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Health Risk Assessment of Inhalable Dust Exposure during the Welding and Grinding Process of Subway Aluminum Alloy Components

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Abstract: The subway factory industry is developing rapidly in China, but there are some occupational health risk assessments of inhalable dust in this industry. Therefore, this study aimed to explore the contamination level and health risks of dust in an aluminum alloy body workshop of subway factories in Hunan Province, China. A total of 160 dust samples were collected from the welding and grinding areas. The main elements of PM_{10} were analyzed. The health risks of aluminum dust and $PM_{2.5}$ were evaluated. The Monte Carlo method was adopted to compare the sensitivity of the Hazard Quota (HQ) of aluminum dust and carcinogenic risk (CR) of $PM_{2.5}$ to the exposure parameters for workers. The results showed that the PM_{10} concentration in the grinding area was higher, while the $PM_{2.5}$ concentration in the welding area was higher. The metal element with a mass fraction of 27.7% was aluminum. In both areas, the probability of the aluminum dust HQ exceeding 1 was approximately 17% and 68%, respectively. The $PM_{2.5}$ CR exceeded the acceptable upper limit value (1.0×10^{-4}). The main risk factor of aluminum dust HQ was concentration, while the main risk factors of $PM_{2.5}$ CR were concentration and exposure duration. These findings provide basic data for enhancing health risk management in the subway industry.

Keywords: inhalable dust; health risk assessment; quantitative evaluation; sensitivity analysis

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1. Introduction

With the acceleration of China's urbanization process, the subway has become an important part of urban public transportation. In the subway factory industry, aluminum products are widely used for welding because of their unique physical and chemical properties [1], and the performance and lifespan of welded products, such as the subway aluminum alloy car body, are directly affected by welding quality [2]. During the welding and grinding processing of aluminum subway components, a large quantity of dust particles is inevitably generated. In the post-pandemic era, the human health risks of particulate matter have received widespread attention. These dusts contain harmful metallic elements and metal oxides, such as Aluminum, Manganese, etc. [3] Long-term exposure to low doses of these dusts, especially $PM_{2.5}$, is very detrimental to worker health [4,5]. Fine particles entering the human body will harm human organs such as the respiratory tract, heart, lungs and blood vessels [6]. For example, the heart rate variability of shipyard welders is mainly caused by their exposure to welding fumes [7]. The metal oxide of aluminum in welding smoke is the main cause of metal fume fever, which may trigger respiratory problems [8]. Therefore, it is necessary to monitor the dust concentration and accurately assess the health risks of dust to enhance the management of the subway factory working environment.

Over the past few decades, extensive research has been conducted in particle properties and their interactions with human health [9]. Numerous reports on the health risk assessment of dust exposure have also been published. Huang et al. [10] investigated the characteristics and health effects of the fine particulate matter ($PM_{2.5}$) at the subway sites in

Chengdu, China. The results showed that arsenic was the predominant element affecting the potential non-carcinogenic and carcinogenic risks of subway workers. Alias et al. [11] identify the composition and health risk of $PM_{2.5}$ in naturally ventilated schools located in the state of Selangor and Kuala Lumpur in Peninsular Malaysia. The authors found that for all stations, the Hazard Quota (HQ) value was lower than the acceptable limits, while the excess lifetime carcinogenic risk (CR) value was slightly higher than the acceptable level (1.0×10^{-6}) for Cr and Ni. Wang et al. [12] conducted a health risk assessment on exposure to particulate matter and other air pollutants in the underground parking garage environment under natural ventilation conditions in Xi'an, China. The results indicated that the entropy values of cardiac and non-cardiac risks of staff were the highest. Hamzah et al. [13] investigated the association between metal dust exposure and respiratory health in male factory workers. Dueck et al. [14] found that compared to welder apprentices, professional welders should pay more attention to the health risks of the exposure to manganese in inhalable particles. Tong et al. [15] analyzed contamination levels and health effects of automobile factory dust. The results showed that reducing the average time spent in the factory could effectively mitigate the health risks of dust to workers. In automotive plants, the method of local exhaust ventilation could also reduce worker particle exposure [16]. However, few studies have been conducted on the health risk assessment of dust in the welding and grinding environment of subway factory industries.

