Particle size and metal composition of gouging and lancing fumes

Marelé Keyter, Alicia Van Der Merwe & Anja Franken

To cite this article: Marelé Keyter, Alicia Van Der Merwe & Anja Franken (2019) Particle size and metal composition of gouging and lancing fumes, Journal of Occupational and Environmental Hygiene, 16:9, 643-655, DOI: 10.1080/15459624.2019.1639719

To link to this article: https://doi.org/10.1080/15459624.2019.1639719

Published online: 30 Jul 2019.

Submit your article to this journal

Article views: 130

View related articles

View Crossmark data
Metal gouging and lancing liberate particles of an unknown size and composition. Fumes are formed when vaporized materials condense in air, creating fine and ultrafine particles which can agglomerate. Particle sizes may be <1 μm in diameter. Inhalation of this mixture of metal fumes can lead to adverse health effects. This study characterized fumes by particle size fractions and metal composition. As particles may be in the submicron range, the nano-size fraction was included. Randomized, side-by-side area samples of fumes liberated during gouging and lancing were collected. Samplers included the conductive plastic Institute of Occupational Medicine (IOM) samplers (inhalable fraction), GK2.69 stainless steel thoracic cyclones (thoracic fraction), aluminum respirable cyclones (respirable fraction), Nanoparticle Respiratory Deposition (NRD) samplers (nano-size fraction), and open-face filter cassettes (particle size distribution—PSD). Samplers were mounted at a height of between 1.3 m and 1.7 m, in the worst-case scenario area (down-wind). Forty-six samples were collected during gouging and 26 during lancing. Mass concentrations per fraction ranges (excluding nano-size) were found to be 1.27–17.27 mg/m³ (inhalable), 1.83–13.96 mg/m³ (thoracic) and 0.88–15.82 mg/m³ (respirable) for gouging; and 2.34–5.60 mg/m³ (inhalable), 2.82–4.01 mg/m³ (thoracic), and 1.89–3.24 mg/m³ (respirable) for lancing. PSD analysis confirmed the presence of nano-size particles with a mean size of 171.76 (±56.27) nm during gouging and 32.33 (±7.17) nm during lancing. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis of samples indicated the presence of chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and tin (Sn) in the respective particle size fractions (including nano-size) of both processes. Negative health effects associated with metal inhalation are well known, while nanoparticles’ unique properties enable them to cause further detrimental health effects. The nano-size fraction should be included in personal exposure assessments and control measures.

**Introduction**

Thermal metal cutting is related to welding and regularly performed by welders during gouging and cutting processes. Welding merges metal by melting it together, while gouging removes surface metal, forming a groove where molten metal was removed. Gouging can be used to remove defective welds. Air carbon arc gouging melts the base metal with an electric arc created between the tip of a copper-coated graphite electrode and the base metal where the molten metal is removed by jets of compressed air. With plasma arc gouging, an electric arc from an electrode heats and ionizes gas, creating a plasma, which is used to melt and remove metal. With adjustments to each gouging process’ operational parameters, both can be used to also cut through metal, which is then referred to as arc cutting. Oxygen lance cutting (lancing) employs the heat from the exothermic reaction between oxygen and an iron consumable pipe lance to melt and cut through the base metal.

Globally, approximately 11 million workers are employed as full-time welders, and there is an estimated 110 million workers being exposed to welding fumes during welding-related processes. These workers are a heterogeneous population employed in diverse settings that range from open areas to confined spaces employing different processes which result in extreme exposure variability. The carcinogenic potential of welding fumes was revised by the International Agency for Research on Cancer (IARC) from Group 2B (“possibly carcinogenic to humans”) to Group 1 (“carcinogenic to humans”).
based on a significant amount of epidemiological studies and a few animal studies, indicating a heightened need to prevent and/or control exposure of workers to welding fumes.\[10,11\]

Both welding and thermal metal cutting are hot work processes associated with the formation of high-temperature metal vapors\[12,13\] and the resultant metal fume emissions.\[1,12,14\] The carcinogenic risk will, therefore, also be applicable to thermal metal cutting processes.\[2\] Welding and thermal metal cutting fumes may, however, differ due to different operational parameters.\[15\] For instance, welding fume is mainly liberated from the partial volatilization of the consumable electrode (wire/filament/rod),\[8,15,16\] whereas plasma arc cutting fume is emitted from the base metal as a consumable material is absent.\[15\] Fume generation is technique dependent, even during similar hot work processes. Air carbon arc gouging forcefully air blasts molten metal from the groove, in contrast with plasma arc gouging which uses plasma gas to gently propel molten metal from the groove.\[4\] Molten metal will, therefore, vaporize to a lesser extent and consequently less metal fumes are formed during plasma arc gouging.\[4\] For welding, particle size and composition depend on the technique and the involved materials.\[9\] Small parameter alterations (e.g., voltage) can influence the quantity of ultrafine particles (UFPs) that form.\[8\] Variability between hot work processes exist and welding fume characteristics may not be applicable to other hot work processes.\[15\]

