlights the effects of different cooling strategies used in machining, such as flood and MQL. Inhalation of cutting fluid mist or aerosol can irritate the lungs, throat, and nose, affect the airways and alveoli, and may worsen pre-existing lung conditions [19]. The Occupational Safety and Health Administration (OSHA) has established permissible exposure limits for air contaminants (total particles) at 5 mg/m³ for mineral oil mist and 15 mg/m³ for all other metalworking fluids, based on an 8 h time-weighted average [19]. MQL is often considered sustainable because it consumes minimal lubricant and requires no disposal [20]. However, the presented results indicate that MQL can generate high levels of airborne particles that remain suspended for longer periods compared to the flood system. In this regard, these findings can assist in establishing procedures to reduce environmental pollution, thereby enhancing worker safety and health. Additionally, the results indicate that airborne particles generated during MQL machining remain suspended for a longer time compared to the flood type, which implies longer operator waiting times and increased costs due to ineffective working periods. Furthermore, by considering different particle sizes, the presented findings help in identifying potential health impacts on workers, as particles of varying sizes can affect different parts of the human body [21,22]. Particles smaller than 10 µm can penetrate deep into the lungs and even enter the bloodstream, with those under 2.5 µm (PM_{2.5}) posing the most significant health risk [23]. For instance, particles with a diameter of 10 µm or larger can affect the nasopharyngeal membranes [24]. Particles with a diameter of 2.5 µm or lower easily find their way into lung alveoli [25] and induce neuroinflammation [26]. Airborne particles (1–2.5 µm) can penetrate deeply into the lungs, settle in the terminal bronchioles, and contribute to lung tissue destruction typical of centrilobular emphysema [24]. Fine particles with a diameter of less than 1 µm can penetrate deep into the alveoli, causing more severe and persistent lung inflammation, disrupting normal cell function, and initiating early fibrosis [24]. The National Ambient Air Quality Standards (NAAQS) establish criteria for air pollutants, setting a 24 h average exposure of 35 µg/m³ for particulate matter less than 2.5 µm and 150 µg/m³ for particulate matter less than 10 µm [27]. Identifying these sizes and their concentrations, as well as establishing procedures to minimize/avoid exposure by selecting the appropriate scenario and cutting fluid, is critical for ensuring worker safety and health. To conclude, the findings of this work provide insights into manufacturing sustainability by addressing scenarios

and cooling strategies that help minimize operator waiting time, reduce particle emissions, and reduce or avoid exposure, which in turn enhances worker safety and health.

5. Conclusions

This study conducted experimental research work to analyze the effects of machining speed and cutting fluids on particle emissions during milling EBM-printed Ti6Al4V. Also, the standby time to open the machine door at safe concentration levels was studied for two scenarios: open the door and wait until particle levels are acceptable, or wait and then open the door. From the results of this study, we can conclude the following:

- Statistical analyses indicated that cutting fluids significantly affect particle emissions, contributing to the majority of the variation in particle concentration.
- The effect of cutting fluid on the particle concentrations shows different patterns depending on the particle size.
- The particle concentration peak is observed at various time intervals subsequent to the machining process. For example, flood exhibited a peak immediately following machining, whereas MQL exhibited it at varying times based on the particle size.
- MQL results in a higher particle concentration and higher sizes. For example, the variation in the concentration peaks between the MQL and flood increases significantly, from 8.18% at a particle size of 0.3 μm to 538.22% at 10 μm , suggesting that MQL produces higher peak concentrations and larger particles.
- When MQL is employed, the operator needs to wait longer before interacting with the machine, with the standby time being ~328% greater than that of the flood system.
- The findings of this work provide insights into manufacturing sustainability by addressing scenarios and cooling strategies that help minimize operator waiting time, reduce particle emissions, and reduce or avoid exposure, which in turn enhances worker safety and health.

The study is limited to the particle emissions, considering variations in cutting speed and cutting fluid conditions (flood and MQL). Future investigations could consider additional machining parameters (such as feed rate and depth of cut), high-speed machining, and dry machining conditions to provide a more comprehensive understanding. Moreover, the current setup does not include an extraction system; therefore, implementing such a system could help reduce particle generation in the machining area and shorten operator waiting time. An automated extraction system integrated with an online particle emission detector during or after machining would be beneficial to better control the machining environment.