Furthermore, the Monte Carlo simulation method is a very effective method for the human health risk assessment of environmental contaminants. Dehghani et al. [17] adopted the Monte Carlo simulation technique to assess the health risks of heavy metal exposure in a steel plant, and found that further improved control measures should be proposed for reducing the occupational exposure levels. In addition, quantitative health risk analysis based on the Monte Carlo simulation can provide an important scientific basis for evaluating potential human risk assessment [15,18]. Therefore, this probabilistic simulation method was employed to analyze the uncertainty of exposure parameters in this study.

We selected an aluminum alloy body workshop within subway manufacturing plants located in Hunan Province, China as a case study. First, dust samples in the welding and grinding areas were collected at fixed points. In addition, the dust mass concentrations were determined via the membrane-weighing method. Then, the probabilistic health risk evaluation model was adopted to evaluate the non-carcinogenic Hazard Quota (HQ) and carcinogenic risk (CR) of inhalable dust. Finally, the sensitivities of the exposure parameters influencing the HQ and CR of dust were investigated. The research results could provide reference for managers to make health risk management decisions in the subway factory industry.

2. Materials and Methods

2.1. A Subway Aluminum Alloy Body Workshop

At present, China has taken the global lead in terms of the speed and scale of subway system planning and construction. With the increase in Gross Domestic Product (GDP), major cities in China tend to develop longer subway systems [19]. Thus, an aluminum alloy body workshop within subway factory industries in Hunan Province was selected in this study. In the workshop, the subway aluminum alloy bodies are welded and grinded. Their sizes were 67 m long × 18 m wide × 15 m high. The dust generated mainly included welding fumes and grinding particles. A displacement ventilation system with 14 cylindrical air supply outlets (2 m height) and 14 louvers return air outlets (12.5 m height) was adopted to meet the indoor air quality of the Chinese mandatory national occupational health standard "GBZ 2.1—2019 Occupational exposure limits for hazardous factors in the workplace Part 1: Chemical Hazardous Factors" [20].

2.2. Sample Collection and Analysis

A total of 160 dust samples were collected from 8 to 21 June 2020 under normal welding and grinding conditions. The fixed-point sampling process follows the national standard "Specification for Air Sampling for Monitoring Hazardous Substances in the Workplace" [21]. As shown in Figure 1, two sampling points (S1–S2) are set up in the welding and grinding area (height 1.5 m) of the workshop, where S1 is located in the welding area and S2 is located in the grinding area. In this study, the mass concentrations of total suspended particulate matter (TSP), PM_{10} and $PM_{2.5}$ were monitored and recorded. The surface charge of particles is a common phenomenon. For example, laser printers emit negatively charged particles during operation [22]. The maximum surface charge density of large spherical particles in a normal atmosphere is 27 $\mu C/m^2$, and decreases inversely with the increase in the square root of particle size [23]. When charged colloidal particles interact with oppositely charged ions, they can form relatively large aggregates that are stable for days or weeks [24]. In order to avoid the influence of particle surface charge on sample collection, a neutral adsorption film, namely carbon support film (effective diameter of the membrane Φ40 mm, China), was selected in this study. An intelligent small-flow $TSP/PM_{10}/PM_{2.5}$ sampler (Laoying 2030D, Qingdao, China) equipped with the carbon support membrane was used for dust sampling with a flow rate of 16.67 L/min. During the two-week period, samples were collected at each sampling point at 9:30–9:45, 11:00–11:15, 14:30–14:45, and 16:00–16:15 on each weekday for 15 min.

