Journal of Hazardous Materials 203–204 (2012) 308–316

Contents lists available at SciVerse ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Identification and chemical characterization of particulate matter from wave soldering processes at a printed circuit board manufacturing company

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ARTICLE INFO

Article history:
Received 29 August 2011
Received in revised form
25 November 2011
Accepted 10 December 2011
Available online 19 December 2011

PACS:
82.80.Ej
82.80.Yc
92.60.Sz
68.37.Yz

Keywords:
Wave soldering
Workplace aerosol
Ion beam analysis
PIXE
Single particle analysis

ABSTRACT

In this case study, the elemental composition and mass size distribution of indoor aerosol particles were determined in a working environment where soldering of printed circuit boards (PCB) took place. Single particle analysis using ion and electron microscopy was carried out to obtain more detailed and reliable data about the origin of these particles. As a result, outdoor and indoor aerosol sources such as wave soldering, fluxing processes, workers' activity, mineral dust, biomass burning, fertilizing and other anthropogenic sources could be separated. With the help of scanning electron microscopy, characteristic particle types were identified. On the basis of the mass size distribution data, a stochastic lung deposition model was used to calculate the total and regional deposition efficiencies of the different types of particles within the human respiratory system. The information presented in this study aims to give insights into the detailed characteristics and the health impact of aerosol particles in a working environment where different kinds of soldering activity take place.

1. 1.Introduction

Several studies have shown that aerosol particles have a negative impact on human health [1–3]. The risk from the inhaled particles depends on their chemical composition, their size distribution as well as their deposition in the human respiratory system. Research of particulate matter (PM) toxicity has shown that, in general, the smaller PM size fractions (< PM_{10}) have the highest toxicity through containing higher concentrations of extractable organic matter (comprising a wide spectrum of chemical substances), and possessing a relatively high radical-generating capacity [4,5]. Since smaller particles have a larger surface area, these particles can transport a greater amount of toxins into the lower respiratory tract, leading to more adverse health effects [6]. In workplaces fine and ultrafine particles are often associated with anthropogenic activities such as soldering, smelting, welding and spraying [7–10].

It is well known that the electronics products industry has exposed workers to high doses of metals [11]. Several studies have reported that the inhalation of metal dust and fumes is associated with adverse health effects such as metal fume fever and other respiratory diseases [12–14]. Quansah and Jaakkola [13] have shown that maternal exposure to metal dust or fumes during pregnancy may reduce fetal growth. They also implied that paternal exposure to welding fumes may increase the risk of preterm delivery and small-for-gestational age. Because of these facts it is crucial to analyse PM (with metal content) in environments where people are working in a restricted space during long periods of time.

Tin is the most abundant heavy metal used in soldering processes. An adverse health effect on workers exposed to tin oxide from the smelting or production of tin has been observed in studies and it has been documented as stannosis [14]. Through the occupational contamination of clothing, tin can also appear in indoor dust at the homes of the workers [15]. Lead, one of the most toxic metals that can appear in this kind of workplace, affects the brain and the nervous, renal, reproductive and cardiovascular systems (e.g. a review by Chang, [16] and Golub [17]). Long-term exposure to

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doi:10.1016/j.jhazmat.2011.12.030

lead can cause nephropathy and colic-like abdominal pains, and can result in decreased performance in certain tests that measure functions of the nervous system [18]. According to Lilis et al. [19], lead containing indoor PM induced biological effects on workers. However, most studies dealing with lead-containing PM have focused on the environmental effect of outdoor aerosols and only a few of them have dealt with indoor PM collected at workplaces.

To the best of our knowledge, there is as yet no study concerning the chemical composition and the mass size distribution of PM originating from wave soldering processes.

In this case study our aim was to determine the parameters which might help to better estimate the impact on human health in a workplace where the soldering and testing of different kinds of printed circuit boards (PCBs) and other electronic components takes place. Wave soldering is one of the main processes used for attaching metal components to the board during the manufacturing of PCBs [20]. The name is derived from the use of waves of molten solder. The constituents of the solder alloy are dependent on the type of wave solder e.g. leaded (Sn–Pb) or lead free wave solder (Sn–Ag–Cu–Sb) [21]. Since lead is one of the common solder alloys, knowledge of the workers' exposure to this element was particularly important. We utilized a stochastic lung model to calculate the total and regional deposition efficiencies of the different types of particles within the human respiratory system (in the case of different activities: sitting and manual work) [22–24].

2. Experimental

2.1. Sampling

Two 48-h long sampling campaigns were carried out. One was in October 2008 and the other was in May 2009. Aerosol samples were collected in a large working hall where approximately 100 people (male and female) worked. In this working environment the production, soldering, and testing of different kinds of PCB and other electronic components took place. Hence several supply air ventilators operated continuously during working hours, ensuring that only filtered air got into the hall. During the first sampling in 2008 the employees worked around the clock but during the second sampling campaign in 2009 there were only two shifts. From 2008 to 2009 some of the leaded wave solders were put out of operation or switched to lead-free alternatives.

