Ann. occup. Hyg., Vol. 46, Supplement 1, pp. 315–319, 2002
Published by Oxford University Press
DOI: 10.1093/annhyg/mef654

Evaluation of Grinding Aerosols in Terms of Alveolar Dose: the Significance of Using Mass, Surface Area and Number Metrics

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Aerosols generated by mechanical means are generally assumed to have low particle number and surface area concentrations compared with mass concentration. As a result, they have received little attention in the current debate over the use of number- and surface area-based metrics for low-solubility particles. However, it is plausible that some high-energy mechanical processes found in workplaces may lead to the generation of fine aerosols that are characterized by high number and surface area concentrations. A preliminary investigation has been carried out into the aerosol generated during high-speed grinding to investigate the generation of fine particles from mechanical processes. Aerosol size distribution measurements between 5 nm and 20 µm were made during grinding on steel, aluminum, polytetrafluoroethylene, granite, ceramic tile and hardwood. Distributions were weighted by alveolar deposition probability to provide an indication of potential dose against metrics of number, surface area and volume. In all cases, the number-weighted size distributions showed most particles to lie in the ultrafine particle range (diameter <100 nm). Surface area-weighted distributions show substrates susceptible to thermal aerosol formation to be dominated by ultrafine particles. Weighting measurements by particle volume led to distributions dominated by particles >1 µm, although aluminum, hardwood and steel all show substantial volume-fractions in the ultrafine region. There was evidence that the grinding tool contributed to the measured ultrafine aerosol fraction. Further work is required to isolate particle sources during similar operations.

Keywords: grinding; ultrafine aerosol; exposure metrics

INTRODUCTION

A number of toxicology studies have indicated that for some classes of material, biological response following deposition in the lungs is dependent on particle size, and may be influenced by either particle number or surface area (Donaldson *et al.*, 1998; Oberdörster, 2000). Materials of interest typically have low solubility, leading to extended persistence in the lungs, are composed of ultrafine primary particles (nominally defined as being <100 nm in the context of inhalation toxicology) and have high specific surface areas. Naturally, these investigations have raised concern over whether exposure to workplace aerosols typified by small particle sizes and high surface areas is more appropriately measured using metrics of number or surface area, rather than mass. Such particles are traditionally associated with hot processes such as combustion, welding and metal processing. Aerosols generated through mechanical means such as grinding, cutting and machining are generally assumed to be dominated by particles much larger than 100 nm in diameter, leading to the widely held assumption that number and surface area concentrations are relatively low, and that respirable mass is the more appropriate exposure metric. A potentially misleading supposition arising from this assumption is that the contribution from ultrafine aerosols to health effects associated with mechanically generated aerosols is of no consequence. It is possible that when such aerosols are evaluated in terms of alveolar dose and particle number or surface area, the ultrafine fraction takes on a greater significance than is indicated by respirable mass concentration alone.

The assumption that ultrafine particles do not form a significant component of mechanically generated aerosols has been investigated using particles generated during high-speed grinding on a number of substrates. Significance has been interpreted qualitatively by considering the fraction of ultrafine particles predicted to deposit in the alveolar region of the lungs