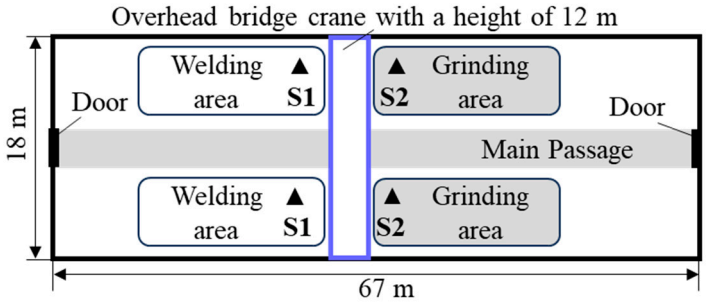


Figure 1. Location of the sampling points in the welding and grinding area.

The dust concentration was calculated using the membrane increment method. All membranes were placed in a desiccator for 2.5 h prior to sampling. Then, the weight and number of these membranes were recorded. At each sampling point, a dust sampler equipped with a filter membrane collected a 15 min air sample at the height of the breathing belt of the welding and grinding workers. After dust sampling, the membrane was accurately weighed using a microbalance with a sensitivity of 0.01 mg. When the diameter of the filter membrane was 40 mm, the increase in the total dust of the filter membrane should have been controlled within the range of [0.1 mg, 10 mg] to avoid dust falling off due to overload. The dust concentration in the working environment in the workshop was equal to the dust increment of the filter membrane divided by the volume of the air sample. The main elements and their weight percent of dust sample micro-area in the welding and grinding area were analyzed using the method of scanning electron microscopy combined with energy spectroscopy method.

2.3. Health Risk Assessment

This study aimed to evaluate the dust health risks of welding and grinding workers in an aluminum alloy body workshop of subway factory factories. Therefore, the purpose of this study was to evaluate the health risks of inhalable exposure to aluminum dust and $PM_{2.5}$. A non-carcinogenic HQ greater than 1 indicates that the worker is at risk of developing adverse health effects, and the opposite means that there is less health risk. The HQ of respirable dust is calculated as follows [25]:

$$HQ = ADD/RfC \quad (1)$$

$$ADD = \frac{C \times IR \times ET \times EF \times ED}{BW \times AT} \quad (2)$$

where RfC is the reference concentration, mg/m^3; RfCs for $PM_{2.5}$ [25] and aluminum dust [26] are 0.005 mg/m^3, respectively; ADD is the average daily dose (ADD) of indoor air pollutants inhaled through the respiratory tract, mg/(kg·d); C is the mass concentration of air pollutants inhaled through the respiratory tract, mg/m^3; BW is the body weight, kg; IR is the inhalation rate, m^3/d. Based on data from Ref. [27], the linear fitting relationship between IR and BW is: IR = 0.0325 × BW + 0.6045 (R^2 = 0.9985).ET is the exposure time, h/d; EF is the exposure frequency, d/a; ED is the exposure duration, a;AT is the average exposure time, h. AT for non-carcinogenic effects: ED × 365 × 24 (h). For carcinogenic effects fixed as: 70 × 365 × 24 = 613,200 (h).

The CR values were divided into three scales: an insignificant CR less than 10^{-6} indicated a negligible CR, an acceptable CR value between 10^{-6} and 10^{-4} indicated that the CR should be considered, and a significant CR value greater than 10^{-4} indicated a strong CR must be considered [28–30]. The CR value of $PM_{2.5}$ through the inhalation route was calculated as follows:

$$CR = ADD \times IUR \times CF \quad (3)$$

where IUR is the inhalation unit risk, IUR for $PM_{2.5}$ is 0.008 $(\mu g/m^3)^{-1}$; CF is the conversion factor, 1000 μg/mg.