The current IARC classification\[3\] does not differentiate between carcinogenic potential of various metal mixtures and the welding or thermal metal cutting process implicated.\[11\]

Fume is formed when volatilized material condenses in air.\[16–18\] When metal is melted during hot work processes, metal vapors form\[7,12,19\] which in turn condensate in ambient air\[7,12\] to create solid particles\[12,17,18\] of fine (<2 \(\mu\)m)\[7\] and ultrafine (<100 nm) size.\[7,8,12,16,19,20\] Metal vapors form ultrafine primary metal nanoparticles (<100 nm) during nucleation.\[8,13\] Fume aging\[17\] results in aerosol growth\[8\] as primary particles collide, forming larger agglomeration chains during coagulation\[8,13\] referred to as secondary particles\[13\] in the submicron range.\[21\] The size of primary particles and agglomerates are of respiratory health interest,\[12,20\] as welding fumes are present in both configurations\[21,22\] and are <1 \(\mu\)m in diameter.\[5,21\] According to Zeidler et al.,\[9\] welding fume particle size is process dependent and may range from 10 nm to 20 \(\mu\)m,\[9\] with agglomerates in the 0.05–20 \(\mu\)m size range according to Cena et al.\[7\] Literature is, however, in general agreement that the majority of welding fumes have a mass median aerodynamic diameter of <1 \(\mu\)m (0.20–0.50 \(\mu\)m).\[8,9\]

The complex mixture of various toxic metals present in welding fume may elicit harmful health effects when inhaled\[8,9,13,16,23–25\] Acute health effects include metal fume fever\[23,24\] and chemical pneumonitis.\[26\] A decline in lung function, asthma, bronchitis, pneumonia,\[24,25\] immunosuppression,\[8,9\] and an increase in the prevalence of lung\[27,28\] and kidney cancer\[8,9\] are chronic health effects amongst others. Formed particles’ physicochemical properties influence their toxicity.\[12,13,20\]

Physical characteristics include particle size, particle size distribution (PSD),\[20\] morphology,\[12,13,25\] and particle surface area.\[13,20,25\] Particle size and shape affects the deposition location within the respiratory tract.\[13,21,25,29,30\] Chemical characteristics include solubility\[12,16,20,25\] and elemental state which may influence speciation.\[25\] The UFPs’ large surface area change their reactivity and solubility compared to larger particles. In addition, their chemical composition also differs.\[29\] Welding fume particles’ size, shape and chemical composition are diverse,\[29\] with a multimodal PSD that changes continuously, each with different chemical constituents and morphology.\[13\]

Particle size fractions of biological relevance include the inhalable (mass fraction of ambient airborne particles inhaled into the nose and mouth), thoracic (mass fraction of inhaled particles that penetrate beyond the larynx), and respirable fractions (mass fraction of inhaled particles which penetrate to non-ciliated airways) based on the difference in their aerodynamic diameter.\[31–33\] The thoracic and respirable fractions are inhalable sub-fractions.\[31,32\] The UFPs, synonymous with nano-size particles (NSPs), occur in the submicron range (<100 nm)\[7,12,19,29,34–36\] and is considered to be of greater toxicological importance compared to fine particles due to greater lung accumulation.\[36\] The extent to which UFPs are present in workplaces are not well-known as the more familiar particle-size conventions, i.e., the inhalable, thoracic and respirable size fractions usually take measurement preference.\[19\] These conventions were established for particles >1 \(\mu\)m and are based on penetration which is very different from true exposure (particle deposition).\[37\] An agreement on nanoparticle sampling criteria is absent.\[19,37,38\] NSPs have a large surface area per unit mass, and are therefore highly reactive (e.g., catalysts) with an increased toxicological activity.\[19,29,34,36,39–43\] Their ability to move to the alveoli enables them to easily become part of the blood circulation\[40\] depending on their solubility.\[15\] While
particles may de-agglomerate in the lung fluid, it is uncertain whether agglomerates keep their form or if they are broken down into aggregates or primary particles when reaching the lung surface. Lung clearance is poor as their small size is not easily recognized and phagocytized by alveolar macrophages. NSPs could, therefore, potentially more toxic responses than larger particle sizes as they are able to travel to secondary organs such as the kidneys, liver, heart, or spleen leading to pathological, morphological, and cellular changes and subsequently tissue dysfunction. Nanoparticles’ toxicological processes are somewhat unclear with a lack in comprehensive information on their effect on specific organs and cellular structures. Furthermore, nanoparticles can cross the blood-brain barrier and may damage its integrity by changing the endothelial cell membrane permeability. When reaching the brain, cellular changes may be brought about which may lead to neurological dysfunction.