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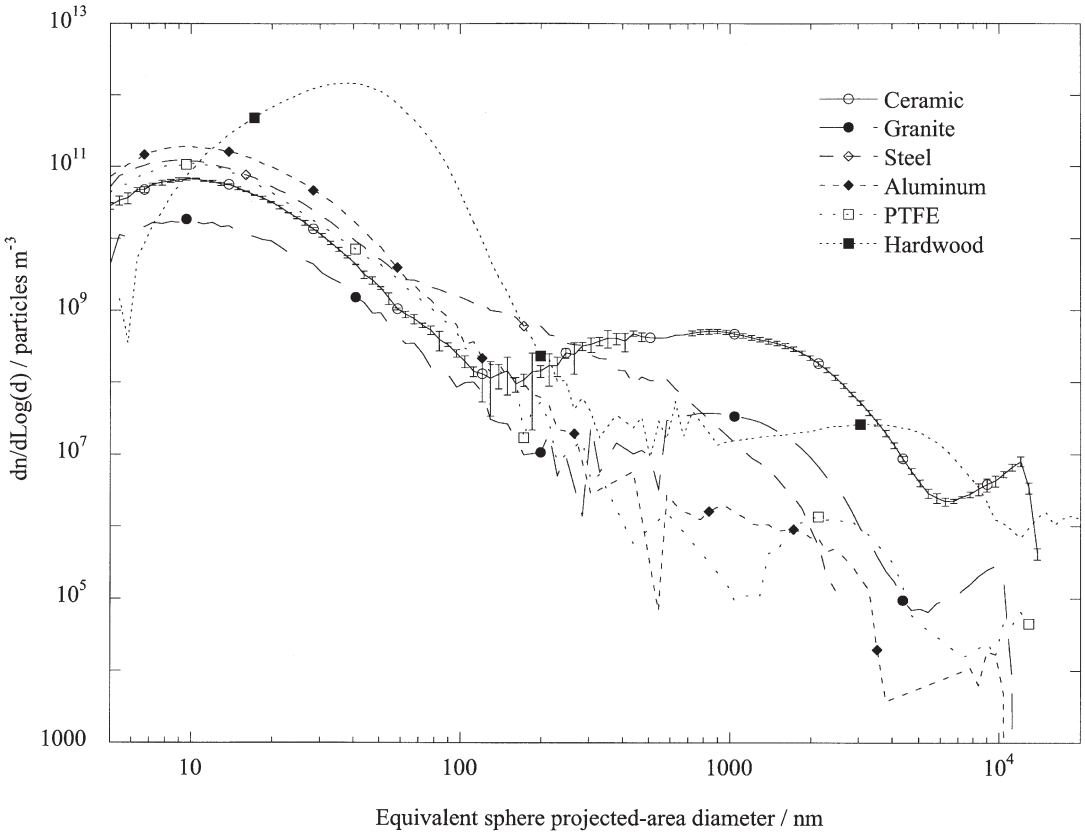

Fig. 1. Measured aerosol size distribution resulting from high-speed grinding on six different substrates, after background subtraction of the aerosol associated with the grinding tool. ±1 SD error bars are shown for the ceramic distribution; these are indicative of the measurement errors estimated for each substrate.

following inhalation, weighted by either particle number, surface area or volume.

MATERIALS AND METHODS

Grinding was carried out on six substrates—mild steel, aluminum, ceramic tile, granite, hardwood and polytetrafluoroethylene (PTFE)—using an aluminum oxide grinding wheel. The wheel was attached to a Dremel® Multipro rotary tool (Dremel, USA). The grinding wheel was applied to each substrate with a constant contact force of 3.96 N and rotated at ~20 000 r.p.m. Grinding took place within an enclosed chamber. Prior to grinding, the chamber was flushed with HEPA-filtered air, then sealed. During grinding and aerosol measurements, air within the chamber was mixed using a small fan. Aerosol was extracted from the chamber and sized by two TSI Scanning Mobility Particle Sizers (SMPSs; TSI, USA); one using a 3080N nano Differential Mobility Analyser (DMA), the other using a 3080L long DMA (each with a 3022 condensation particle counter), and a TSI 3320 Aerodynamic Particle Sizer (APS). The APS data were corrected for estimated losses within the sampling train and the instrument inlet. As the Dremel motor was found to generate a significant number of particles when no substrate was present, separate measurements were made of this aerosol with the tool free-running at 20000 r.p.m.; these were subsequently subtracted from the measurements made with the substrates in place. Resulting aerosol size distributions were evaluated in terms of particle equivalent sphere projected-area diameter between 5 nm and 20 μm.