2.4. Sensitivity Analysis

As a very important class of methods, sensitivity analysis has been widely applied in many research fields, such as the occupational health risk assessment. It could quantitatively describe the importance of risk assessment model input variables to output variables. Monte Carlo simulation, which is a technique used to perform sensitivity analysis, could be used to quantitatively assess the health risks of air pollutant exposure and deal with the uncertainties associated with it [31,32]. Based on the Monte Carlo simulation, sensitivity analysis was adopted to evaluate the influence of exposure parameters on health risk evaluation indicators. In the simulation results, when the sensitivity is greater than 0, the variable has a positive impact on the prediction results, and when the sensitivity is less than 0, it indicates a negative impact. The impact of variables on health risk increases as the absolute value of sensitivity increases. Previous studies have shown that based on Oracle Crystal Ball software (Version: 11.1.3.0.0), 10,000 iterations are sufficient to ensure the stability and accuracy of simulation results [33]. Therefore, the number of iterations was set to 10,000.

3. Results and Discussion

3.1. Monitoring Results and Analysis

3.1.1. Dust Mass Concentration

The statistical analysis results of the dust mass concentration in the working environment of this workshop are shown in Table 1. Based on the mass concentration data of dust samples, the probability distribution law of dust concentration was obtained by using Crystal Ball software. The results of the Anderson–Darling test show that the dust concentration distribution in the workshop working environment is normally distributed. The results of the existing studies show that the same is true of the distribution of dust concentration in foundries [15]. The mean mass concentration (MMC) ± standard deviations (SD) of total suspended particulate matter (TSP) in the welding and grinding areas were (1052 ± 509 μg/m^3) and (2562 ± 1528 μg/m^3), respectively, with PM10 fraction accounting for more than 75%. To date, the particulate matter with the greatest impact on human health has been recognized as less than 10 μm in diameter [34]. Adverse health effects may increase with decreasing particle size, especially for dusts less than 2.5 μm in diameter [35]. As shown in Table 1, the mass concentration of $PM_{2.5}$ (237 ± 116 μg/m^3) in the welding area is higher, whereas those of TSP (2562 ± 1528 μg/m^3) and PM10 (1937 ± 1487 μg/m^3)

in the grinding area are higher. The dust concentration is lower than the occupational exposure limits for welding fumes of 4 mg/m^3. The average mass concentration of $PM_{2.5}$ (237 μg/m^3) in the welding area is more than that (88 μg/m^3) in the grinding area. PM_{10} and $PM_{2.5}$ can deposit deeply in the upper and lower respiratory tracts, respectively, while ultrafine particles (<0.1μm) are mainly deposited in the alveoli [36]. Therefore, the occupational health risk management of the working environment, especially the welding area, should be enhanced.

Table 1. Dust mass concentration (μg/m^3) in the workshop environments.

Working Area	Dust	Distribution	Mean	SD	Min	Max
Welding area	TSP	Normal	1052	509	475	1714
	PM10	Normal	838	518	260	1517
	PM2.5	Normal	237	116	117	394
Grinding area	TSP	Normal	2562	1528	756	4283
	PM10	Normal	1937	1487	304	3565
	PM2.5	Normal	88	16	67	108

3.1.2. Main Elements of PM_{10}

The deposition characteristics of inhaled particles depend on flow velocity and particle size, and their chemical composition is very complex [36]. As shown in Figure 2, the main elements and their weight percentages of respirable particles PM_{10} in the microregion of dust samples were analyzed using scanning electron microscopy combined with energy spectroscopy. The trajectory of submicron particles is similar to that of tracer gases [37], and it is easy to aggregate during airborne propagation, making the particle size larger and becoming a botryoidal aggregate. Among these dusts, the mass fractions of the elements O, Al and Si are 46.0%, 27.7% and 7.5%, respectively. The metal element with a mass fraction of more than 10% is aluminum, followed by Mg (4.6%), Fe (3.6%) and Ca (2.5%). Mg, Fe, Ca and Na in $PM_{2.5}$ were not harmful to the human body [38]. The Mn element in $PM_{2.5}$ might pose a non-carcinogenic risk to adults and children through respiratory pathways [26,39]. In this study, the impact of manganese on workers' health risks was ignored due to its low mass fraction (0.7%). The mass fraction of non-metallic elements C is 2.1%. Elemental carbon can cause lung cancer or inflammation [40], while the adverse effects of organic carbon, such as Polycyclic aromatic hydrocarbons (PAHs) in an office room with intense printing activity, on respiratory health are more significant [29]. In addition, the lung deposition and the toxicity of airborne carbon nanotubes are both dependent on the nanotubes' shape and form [41]. Therefore, the health risk assessment of respirable aluminum dust exposure is mainly considered.