This study aimed to characterize thermal metal cutting (gouging and lancing) fumes with specific interest in the metal composition of different particle size fractions. The chemical composition of the different particle size fractions, as well as the PSD, are important facets of fume characterization. Characterization of particle mass by size fractions is an important toxicity determinant as particles’ entry into and deposition in the respiratory system is dependent on their size. Smaller particles possess a much higher toxicity potential due to their unique properties such as penetration ability and large surface area.

Metal fume composition is complex—metals have different evaporation rates and the concentrations at which they occur is dependent on the workpiece and hot work process involved. Metal composition of particles in the inhalable, thoracic, respirable, and nano-size fractions were determined. The Nanoparticle Respiratory Deposition (NRD) sampler was used to quantify the metal composition in the nano-size fraction. Cena et al. described the NRD method of collecting nanoparticles as novel, since this samplers’ nanoparticle collection efficiency resembles physiological deposition in the respiratory tract. The NRD sampler differs from conventional samplers as the majority of the size-selective samplers overestimate particle deposition as they collect all particles in the particular fraction which can penetrate the respiratory tract which does not necessarily imply deposition. In addition to particle size-selective sampling (gravimetric), PSD was determined. PSD is used to determine the size of particles providing the distribution profile of particles which is important since the diameter of particles determine respiratory tract deposition location and particle clearance. Studies of welding fume characterization are abundant, with some referring to thermal metal cutting. In contrast, literature on metal mixtures in different particle sizes, present in gouging and lancing fumes in particular, are limited. Other hot work processes may have been neglected in comparison with welding with regard to fume characterization and exposure thereeto.

Methods

Site description

This study was conducted at metal workshops where gouging and lancing was performed. During gouging, a copper-coated carbon graphite electrode was used and during lancing, an iron rod ignited with an oxygen-acetylene cutting torch.

Collection of samples

Area samples of fumes generated during gouging and lancing processes were collected at various workshops. Inhalable, thoracic, respirable, and nano-size particles were collected by using a randomized, side-by-side sampling stand. No sources of potential secondary emissions could be identified, and background sampling was not conducted as it was outside the scope of this study which was the characterization of particles emitted. Samplers were mounted on a sampling stand between 1.3 m and 1.7 m which is representative of workers’ breathing zone height when working. In all instances the sampling stand was positioned in the worse-case scenario area, down-wind of the source as determined through the use of smoke tubes so that fumes liberated could be sampled optimally. The sampling stand was positioned 2 m from the source during gouging as the worker position made it possible to place the sampling stand close to the process. Due to space restriction, the workpiece size and worker position during lancing, the sampling stand was placed further away at between 5–10 m. In all instances the workers were within 1 m of the respective sources.

Conductive plastic Institute of Occupational Medicine (IOM) personal inhalable samplers (SKC Inc., Eighty Four, PA) with a 25 mm diameter, 0.8 μm pore size mixed cellulose ester (MCE) sampling filter
(SKC Inc.) were used to determine the inhalable particle size fraction (50% sampling efficiency from ~50–100 µm), set to operate at 2.0 L/min according to Methods for the Determination of Hazardous Substances (MDHS 14/4).\[52\] GK2.69 stainless steel thoracic cyclone personal samplers (BGI Inc., Waltham, MA) with a 37-mm diameter, 0.8 µm pore size MCE sampling filter (SKC Inc.) were used to determine the thoracic particle size fraction (50% cut-point of 10 µm), set to operate at 1.6 L/min according to MDHS 14/4.\[52\] Aluminum respirable cyclone personal samplers (SKC Inc.) with a 37-mm diameter, 0.8 µm pore size MCE sampling filter (SKC Inc.) were used to determine the respirable particle size fraction (50% cut-point of 4 µm), set to operate at 2.5 L/min according to the National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods (NMAM), NIOSH method 0600.\[53\] NRD personal samplers (Zefon International Inc., Ocala, FL), with eight 25-mm hydrophilic nylon mesh screens, 11 µm pore size, and 6% porosity (Zefon International Inc., Ocala, FL) were used to determine the nano-size particle fraction (50% collection efficiency of the diffusion stage for 40 nm particles), set to operate at 2.5 L/min according to manufacturer specifications.\[7, 38, 54, 55\]