Three aerosol size distribution measurements were made on each substrate using a randomized protocol. In each case the substrate was ground for 10 s, the aerosol allowed to stabilize and fully mix within the chamber for a further 60 s, then the size distribution measurement made over a 200 s period. Overall particle number concentrations were typically $<10^{11}$ particles/m^3.

Measured size distributions were weighted using a multiple path alveolar deposition probability model (MPPDep v. 1.11, CIIT, USA), using 12 breaths/min,

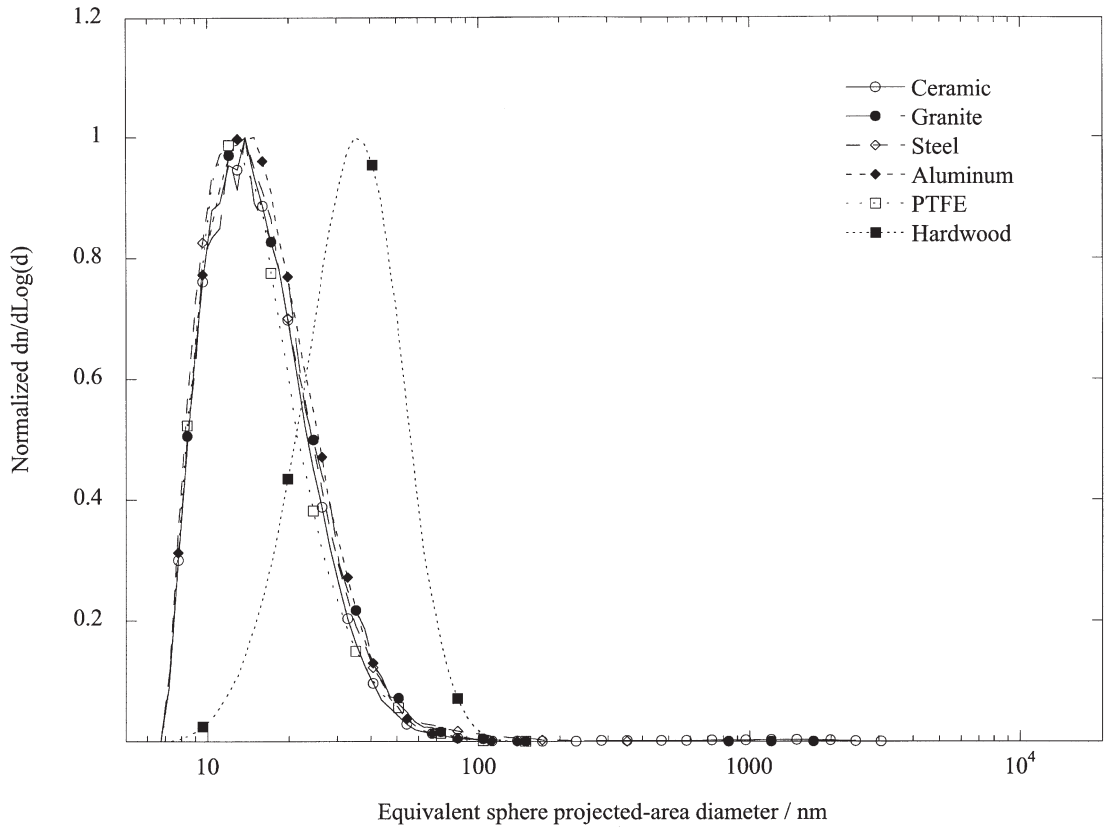

Fig. 2. Normalized aerosol number concentration as a function of particle equivalent sphere projected-area diameter, weighted by alveolar deposition probability.

with a tidal volume of 0.625 l, and also by particle surface area and volume, assuming spherical particles.

RESULTS

Figure 1 shows the measured aerosol distributions. Error bars show ±1 SD at each particle diameter, calculated from replicate sample runs.

