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GRAVIMETRIC ANALYSIS OF PARTICULATE MATTER EMISSIONS FROM MILLING PROCESSES

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Abstract: The milling process is recognized as a significant source of airborne particulate matter, particularly within the inhalable and respirable fractions that pose health risks to workers and contribute to environmental pollution. This study investigates the influence of milling operations on the generation of inhalable particles and evaluates their concentration using gravimetric measurement techniques. Air samples were collected on filters with a personal sampler pump during milling operations and analyzed to determine mass concentrations and compliance with occupational exposure limits. The results indicate that particle emissions are strongly dependent on the type of material, milling speed, and tool condition. The findings highlight the importance of continuous monitoring of airborne particulate matter and the implementation of effective dust control strategies to reduce occupational exposure and improve workplace air quality.
Key words: inhalable particles, concentration, milling

INTRODUCTION

Particulate matter (PM) refers to solid or liquid particles suspended in the air, with the PM_{10} and $PM_{2.5}$ fractions being the most significant in terms of health risks and regulatory standards. The milling process, which involves the size reduction of raw materials such as metals, grains, minerals, or wood, is a well-known source of airborne dust and fine particles [1]. Emissions of particulate matter during milling can adversely affect workplace air quality, contribute to environmental pollution, and pose challenges for compliance with occupational health and safety regulations [2,3]. Understanding the characteristics and concentrations of PM generated in milling operations is therefore essential for assessing exposure risks and implementing effective control measures.

Particulate matter generated during milling originates from multiple sources. Mechanical abrasion between the material and milling tools produces dust, while cutting and grinding edges contribute to the formation of fine particles. Additional emissions arise from the handling and transport of materials within the milling facility, including loading, unloading, and conveyor movement [4]. Secondary resuspension of settled dust, caused by air currents or vibrations, further increases airborne particle concentrations. The type of material processed, milling speed, tool wear, and operational conditions significantly influence the quantity and size distribution of particulate emissions [5]. Understanding these sources is critical for designing appropriate monitoring strategies and implementing effective dust control measures to minimize occupational exposure.

In this study, we measured the inhalable fraction of particles generated during the milling process using a personal air sampler. A personal air sampler is designed to simulate the amount of particles that may enter a worker's respiratory tract during specific machining operations. Measurements were conducted on various milling machines within a company specializing in conventional milling, extrusion, simulation, rapid prototyping, as well as precision CNC milling and machining of metals and plastics for the production of small- and medium-series parts. Following the sampling phase, filters containing the collected particulate matter were analyzed gravimetrically using an analytical balance to determine particle concentrations.

MATERIAL AND METHODS

The measurements were carried out in a company specializing in CNC precision milling, metal and plastic machining, as well as the production of small- and medium-series parts. The production processes also include welding, part protection, and component assembly. In addition, the company provides services such as conventional milling, extrusion, simulation, rapid prototyping (sand/PE electrodes), 3D solid modeling, HURCO machining center operations, and Charmilles CNC electrical discharge machining.
The measurements were conducted only during the plastic milling process on a Vertical Machining Center (VMC). A VMC is a fundamental component in contemporary manufacturing, particularly in the precision machining of polymeric (plastic) materials. Defined by a vertically oriented spindle that moves along the Z-axis, the VMC is a high-speed Computer Numerical Control (CNC) machine utilized for complex operations, including milling, drilling, and tapping. Its structural rigidity and advanced control capabilities ensure the tight tolerances and smooth surface finishes required for producing intricate plastic components, prototypes, and tooling molds. The process of high-speed plastic milling inherently generates airborne particulate matter (dust). Due to the potential health risks associated with inhaling fine polymer dust, the design and operation of the VMC are critically evaluated from an occupational safety perspective. A key feature of modern industrial VMCs is the fully enclosed workspace, which serves two primary environmental and safety functions.
Dust particle sampling in engineering practice is commonly performed using time-integrated methods to determine aerosol concentration. In this approach, the sampler draws air through a pump, simulating the breathing rate of workers. Airborne particles are carried into the device with the airflow and subsequently deposited on a filter medium.
When personal sampling is applied, the device is positioned in the operator’s breathing zone (approximately 20–30 cm from the nose and mouth) (Figure 1), allowing for an accurate assessment of occupational exposure. The sampler is lightweight and worn by the worker, enabling unrestricted movement during regular work activities.

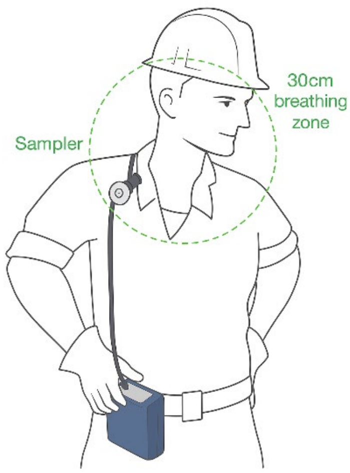

Fig. 1. *Position of a personal sampler*

In this study, sampling was conducted using a personal sampler EGO PLUS TT (Zambelli), equipped with a conical nozzle and 25 mm cellulose mixed ester filters, which are suitable for microscopic examination. The airflow was maintained at 3.5 L/min in accordance with the manufacturer’s specifications. The measurements were performed during machine operation, typically lasting several hours. They were conducted at a stable room temperature of 25 °C under conditions with no air movement, and with relative humidity ranging from 40% to 43%. The sampler was positioned on the upper chest, close to the collarbone, within the worker’s breathing zone.