The NRD sampler consists of three sections: a cyclone stage (respirable cyclone with a 50% cut-point of 4 µm; removes particles >10 µm), an impaction stage (metal impaction plate) which receives the respirable particles and further removes particles >300 nm (50% cut-point of 300 nm), and a diffusion/deposition stage where the remaining nanoparticles diffuse/deposit onto a nylon mesh screen, collecting particles <300 nm with an efficiency matching respiratory tract deposition (50% collection efficiency of the diffusion stage for 40 nm particles).\[7, 38, 54\]

Open-face filter cassettes (SKC Inc., Eighty Four, PA) with a 37-mm diameter, 0.8 µm pore size MCE sampling filter (SKC Inc.) were used to collect "total" particles in the worst-case scenario area, set to operate at 2.0 L/min according to NIOSH method 0500.\[56\] These samples were analyzed to determine PSD. One sample was collected per day at each area of sampling. A total of eight samples were collected for PSD analysis (six for gouging and two for lancing). Gilian GilAir Plus sample pumps (Sensidyne, LP, St. Petersburg, FL) were calibrated at the respective flow rates of the different samplers by means of a Gilian Gilibrator-2 Primary Standard Air Flow calibrator (Sensidyne, LP), in line with the particle size fraction-specific sampler. One field blank was collected per fraction sampling method; therefore, a total of four field blanks were collected (one field blank for the IOM sampler, one for the GK2.69 sampler, one for the respirable cyclone sampler and one for the NRD sampler). Laboratory blanks were prepared and analyzed by the laboratory for blank-correction quality control. Pump calibration took place prior to sampling and were verified after sampling. The total number of samples collected for mass concentrations and metal composition concentrations amounted to 64, which was divided into 40 samples during gouging and 24 during lancing. Inhalable, thoracic, respirable, and nano-size particles were collected over eight days. Sampling was conducted over a period of 45–108 min during gouging and 75–85 min during lancing. Both processes were dependent on work availability. The sampling duration included continuous operation of the process, therefore sampling was stopped as soon as the gouging/lancing process ceased.

**Analysis of samples**

**Gravimetric analysis**

The mass concentration of particulate matter in the inhalable, thoracic and respirable fractions were determined by gravimetric analysis (Method: MDHS 14/4, NIOSH 0600 and NIOSH 0500).\[52, 53, 56\] The pre- and post-weight of the filters was determined with a Precisa 360 EP analytical balance (Precisa Gravimetrics AG, Dietikon, Switzerland)\[57\] which has a limit of detection (LOD) of 0.01 mg and a limit of quantitation (LOQ) of 0.03 mg. Field blanks indicated that contamination did not occur during sampling while three control filters kept in the laboratory weighing room were used to correct for temperature and humidity variation. Variation was determined to be below the LOQ.

**Metal composition analysis**

After gravimetric analysis, the inhalable, thoracic, and respirable samples, as well as the nano-size fraction samples, were analyzed for metal composition by means of metal elements scan (Method: OSHA ID125G and NIOSH 7300).\[58, 59\] For analysis of the inhalable samples, the filters were removed from the IOM cassettes while care was taken to remove any dust adhering to the inside walls of the cassettes in order to include it in the metal elements scan. The metal composition of the nano-size fraction was determined from the diffusion/deposition stage of the NRD sampler. For metal elements scan analysis, a Thermo Scientific Element 2 High-Resolution Inductively
Coupled Plasma Mass Spectrometer (ICP-MS) (Waltham, MA) was used to quantify the metal elements present. After chemical analysis, the laboratory performed blank corrections. The LOD and LOQ is dependent on the element quantified during the analysis and is indicated below Figure 2. Analyses were performed by a South African National Accreditation System (SANAS) accredited laboratory. The authors acknowledge the quantitation limit of the ICP-MS analysis method and, therefore, values below the detection limit were substituted utilizing the β-substitution method as described under statistical methods.

**Particle size distribution analysis**

The eight samples that were collected using the open-face, 37-mm filter cassettes were analyzed by means of Dynamic Light Scattering (DLS) using a Horiba LB-550 PSD analyzer (Horiba Ltd, Kyoto, Japan) to determine the PSD range of the collected particles. This analysis allows particle sizing down to a diameter of 1 nm.