Weighting the number concentration size distribution data by alveolar deposition probability (Fig. 2) indicates that all aerosols are dominated by ultrafine particles. All substrates except for hardwood show a similar normalized distribution. The hardwood aerosol has a significantly higher count median diameter, probably reflecting combustion-dominated aerosol generation.

Weighting the surface area concentration size distribution data by alveolar deposition probability (Fig. 3) distinguishes clearly between substrates where generation through abrasion was predicted to dominate (ceramic and granite), and those where nucleation and condensation were likely to be significant particle formation routes.

The alveolar deposition probability-weighted volume concentration size distribution (Fig. 4) places the dominant mode for each size distribution above 1 μm. However the ultrafine volume fractions of aluminum, hardwood and steel are 37, 15 and 12%, respectively, indicating that even on a mass basis the ultrafine fraction of these aerosols may be relevant.

DISCUSSION

The six substrates chosen for testing were selected to be representative of the types of material subjected to high-speed mechanical abrasion within the workplace. Ceramic and granite are hard, composite materials with high melting points, and it was predicted that mechanical abrasion, leading to the formation of large particles, would dominate the aerosol generation process. Steel and aluminum are ductile and have significantly lower melting temperatures. It was thought that for these materials the substrate interface temperature could potentially lead to vaporization and the formation of fine particles through condensation. The softness and relatively low thermal decomposition point of PTFE were expected to lead to an aerosol dominated by particle generation through vapor condensation. Charring of the hardwood was anticipated, leading to a combustion-dominated aerosol.