Two different sampling devices were used at the abovementioned work location. One was Nuclepore two-stage samplers. This sampling head collects the aerosol particles in two size fractions: the fine ($PM_{2.5}$= particles with aerodynamic diameter less than 2.5 μm) and coarse ($PM_{2.5-10}$= particles with aerodynamic diameter bigger than 2.5 μm). Two Nuclepore polycarbonate filters with 8 μm and 0.4 μm pore diameter are placed one behind the other in the sampling head, and the air is pumped through this system with 250–300 l/min flow rate. Coarse particles are deposited on the filter with 8 μm pore diameter, while fine particles passes through its pores, and are collected on the other filter.

In addition, a ten-stage PIXE International cascade impactor [25] was used to provide size resolved samples in the following ten fractions >16, 16–8, 8–4, 4–2, 2–1, 1–0.5, 0.5–0.25, 0.25–0.12, 0.12–0.06 and <0.06 μm aerodynamic diameter. These samples were collected on kapton foils. In the first campaign the sampling was done next to a lead-free wave solder equipment (the main constituent of the melt were Sn, Ag and Cu), at a height of 1.5 m above ground. During the second sampling campaign, in addition to the previous spot, samples were collected at 3 other sites in order to obtain information about the distribution of the aerosols in the hall. Aerosol samples were collected in the following sites: next to 2 wave solders (in one of them unleaded and in the other leaded melt was used), below a supply air ventilator and close to a location named "store of hazardous materials". The two wave solders (leaded and unleaded) were approximately 10 m apart from each other. The ten-stage PIXE International cascade impactor was only used at the ULWS in both campaigns. Outdoor aerosol samples were also collected parallel to the campaigns in an urban background site, the garden of ATOMKI, approximately 4 km away from the workplace. This sampling was carried out with a two stage Gent stacked [26] filter unit equipped with Nuclepore polycarbonate filters of 8 μm diameter and 0.4 μm pore size.

2.2. Analysis

The total mass concentration was determined by gravimetry. The aerosol filters were conditioned at least 24 h before weighing in the weighing room at 24 °C temperature and 56% relative humidity.

The analytical quantification of aerosols was done by the particle-induced X-ray emission (PIXE) method. PIXE is based on the detection of characteristic X-rays induced by a 2–3 MeV energy proton beam. PIXE is a widely applied multielemental analytical technique in atmospheric aerosol research [27].

The elemental compositions (for $Z \geq 13$) of the bulk samples were measured in the PIXE chamber installed on the left 45° beamline of the 5 MV Van de Graaff accelerator in the IBA Laboratory of ATOMKI. The details of the setup are reported here [28]. The samples were irradiated with a proton beam of 2 MeV energy. The beam spot had a diameter of 5 mm. The beam intensity was typically 40 nA, and the accumulated charge on each sample was 40 μC.

Samples collected with the impactor were further analysed by ion microscopy at the Debrecen scanning ion microprobe facility [29,30]. In this case, the samples were irradiated and scanned by a focused (1.5 μm × 1.5 μm) proton beam. The proton energy was 2 MeV. The concentration and distribution of the elements were determined by light element PIXE and PIXE techniques [31,32].

Additional elemental and morphological analysis was performed using a HITACHI S-4300 CFE scanning electron microscope at the Department of Solid State Physics, University of Debrecen. The SEM analysis was carried out on selected samples where the concentration of Sn or Pb was high. Since the applied nuclear analytical techniques are non-destructive, the same samples were used for the SEM analysis. These were the kapton foil of 0.5–1.0 μm size fraction in the impactor and the coarse fraction ($PM_{2.5-10}$) filters.

2.3. Data evaluation

In the case of bulk PIXE measurements, the evaluation of the X-ray spectra was done with the PIXECOM program package [33]. In the case of the ion microprobe measurements, signals from all detectors were recorded in list mode files by the Oxford type data acquisition system (OMDAQ) [34]. The spectra were evaluated with the PIXEKLM-TPI computer code reckoning with the thickness (size) of the particles [35].

On the basis of the obtained data, the total and regional deposition efficiencies of the different types of particles within the human respiratory system were calculated by using the newest version of the IDEAL stochastic lung deposition model [36,37]. This model is under continuous development and it was originally developed by Koblinger and Hofmann [22–24]. The ratio of deposited particles in the extrathoracic, tracheobronchial and the acinar regions was calculated for an adult male and female under sitting and light exercise breathing conditions. The stochastic term means that this model use Monte Carlo simulations to generate several geometric parameters: generation number, diameter of airways, length of airways, diameter of daughter branches, length of daughter branches, branching angles. To calculate particle trajectories, the model takes into consideration the main deposition mechanisms, that is inertial