For the determination of particle concentration by the gravimetric method, an analytical balance Kern & Sohn ABJ 120-4NM with an accuracy of ±0.0002 g was used.

RESULTS AND DISCUSSION

The analytical balance is a high-precision instrument that ensures reliable and reproducible mass determination. It is suitable for gravimetric analyses and other laboratory applications requiring fine measurement resolution (Figure 2).

Fig. 2. *The weighing scale for the gravimetric filter analysis.*

The volume of airflow through the sampler is calculated by multiplying the mean volumetric flow rate, expressed in cubic meters per minute (m^3/min), by the sampling duration in minutes. (Note: the flow rate in L/min equals 1000 times the flow rate in m^3/min.) The net weight of the collected particulate matter on the filter, measured in milligrams (mg), is then divided by the sampled air volume in cubic meters (m^3), yielding the average particle concentration in milligrams per cubic meter of air (mg/m^3) [6,7].

$$x = \frac{m_2 - m_1}{V} * 1000 \quad (1)$$

where:
x – Particulate concentration [mg/m^3]
m_2 – Filter mass after sampling [mg]
m_1 – Filter mass before sampling [mg]
V – Volume of sampled air, calculated as the product of the volumetric airflow rate [L/min] and the sampling duration [min], expressed in liters [L].
The VMC measurements included the assessment of two distinct scenarios during the plastic milling process:

1. Closed machine scenario
2. Open machine scenario

Emulsions were present in both cases.

Closed machine scenario
The sampling duration was 3 hours (h), and the airflow rate was 3.5 L/min. Multiplying the flow rate by the sampling duration gives a volume of 630 L. However, the EGO PLUS TT personal sampler provides data via its software as a normalized volume in "N-litres." Thus, the normalized volume of sampled air was 628.8 L for the closed machine scenario and 628.1 L for the open machine scenario.

The filter mass before sampling (m_1) was 0.0222 g, and the mass after sampling (m_2) was 0.0287 g.
The particulate concentration is calculated as:

$$x_1 = \frac{28.7 - 22.2}{628.8} * 1000 = 10.4\, mg/m^3$$

Open machine scenario
The sampling duration was 3 hours (h), and the airflow rate was 3.5 L/min. The normalized volume of sampled air was 628.1 L.
The filter mass before sampling (m_1) was 0.0222 g, and the mass after sampling (m_2) was 0.0299 g.

$$x_2 = \frac{29.9 - 22.2}{628.1} * 1000 = 12.6\, mg/m^3$$

In European Union member states, as well as in most countries adhering to EU or international standards (such as ACGIH), the general occupational exposure limit (OEL) for inhalable dust is 10 mg/m³ for an 8-hour Time-Weighted Average (TWA) [8]. The term *inhalable fraction* (or *inhalable dust*) refers to the total airborne particulate matter that can be inhaled and deposited anywhere within the respiratory tract, from the nose to the terminal bronchioles. Scientifically, this fraction consists of particles with an aerodynamic diameter of up to approximately 100 µm.

CONCLUSION

The enclosure facilitates the efficient operation of local exhaust ventilation (LEV) or aspiration systems, effectively capturing plastic dust and chips at the source and preventing their dispersal into the ambient air.
When assessing occupational exposure, a critical distinction must be made between the machine's operational states. Measurements taken with the VMC enclosure closed represent the standard, controlled exposure level during routine operation, reflecting the protective efficacy of the machine's integrated safety features. Conversely, measurements taken with the enclosure open—for example, during material setup, monitoring, or maintenance—represent a worst-case scenario or maximum potential exposure.
The results confirm the protective efficacy of the machine's enclosure and integrated safety systems. The closed machine scenario resulted in a particulate concentration of 10.4 mg/m³, while the open machine scenario yielded a significantly higher concentration of 12.6 mg/m³. This difference (≈21% increase) clearly demonstrates that opening the machine's doors or guards directly results in a worst-case exposure scenario, allowing greater dispersal of plastic dust and chips into the ambient air, despite the continued presence of emulsions in both cases. However, it is critical to note that both measured concentrations—10.4 mg/m³ (closed) and 12.6 mg/m³ (open)—exceed the permissible occupational exposure limit (OEL) of 10 mg/m³ (8-h TWA). Measurements were conducted over a 3-hour period during active machine operation, not averaged across a full 8-hour shift. This methodological difference likely influenced the reported concentrations, since OEL values are defined for an 8-hour time-weighted average exposure. Importantly, the measurements did not take into account the use of personal protective equipment (PPE), which, based on the results, must be considered mandatory in this working environment. Furthermore, the presence of dispersed emulsion droplets during machining may have contributed to additional loading of the sampled filters, potentially influencing the gravimetric results.
In summary, the enclosure is essential for reducing exposure during the plastic milling process, but on its own it is insufficient to ensure compliance with occupational exposure limits. Continuous monitoring, the mandatory use of PPE, consideration of full-shift exposure

durations, and the implementation of enhanced dust control strategies are therefore necessary to safeguard worker health.

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