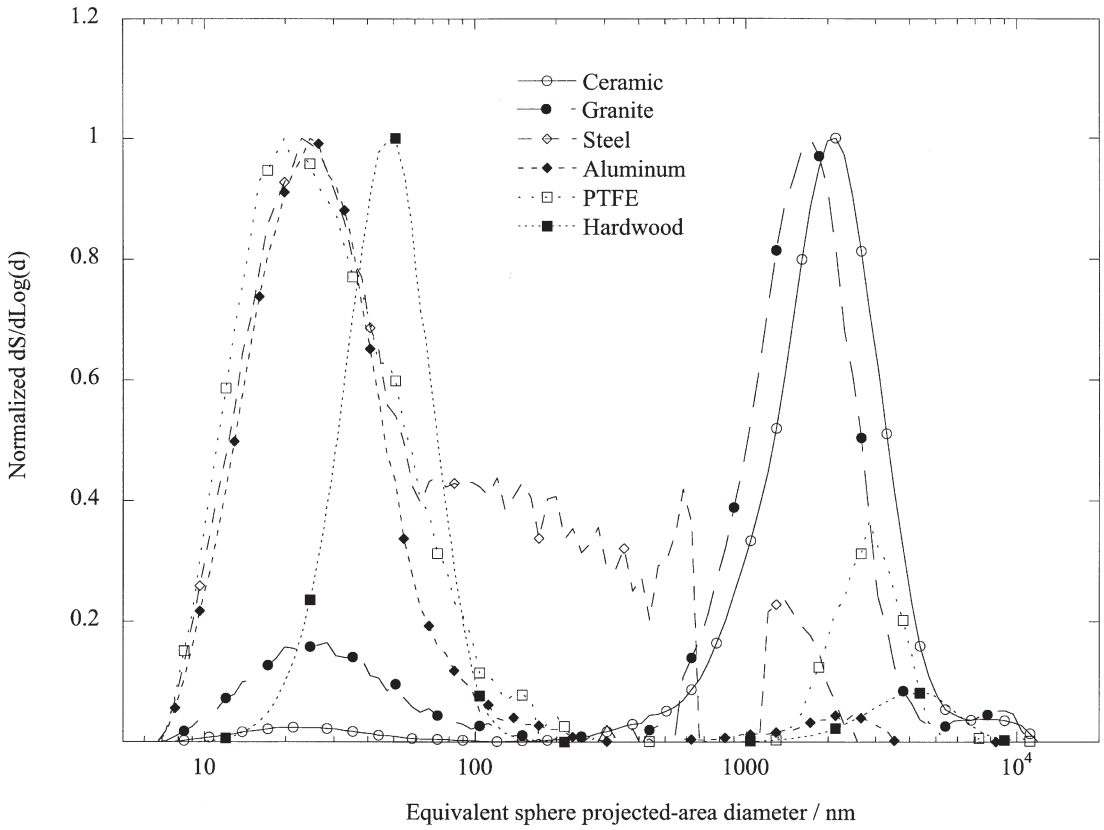

Fig. 3. Normalized aerosol surface-area concentration as a function of particle equivalent sphere projected-area diameter, weighted by alveolar deposition probability.

Examination of Fig. 1 partially supports these predictions. The granite and ceramic substrates dominate the distributions above 1 μm, while the hardwood substrate shows what looks to be a typical combustion mode below 100 nm. However, in all cases there appears to be a substantial fraction of ultrafine particles in the generated aerosol. This similarity is highlighted in Fig. 2, showing the alveolar deposition probability-weighted number concentration distributions. The subtraction of the background aerosol generated by the unloaded grinding tool would indicate that these results are directly associated with the grinding process. Negligible changes in grinding wheel rotational velocity were observed on and off the substrates, indicating that changes in rotation velocity were not responsible for the results. However, it is possible that the distributions below 100 nm are associated with an increase in particle generation rate from the Dremel as a function of loading. The aerosol generated in this region could also be associated with the aluminum oxide grinding wheel in the case of hard substrates. In either case, each distribution is indicative of the aerosol generated during high-speed grinding, irrespective of the aerosol source.

The volume-weighted distributions in Fig. 4 show that out of the six substrates only three can be said to have a significant volume component in the ultrafine region. This is important in itself, as it indicates that the mass-based analysis of combustible materials, and those likely to vaporize during mechanical processing, should be inclusive of ultrafine particles. A first inspection of the surface-area-weighted distributions (Fig. 3) indicates that the ultrafine fraction is considerably increased compared to the volume-weighted distributions, and shows a clear distinction based on the expected aerosol generation mechanisms. However, it is interesting to note that three of the distributions (PTFE, granite and steel) do not appear to conform to the expected pattern. PTFE is known to form large numbers of ultrafine particles through thermal degradation above 400°C (Oberdörster *et al.*, 1995). In this instance, although there was a clear ultrafine mode, the surface-area-weighted distribution is dominated by the super-micrometer mode. The steel distribution is unique in that above 100 nm an elongated tail extends up to micrometer diameters. A possible explanation lies in the combustion of the abraded material (seen as sparks during grinding), leading to very high initial ultrafine concen-