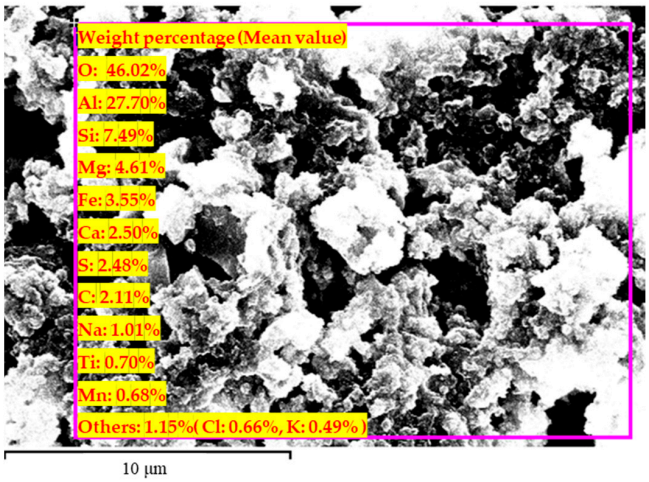


Figure 2. Sample particles observed under scanning electron microscopy and their main elemental components obtained by energy spectrum analysis.

The statistical analysis results of the mass concentration of respirable aluminum dust in the working environment are shown in Table 2. The mass concentrations of aluminum dust in the welding and grinding areas are normally distributed, and their MMC ± SD are 235 ± 145 μg/m^3 and 484 ± 372 μg/m^3, respectively. The concentration of aluminum dust is lower than the occupational exposure limits for aluminum metal and aluminum alloy dust of 3 mg/m^3 and aluminum oxide dust of 4 mg/m^3.

Table 2. Inhalable aluminum dust concentration (μg/m^3) in the working environments.

Working Area	Distribution	Mean	SD	Min	Max
Welding area	Normal	235	145	73	425
Grinding area	Normal	484	372	76	891

3.2. Exposure Parameters

Exposure parameters play a vital role in human health risk assessment. We interviewed 18 welders and 10 grinding workers (all men) under their normal working conditions. Data such as workers' body weight (BW), exposure time (ET), exposure frequency (EF) and exposure duration (ED) were collected through the method of site survey. Crystal Ball software was used to test the statistical values (Chi square, Kolmogorov–Smirnov, and Anderson–Darling) to analyze the distribution of these exposure parameters. In this study, BW and IR were normally distributed based on the Anderson–Darling test. Based on data from Ref. [27], the linear fitting relationship between IR and BW was obtained. Triangular distributions of ET, EF and ED fit best. These exposure parameters are shown in Table 3.

Table 3. Exposure parameters of male workers engaged in welding and grinding.

Exposure Parameter	Unit	Distribution	Probable Value	Min	Max	SD
IR	m^3/h	Normal	2.37	2.12	2.97	0.81
ED	a	Triangular	26	5	35	
EF	d/a	Triangular	296	272	318	
ET	h/d	Triangular	9.50	8	10.25	
BW	kg	Normal	54.3	46.5	72.8	6.2