Particles were removed from the filter by dipping the filter into deionized water and then removing it, repeating this process until as much as possible of the dust particles were dislodged in order to avoid bias in the results. This solution was hand shaken to mix the particles and the deionized water. A sample from the dispersed dust and deionized water mixture was added to a glass cuvette cell holder by using a pipette. The cell holder with the dispersed solution was inserted into the particle size analyzer. The sample was illuminated by a laser beam through the cell holder in order to count the particles suspended in solution. Brownian motion of suspended particles brings about light scattering, and particle sizing is dependent on particle settling rate in the dispersant, as well as the refractive index. Fluctuations of the scattered light were detected at a known scattering angle by a fast photon detector. Once the analysis was complete, a distribution curve was generated taking the refractive index of deionized water into account. Particle settling rate measurement times were short in order to avoid biased average results towards lighter particle size fractions as the heavier particles settle down with time.

**Statistical methods**

For interpretation of results, descriptive statistics (mean, minimum, maximum, median and standard deviation) were determined by means of SPSS (Version 25.0 IBM SPSS Statistics for Windows, IBM Corp., Armonk, NY) and Microsoft Excel. Figures were created by means of GraphPad Prism (Version 6, GraphPad Software, San Diego, CA). The median was included as an indication of the location of 50% of the data above and below this value. A single value, such as an average, cannot describe data fully. Data of mass concentrations of each particle size fraction, in addition to mass concentrations for metals, were examined for normality (Q-Q plots and Shapiro-Wilk tests). Tests indicated a skewed data set, and data were log transformed. Data set skewness was not improved by means of log transformation and, therefore, non-parametric statistical tests were used. Gouging and lancing were compared with regard to metal concentration in all size fractions using a Mann-Whitney U test. Tests with a p ≤ 0.05 were considered as statistically significant.

Metal elements scan analysis values that were below the limit of detection were substituted with values that were calculated using β-substitution. The β-substitution method is considered to be superior to the LOD divided by two and the LOD divided by the square root of two methods, as these methods are considered to be biased. Ten samples were collected for each fraction during gouging and six samples were collected for each fraction during lancing. Fifty percent of the data should be uncensored (available) to enable β-substitution, meaning that more than half of the collected samples should have values of above the limit of detection. Where less than 50% of the data was available (less than five values for gouging and less than three values for lancing), β-substitution could not be performed and these values were not included in statistical analysis. A total of 101 values were calculated by using β-substitution.

**Ethical considerations**

The aim of this study was to determine particle size fractions and composition of the liberated fumes and not to compare concentrations with occupational exposure limits (OELs). Area sampling was, therefore, chosen rather than personal sampling, since it is unpractical to equip a worker with five personal sampling pumps. Area sampling, furthermore, eliminates the variation inherent to personal sampling due to factors that cannot be controlled by the researcher. This study was classified as a “No Risk” study by the North-West University’s risk level descriptors for health and health-related research, since no contact with human participants took place and therefore, ethical review was not required.
Results

Particulate mass concentration, PSD and metal composition were determined and results are discussed in the paragraphs that follow.

Summary of mass concentrations by process for the inhalable, thoracic, and respirable size fractions

Table 1 provides summary results for the airborne mass concentration of the inhalable, thoracic and respirable size fractions collected during gouging and lancing. Considering the range of mass concentrations measured, in addition to SD values, gouging samples showed more variance than lancing samples across all three size fractions. Based on the mean values, gouging liberated a higher mass concentration than lancing for all three fractions. If the median values are considered, lancing liberated higher mass concentrations with the exception of the inhalable fraction. These differences were, however, not statistically significant with values of p = 0.635, p = 0.093, and p = 0.181, respectively, for the inhalable, thoracic, and respirable size fractions.

Descriptive data of particle size distribution

PSD was used as an index (either in figure or table format) to depict the total number of particles (as a percentage) present in various particle size intervals. Figure 1 indicates a percentage of particles (y-axis) that fall within a specific particle size range in nanometer (x-axis) and illustrates the PSD range of fumes emitted during gouging (Figure 1a) and lancing (Figure 1b). PSD analysis revealed that gouging particles ranged from 15.0–2269 nm with a mean of 171.76 (±56.27) nm and a median of 110.40 nm and that lancing particles ranged from 11.40–76.20 nm with mean of 32.33 (±7.17) nm and a median of 31.70 nm. The PSD profile for gouging was unimodal for Day 2, bi-modal for Days 6–8 and multi-modal for Days 3 and 5 while the PSD profile for lancing was unimodal on both Days 1 and 4.

Descriptive data of metal composition of inhalable, thoracic, respirable, and nano-size particle fractions

This study used the NRD sampler to collect the nano-size fraction of particles released. This fraction was considered for metal analysis in addition to the inhalable, thoracic, and respirable size fractions. Metals were found in all particle size fractions, including the nano-size fraction. From the highest to the lowest the metal concentrations for gouging were: iron (Fe), manganese (Mn), copper (Cu), tin (Sn), chromium (Cr), nickel (Ni), and molybdenum (Mo); and for lancing: Fe, Mn, Mo, Sn, Cu, Cr, arsenic (As), lead (Pb), and Ni. Metal concentrations present in the different fractions of the different processes were compared to each other. Figure 2 depicts the mean (±SD) ambient concentration of various metals measured within the different particle size fractions during gouging and lancing. Although Cr, Cu, Fe, Mn, Mo, Ni, and Sn were present in all four particle size fractions for both processes, the mean ambient workplace concentration levels of Fe were the highest in all four fractions.