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References

1. Cozzolino, E.; Astarita, A. Wet and Dry Turning of Ti6Al4V EBM Parts: Implications on the Life Cycle Assessment and Surface Roughness. *Mater. Manuf. Process.* **2025**, *40*, 1621–1633. [\[CrossRef\]](#)
2. Fayazfar, H.; Sharifi, J.; Keshavarz, M.K.; Ansari, M. An Overview of Surface Roughness Enhancement of Additively Manufactured Metal Parts: A Path towards Removing the Post-Print Bottleneck for Complex Geometries. *Int. J. Adv. Manuf. Technol.* **2023**, *125*, 1061–1113. [\[CrossRef\]](#)
3. Milton, S.; Rigo, O.; LeCorre, S.; Morandeau, A.; Siriki, R.; Bocher, P.; Leroy, R. Microstructure Effects on the Machinability Behaviour of Ti6Al4V Produced by Selective Laser Melting and Electron Beam Melting Process. *Mater. Sci. Eng. A* **2021**, *823*, 141773. [\[CrossRef\]](#)
4. Syrlybayev, D.; Seisekulova, A.; Talamona, D.; Perveen, A. The Post-Processing of Additive Manufactured Polymeric and Metallic Parts. *J. Manuf. Mater. Process.* **2022**, *6*, 116. [\[CrossRef\]](#)
5. Gunaydin, K.; Türkmen, H.S.; Airoidi, A.; Grasso, M.; Sala, G.; Grande, A.M. Compression Behavior of EBM Printed Auxetic Chiral Structures. *Materials* **2022**, *15*, 1520. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Valencia-Cadena, A.; Hangen, U.; Roa Rovira, J.J. Post-Processing of AM-EBM Ti6Al4V for Biomedical Applications: Evolution of Mechanical Properties as a Function of Surface Roughness. *Metals* **2024**, *14*, 1423. [\[CrossRef\]](#)
7. Cozzolino, E.; Franchitti, S.; Borrelli, R.; Pirozzi, C.; Astarita, A. Energy Consumption Assessment in Manufacturing Ti6Al4V Electron Beam Melted Parts Post-Processed by Machining. *Int. J. Adv. Manuf. Technol.* **2023**, *125*, 1289–1303. [\[CrossRef\]](#)
8. Zhao, J.; Liu, Z.; Wang, B.; Song, Q.; Cai, Y.; Khan, A.M.; Wan, Y.; Ren, X. A Comprehensive Review of Generating, Monitoring, Evaluating, and Controlling Particle Emissions during Machining Process. *J. Manuf. Syst.* **2023**, *70*, 395–416. [\[CrossRef\]](#)
9. Ullah, I.; Akinlabi, E.T.; Kouam, J.; Songmene, V. A Comprehensive Experimental Investigation on the Correlation between Chip Formation, Machined Surface Integrity, and Particle Emissions during High-Speed Milling of TC4 Titanium Alloy. *Int. J. Adv. Manuf. Technol.* **2025**, *136*, 3285–3301. [\[CrossRef\]](#)
10. Rodriguez, I.; Arrazola, P.J.; Pušavec, F. The Impact of Airborne Emissions from Coolants and Lubricants on Machining Costs. *CIRP Ann.* **2024**, *73*, 77–80. [\[CrossRef\]](#)
11. Su, Y.; Lu, Q.; Yu, T.; Liu, Z.; Zhang, C. Machining and Environmental Effects of Electrostatic Atomization Lubrication in Milling Operation. *Int. J. Adv. Manuf. Technol.* **2019**, *104*, 2773–2782. [\[CrossRef\]](#)
12. Khettabi, R.; Songmene, V.; Masounave, J. Effect of Tool Lead Angle and Chip Formation Mode on Dust Emission in Dry Cutting. *J. Mater. Process. Technol.* **2007**, *194*, 100–109. [\[CrossRef\]](#)
13. Kasim, M.S.; Husshini, N.H.N.; Hafiz, M.S.A.; Mohamad, W.N.F.; Izamshah, R.; Ghani, J.A.; Haron, C.H.C. Particulate Matter—Monitoring during End Milling under Different Cooling-Lubrication Strategies. *J. Appl. Sci. Eng.* **2021**, *24*, 891–900.
14. Yadav, S.P.; Pawade, R.S. Manufacturing Methods Induced Property Variations in Ti6Al4V Using High-Speed Machining and Additive Manufacturing (AM). *Metals* **2023**, *13*, 287. [\[CrossRef\]](#)
15. Dabwan, A.; Anwar, S.; Al-Samhan, A.M.; Alqahtani, K.N.; Nasr, M.M.; Kaid, H.; Ameen, W. CNC Turning of an Additively Manufactured Complex Profile Ti6Al4V Component Considering the Effect of Layer Orientations. *Processes* **2023**, *11*, 1031. [\[CrossRef\]](#)
16. Wang, F.; Li, Z.; Wang, X.; Yang, Y. A Prediction Model of Emission Characteristics of Oil Particles Induced by Milling Process: Emission Rate and Size Distribution. *Indoor Built Environ.* **2022**, *31*, 1892–1906. [\[CrossRef\]](#)
17. Ameen, W.; Al-Ahmari, A.; Mohammed, M.K. Self-Supporting Overhang Structures Produced by Additive Manufacturing through Electron Beam Melting. *Int. J. Adv. Manuf. Technol.* **2019**, *104*, 2215–2232. [\[CrossRef\]](#)
18. Schraufnagel, D.E.; Balmes, J.R.; Cowl, C.T.; De Matteis, S.; Jung, S.-H.; Mortimer, K.; Perez-Padilla, R.; Rice, M.B.; Riojas-Rodriguez, H.; Sood, A. Air Pollution and Noncommunicable Diseases: A Review by the Forum of International Respiratory Societies’ Environmental Committee, Part 2: Air Pollution and Organ Systems. *Chest* **2019**, *155*, 417–426. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Metalworking Fluids—Metalworking Fluids: Safety and Health Best Practices Manual | Occupational Safety and Health Administration. Available online: <https://www.osha.gov/metalworking-fluids/manual#e> (accessed on 9 November 2025).
20. Khan, A.M.; Rahatuzzaman, R.M.D.; Umayar, A.; Muhammad, J.; Asad, A.M.; Zhao, G.; Abellán-Nebot, J.V. The Recent Advancements in Minimum Quantity Lubrication (MQL) and Its Application in Mechanical Machining—A State-of-the-Art Review. *Lubricants* **2025**, *13*, 401. [\[CrossRef\]](#)
21. Chauhan, B.V.S.; Corada, K.; Young, C.; Smallbone, K.L.; Wyche, K.P. Review on Sampling Methods and Health Impacts of Fine (PM_{2.5}, ≤2.5 µm) and Ultrafine (UFP, PM_{0.1}, ≤0.1 µm) Particles. *Atmosphere* **2024**, *15*, 572. [\[CrossRef\]](#)
22. Garcia, A.; Santa-Helena, E.; De Falco, A.; de Paula Ribeiro, J.; Gioda, A.; Gioda, C.R. Toxicological Effects of Fine Particulate Matter (PM_{2.5}): Health Risks and Associated Systemic Injuries—Systematic Review. *Water Air Soil Pollut.* **2023**, *234*, 346. [\[CrossRef\]](#) [\[PubMed\]](#)