3.3. Health Risk Assessment

The soluble aluminum compounds in inhalable particles can enter the bloodstream from the lungs of workers exposed to aluminum welding fumes. This can cause disturbances in their cognitive processes, memory and concentration, and changes in mood and electroencephalogram [42]. The results of the simulation of non-carcinogenic health risks of inhalable exposure to aluminum dust are shown in Figure 3. The geometric mean ± SD of the aluminum dust HQ in the welding and grinding areas was 0.697 ± 0.286 and 1.37 ± 0.663, respectively. The probability of the HQ of aluminum dust in both areas exceeding 1 was approximately 17% and 68%, respectively. The aluminum dust generated during the grinding process far exceeded that generated during the welding process, which led to a greater probability that the grinding workers could inhale aluminum dust and exposed to a non-carcinogenic risk value of more than 1. HQ > 1 indicates that aluminum dust exposure exceeded threshold and has a high non-carcinogenic risk, which should be a cause for concern. Therefore, workers should pay more attention to protection against the non-carcinogenic risks of inhalable aluminum dust, especially grinding workers.

$PM_{2.5}$ can induce lung cancer and chronic airway inflammatory diseases [43]. The results of the simulation of the health risks of $PM_{2.5}$ inhalable exposure to carcinogenesis are shown in Figure 4. The geometric mean ± SD of CR for the $PM_{2.5}$ in the welding and grinding areas was $8.90 \times 10^{-3} \pm 3.98 \times 10^{-3}$ and $3.11 \times 10^{-3} \pm 1.00 \times 10^{-4}$, respectively. The $PM_{2.5}$ CR in the both areas exceeded 1.0×10^{-4}, which meant that $PM_{2.5}$ in the workshop working environment had a significant CR to human health. Existing research results showed that the probability of the inhalation silica dust CR in an automobile foundry was below 1.0×10^{-5} [15], while that of $PM_{2.5}$ CR for male and female technicians in an

academic metallurgy workshop had exceeded 1×10^{-5} [25]. The comparison results indicate that the health risks of all elements in inhalable dust should be evaluated to avoid the impact of a single element on effective risk management in terms of health risk assessment. The $PM_{2.5}$ generated during welding far exceeds that generated during the grinding process. Therefore, workers in an aluminum alloy body workshop of subway factory industries, especially welding workers, should focus on the $PM_{2.5}$ CR.

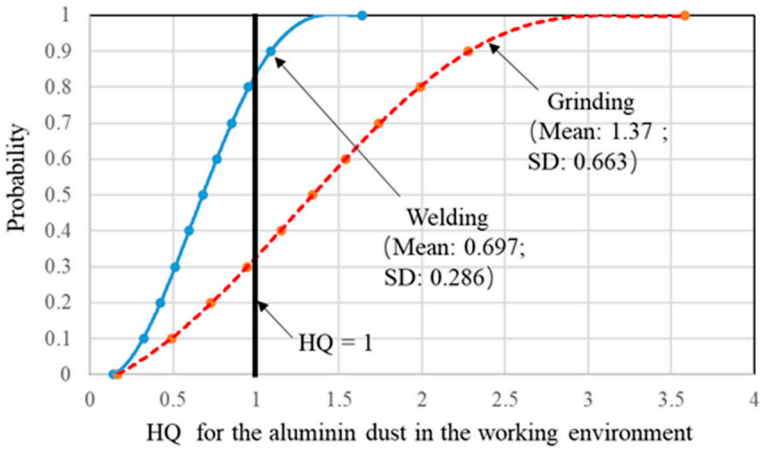


Figure 3. Evaluation of non-carcinogenic HQ of inhalable exposure to aluminum dust.

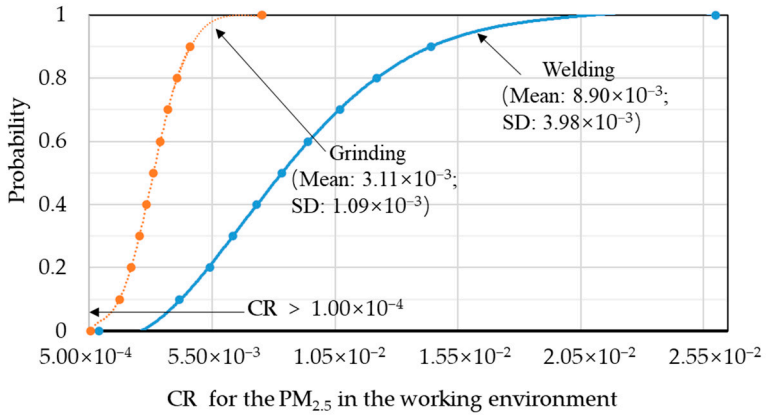


Figure 4. Health risk evaluation of carcinogenic health risk of $PM_{2.5}$ exposure.