Table 1. Summary of mass concentrations by process and size-selected sampler (Note: all measurements are in mg/m³).

<table>
<thead>
<tr>
<th>Process</th>
<th>Inhalable fraction</th>
<th>Thoracic fraction</th>
<th>Respirable fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean (Min - Max)</td>
<td>Median</td>
</tr>
<tr>
<td>Gouging</td>
<td>10</td>
<td>5.95 (1.27–17.27)</td>
<td>4.91</td>
</tr>
<tr>
<td>Lancing</td>
<td>6</td>
<td>4.06 (2.34–5.60)</td>
<td>4.40</td>
</tr>
</tbody>
</table>

Figure 1. Particle size distribution of total fumes emitted during (a) gouging and (b) lancing.
Iron concentrations liberated by gouging were: inhalable: 1.44 (±1.15) mg/m³; thoracic: 1.80 (±1.78) mg/m³; respirable: 1.70 (±2.38) mg/m³; nano-size: 0.30 (±0.16) mg/m³ and for lancing: inhalable: 1.09 (±0.61) mg/m³; thoracic: 1.42 (±0.24) mg/m³; respirable: 1.34 (±0.28) mg/m³; nano-size: 0.30 (±0.04) mg/m³ with no statistical significant difference between the different fractions of the two processes.

Of the other metals (Cr, Mn, and Sn), only Cu, Mo, and Ni showed significant differences between gouging and lancing. For Cu, all four fractions of gouging were significantly higher than the fractions of lancing (p < 0.016) while Mo concentrations were highest in the four fractions of lancing. This difference was significant (p ≤ 0.024), with the exception of the inhalable fraction. All four fractions of gouging were the highest with regards to Ni. This difference was, however, only significant (p = 0.019) concerning the nano-size fraction. With respect to As and Pb, more than 50% of the metal analysis result values of gouging samples were below the detection limit. In contrast, lancing samples had quantifiable levels of As and Pb as indicated in Figure 2.

For both processes, “other hard metals” included aluminum (Al), barium (Ba), cobalt (Co), magnesium (Mg), titanium (Ti), zinc (Zn), and zirconium (Zr) while “other elements” included calcium (Ca), potassium (K), selenium (Se), and sodium (Na) and in each case no significant differences between fractions were found.

Discussion

Mass concentrations of inhalable, thoracic, and respirable size fractions

This study contributes to limited literature on particle size and metal composition of airborne particulate matter present in gouging and lancing metal fumes. Comparison of results with existing literature were, therefore, restricted. The higher variance in mass concentrations for all three fractions with regard to gouging when compared to lancing stood out. This may be due to a limitation of this study, in the sense that gouging samples were taken closer (2 m) to the source, in contrast with lancing samples which were taken further away from the source (5–10 m). Samplers close to an emission source would be subjected to air in which the pollutants have not had time (distance) to disperse uniformly. This scenario would explain the higher variance in mass concentrations measured during gouging. In contrast, samplers located further away from the emission source would have been subjected to air in which the contaminants would have had time (distance) to mix more uniformly resulting in less variance.

While gouging resulted in higher mean mass concentrations over all three size fractions, the inverse was true when the median values were considered (with the exception of the inhalable fraction). This apparent anomaly is explained by the absence of a significant difference in mass concentrations between the two processes over all three size fractions. This is an unexpected result as one would have expected, based on visual observations, that lancing liberated more fumes. The absence of a quantifiable difference may, once again, be explained by the difference in sampling distance as lancing fumes would have had more time (distance) to disperse in ambient air than gouging fumes.

Figure 2. Mean ± SD ambient concentrations of various metals emitted in the workplace during (a) gouging and (b) lancing processes in the inhalable, thoracic, respirable, and nano-size fractions. As and Pb concentrations were below detection limits for gouging. The y-axis is shown in log scale. (LOD of analysis method: 0.00016 mg/m³. LOQ for analysis method: 0.0005 mg/m³).
Particle size distribution

The Dynamic Light Scattering device quantified the PSD of particles in gouging and lancing fumes. As illustrated in Figure 1, particles < 100 nm in diameter were collected, which is consistent with literature indicating the release of nanoparticles during hot work processes.\[22,28,36,66\] The variation in particle size (range) seen during gouging was much larger than that of lancing. This implies that particles released during gouging are much more varied in size than particles released during lancing. This may be explained by the nature of the process involved with the fumes formed during gouging being dependent on the cutting of the base metal and other variables such as the temperature (current) at which cutting takes place which can be controlled by the worker.\[4,15\] In contrast, it could be argued that the fumes released during lancing are primarily dependent on the metal lancing rod being consumed and secondly on the base metal being cut implicating less variables which could affect the size of particles formed.