23. Particulate Matter (PM) Basics | US EPA. Available online: <https://www.epa.gov/pm-pollution/particulate-matter-pm-basics> (accessed on 9 November 2025).
24. Schraufnagel, D.E. The Health Effects of Ultrafine Particles. *Exp. Mol. Med.* **2020**, *52*, 311–317. [[CrossRef](#)] [[PubMed](#)]
25. Schraufnagel, D.E.; Balmes, J.R.; Cowl, C.T.; De Matteis, S.; Jung, S.H.; Mortimer, K.; Perez-Padilla, R.; Rice, M.B.; Riojas-Rodriguez, H.; Sood, A.; et al. Air Pollution and Noncommunicable Diseases: A Review by the Forum of International Respiratory Societies' Environmental Committee, Part 1: The Damaging Effects of Air Pollution. *Chest* **2019**, *155*, 409–416. [[CrossRef](#)] [[PubMed](#)]
26. Wei, S.; Xu, T.; Sang, N.; Yue, H.; Chen, Y.; Jiang, T.; Jiang, T.; Yin, D. Mixed Metal Components in PM_{2.5} Contribute to Chemokine Receptor CCR5-Mediated Neuroinflammation and Neuropathological Changes in the Mouse Olfactory Bulb. *Environ. Sci. Technol.* **2024**, *58*, 4914–4925. [[CrossRef](#)]
27. NAAQS Table | US EPA. Available online: <https://www.epa.gov/criteria-air-pollutants/naaqs-table> (accessed on 9 November 2025).

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