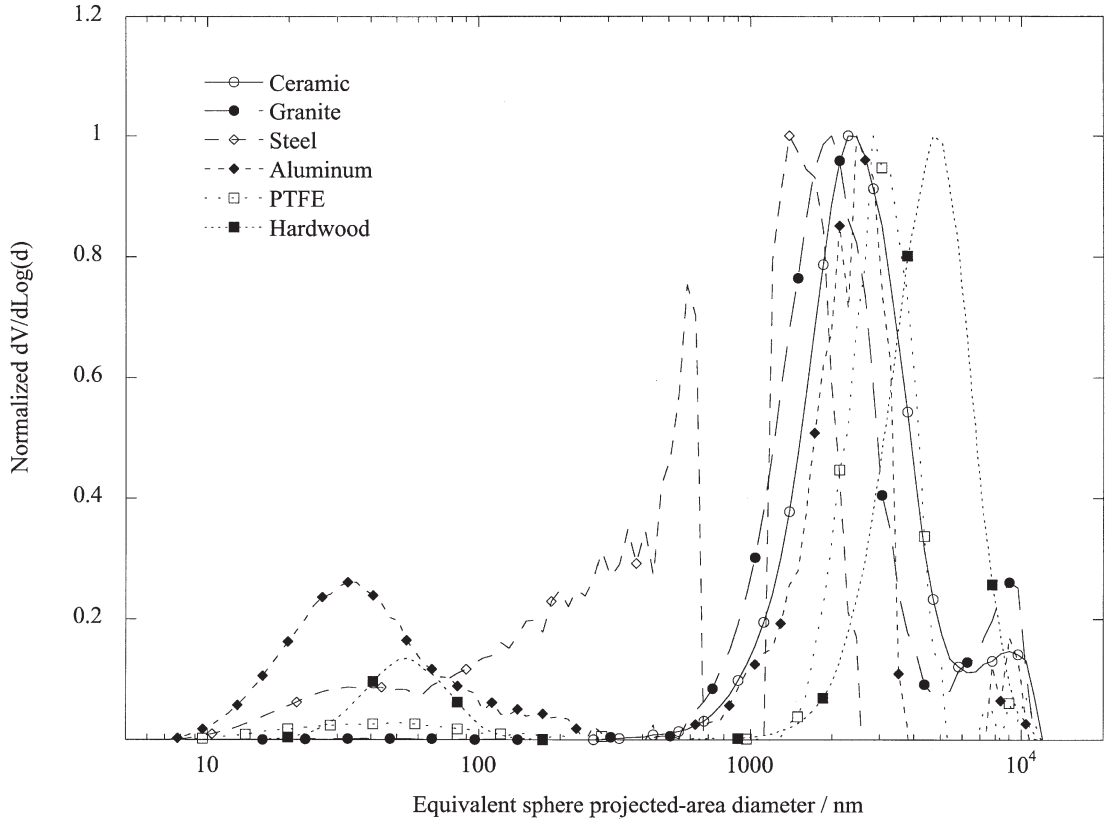

Fig. 4. Normalized aerosol volume concentration as a function of particle equivalent sphere projected-area diameter, weighted by alveolar deposition probability.

trations, followed by rapid coagulation to larger diameters. Finally, while the super-micrometer mode for granite was expected, a substantial fraction of the aerosol surface area lies below 100 nm. This is an unexpected result for grinding of this type of material, and may be significant to the generation of ultrafine silica aerosols during grinding of and drilling through silica-rich rock.

CONCLUSIONS

This investigation has demonstrated that high-speed grinding can lead to a substantial fraction of ultrafine aerosol particles in the generated aerosol, indicating that high-energy mechanical processes should be considered as potential ultrafine aerosol sources. The fraction of particles within the ultrafine region (after weighting by alveolar deposition probability) was dependent on whether the size distribution was weighted by particle number, surface area or volume. In general, it appeared that the ultrafine particles formed a substantial fraction irrespective of weighting, for materials likely to be aerosolized via combustion or vaporization/nucleation during grinding. Data from grinding granite indicated a sizeable ultrafine mode in the surface-area-weighted size distribution, in the absence of an obvious generation mechanism. It is possible that in each measured size distribution there was an ultrafine particle contribution from the grinding tool motor and the grinding wheel. Further investigation is required to isolate these components, although in the workplace it may be considered that the complete generated aerosol is more significant than the component sources.

REFERENCES

Donaldson K, Li XY, MacNee W. (1998) Ultrafine (nanometer) particle mediated lung injury. J Aerosol Sci; 29: 553–60.

Oberdörster G. (2000) Toxicology of ultrafine particles: *in vivo* studies. Philos Trans R Soc Lond A; 358: 2719–40.

Oberdörster G, Gelein RM, Ferin J, Weiss B. (1995) Association of particulate air pollution and acute mortality: involvement of ultrafine particles? Inhal Toxicol; 7: 111–24.