Hot work processes liberate nanoparticles\[7,8,12,13,15–22\] which may agglomerate to form larger chains\[7–9,15–17,20\] within the micrometer range\[5,13\] resulting in a decline in nanoparticle concentrations further from the source.\[7\] Based on median values obtained from the PSD analysis, it is clear that particles released during gouging are at least three times larger than particles released during lancing. Should lancing be considered a process with a higher particle formation rate than gouging, one would expect agglomerated particles (diameter > 100 nm) in favor of nano-size particles which is not the case, in contrast with what was found by Brand et al.\[36\] The reason thereto remains unclear as one would have expected lancing particles to have had more time (distance) to agglomerate.\[7\] the smaller size and narrower size range of particles indicate otherwise. Welding fume formation, particle movement,\[67\] and coagulation\[36\] are complex as these fumes change considerably through space and time.\[67\] This statement is probably true for gouging and lancing as well. The lack of agglomeration pertaining to lancing fumes may be explained by the exothermic process involving the rapid reaction of the metal lancing rod with oxygen and should be investigated further.

Considering the PSD profile for gouging inter-day variability seems pronounced while less so with lancing. This observation may, again, be ascribed to the additional variables at play during gouging such as current and operator use in contrast to that of lancing.\[4\] One should, however, be cautious to make any meaningful deductions from this observation due to the limited number of samples taken during lancing.

Metal composition of inhalable, thoracic, respirable, and nano-size particle fractions

Metals were found in the nano-size fraction of fumes released during gouging and lancing. This corresponds to the findings of Cena et al.\[28\] who found significant amounts of metal particles in the nano-size fraction during welding operations. In addition to Mn, Cr, and Ni identified by other authors to be present in the nano-size fraction, this study also quantified Cu, Fe, Mo, and Sn in both processes and also As and Pb in lancing samples. The type of metals found in the gouging and lancing samples were typical constituents of fumes released during hot work processes,\[5,23–25\] of which many may be in the nano-size range.\[7\] In both processes, Fe had the highest mean concentration in all four fractions. Considering that the main constituent of welding fume is Fe,\[9,68\] this was to be expected. Fe, which is regarded as a nuisance dust with a limited probability of causing chronic lung ailments, has been shown to accumulate in the lungs of welders that have been active for years, but usually lead to less harmful conditions such as siderosis.\[9\] Its toxicity, however, is unclear with conflicting evidence regarding its carcinogenicity as it co-exists with other welding fume constituents\[69\] with Fe-rich mild steel welding fumes having been associated with an increase in lung cancer risk.\[9\] As with the mass concentrations discussed earlier, no significant difference in Fe concentrations between gouging and lancing was found. This is unexpected as one would have thought that the consumption of the Fe lance would have liberated higher Fe concentrations. The absence of a quantifiable difference may, once again, be explained by the difference in sampling distance.

The significantly higher Cu concentrations quantified across all four gouging fractions may be ascribed to the use of copper-coated carbon graphite electrodes.\[5\] It is plausible that the significantly higher Ni concentrations may also be due to the use of these electrodes which may contain Ni as a contaminant often associated with Cu. The reason for the significantly higher levels of Mo in the respirable, thoracic, and nano-size fractions of lancing samples are less clear but may be due to the use of Mo as alloying agent in the manufacturing of thermal lances. Similar to Mo, the presence of As and Pb in lancing fumes may be due to the composition of thermal lancing rods or due to contamination. The absence of literature on the general composition of lancing consumables make any meaningful deductions difficult.

Some of the metals that were present in the gouging and lancing fumes are confirmed human carcinogens.
such as As, Cr(VI) and Ni. Exposure to different metals could lead to metal interaction which result in synergistic effects. When a person is exposed to more than one metal, this interaction might intensify the toxicity of other metals that are present in smaller concentrations. Attributing a health outcome that arise from welding fume exposure to a particular constituent of the fume mixture is complex and an elaboration on the toxicity of individual elements is beyond the scope of the study.

Limitations and future investigations

The placement of samplers during lancing was to some extent dependent on the lancing process itself. Samplers were placed further away (5–10 m) from the workpiece in order to avoid impeding on the lancing process. In contrast, gouging samplers were placed closer (2 m) to the gouging process. The difference in distance between gouging and lancing may have influenced the concentration, size, and distribution of particles which limited our ability to make direct comparisons between gouging and lancing. The primary aim of this study was, however, not to compare the two processes but rather to characterize metal fumes emitted from thermal cutting methods. The difficulty to control variables in the workplace and even in controlled settings due to process limitations have been highlighted elsewhere. In endeavors to directly compare emissions from hot work processes, future studies should attempt to ensure equal sampling distances.

During hot work processes, metal fumes may originate from either the base metal worked on, the consumables used in the process (e.g., welding rods, electrodes, and thermal lancing tubes among others) or a combination of both. These variables may vary greatly between tasks and will impact on the final metal fume composition. A limitation of this study is the unknown metal composition of the base metal that was gouged and lanced as this information was not available. The limited number of samples taken during lancing for the purpose of PSD analysis hampered our ability to make more meaningful conclusions other than that nano-size particles were present in lancing fumes.

A further limitation was observed with pump flow rate deviations of ±5% as verified after sampling. This may be due to filter loading. Cellulose ester membrane filters’ loading capacity is restricted as particulates accumulate on the filter surface. The small pores may become clogged during sampling, which increases resistance to airflow. Pumps compensate for increases in resistance in order to maintain a constant flow rate, e.g., when backpressure increases during filter overloading. Pumps may, however, not be able to readjust the flow rate with a high pressure drop, such as with filters that have small pore sizes, i.e., <1 μm. The authors speculate that filter overloading within a short sampling period occurred with thoracic, respirable, and PSD sampling. This highlights the complications found during sampling in workplace conditions.

Conclusions

This study confirmed the presence of metal particles in gouging and lancing fumes ranging from the nanosize to the inhalable size fraction. Apart from the mass of particles, their size is also of health relevance. This is especially true for nano-size fractions (<100 nm) which have an increased surface area to mass ratio compared to bigger particles. A strong correlation exist between the large surface area of nanoparticles and their toxicity, rather than particle mass. A number of metals were, furthermore, detected in all of the size fractions, including the nano-size fraction, with the majority classified as carcinogenic or potentially carcinogenic. While welding fumes are classified as a human carcinogen, this does not exclude other hot metal processes such as thermal metal cutting (e.g. gouging and lancing). This study indicates the importance of including the nano-size fraction in exposure sampling, and that the occupational risk of gouging and lancing should be considered to be equal to that of welding. Nanotoxicology research may still be premature, and the development and implementation of standards for protecting workers may take years. Our study has indicated that workers are potentially exposed to particles in the inhalable, thoracic, respirable and nano-size fraction. Repeated exposure over a long period of time may lead to the development of health effects, from the upper-respiratory tract to the deepest structures of the lungs and also other areas and target organs in the body.

Recommendations

Nanoparticles remain airborne for longer periods of time when compared to their larger counterparts and are highly mobile. Nanoparticles in gouging and lancing fumes could therefore also expose workers in the immediate vicinity. In light thereof, the following...
recommendations are made: (i) local exhaust/mechanical ventilation systems with high-efficiency particulate air (HEPA) filters should be installed in gouging and lancing areas; (ii) mobile fume extractors with retractable arms could be used in workshops to control fume exposure; (iii) administrative controls such as reduction of work periods and/or rotation of workers should be implemented; and (iv) personal protective equipment (PPE) may be used in addition to other control measures as the health risk profile of nanoparticles are still unknown. PPE may include clothes made out of woven fibers, with sealed seams, covered zippers, and gloves (wearing of a disposable glove underneath a reusable glove) to prevent dermal exposure. Respiratory protective equipment may include air-purifying respirators with P95 or P100 (FFP2) filtering media in conjunction with welding helmets to prevent respiratory exposure.

Acknowledgments

Ms. Marike Cockeran (North-West University: Statistical Consultation Services) is acknowledged for her contribution to data analysis and interpretation. The authors will not provide access to the study data. The authors would also like to thank each and every person who made a contribution to this study in any way. Last but not least, this article has been substantially improved as a result of the reviewers’ guidance and input, and the authors are thankful for their time and effort.

Funding

This study was funded by a world-class mining group. The authors declare that there is no conflict of interest to disclose.

ORCID

Marelé Keyter http://orcid.org/0000-0002-9301-6305
Alicia van der Merwe http://orcid.org/0000-0001-7641-4638
Anja Franken http://orcid.org/0000-0001-9774-4759

References


Chang, C., P. Demokritou, M. Shafer, and D. Christiani: Physicochemical and toxicological