3.4. Sensitivity Analysis

The sensitivity analysis results of aluminum dust HQ (HQ-Al) and $PM_{2.5}$ CR (CR-$PM_{2.5}$) at two types of work area (S1 for welding and S2 for grinding) are shown in Figure 5. Aluminum dust concentration with a sensitivity of 88% is the most important cause of non-carcinogenic health risks of aluminum dust in welding (HQ-Al-S1) and grinding areas (HQ-Al-S2), while the remaining exposure parameters have relatively little sensitivity. This finding is consistent with previous findings [15]. This shows that the mass concentration of inhalable aluminum dust in the working area should be reduced by rationally designing and optimizing the form of indoor ventilation, so as to reduce the health risk of aluminum dust to workers.

Dust concentration and exposure duration have a considerable impact on the results of $PM_{2.5}$ carcinogenic risk assessment of welder (CR-PM2.5-S1) and grinding workers (CR-PM2.5-S2). Dust concentration with a sensitivity of 45.6% and exposure duration with a sensitivity of 45.9% were the two main factors leading to the health risk of $PM_{2.5}$ carcinogenesis in the welded area, while dust concentration with a sensitivity of 12.2% and duration of exposure with a sensitivity of 71.7% were the two main factors leading to the CR of $PM_{2.5}$ in the grinding area. Therefore, managers need to explore different

measures and effective methods of reducing the dust health risks involved. For example, the use of more advanced welding and grinding equipment could reduce dust emissions from pollution sources, and the method of optimizing indoor airflow organization could effectively control the concentration field of dust in the working environment. These are two very effective prevention strategies for improving the health risk management of dust exposure in the work environment.

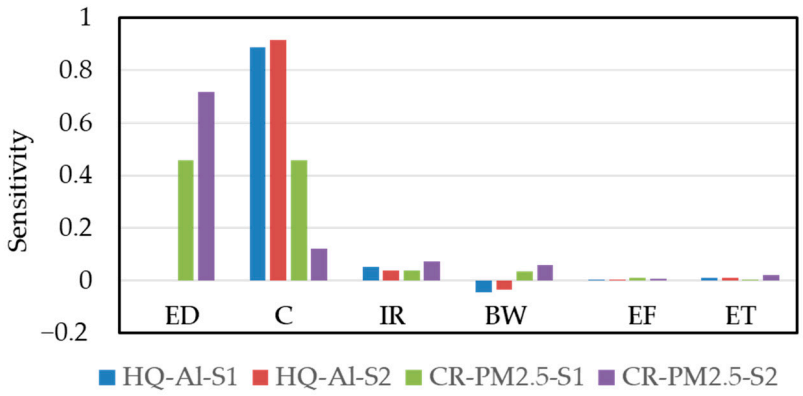


Figure 5. Sensitivity analysis of non-carcinogenic health risk (HQ-Al) and $PM_{2.5}$ carcinogenic health risk (CR-$PM_{2.5}$) of aluminum dust.

3.5. Limitations and Future Research Directions

The above research results indicated the contamination levels and health risks of welding fumes and grinding particles in the aluminum alloy body workshop of subway manufacturing plants, and had theoretical and practical significance in the health risk management for workers. However, some limitations were found in the research process of health risk assessment of inhalable exposure to dust in the workshop. Firstly, the health risk assessment results of welding and grinding workers had certain limitations because of the lack of female workers' participation in this study. In addition, some exposure parameters, such as the respiratory rate of workers, were mainly indirectly selected from existing research results due to the lack of standard reference values. These uncertain factors of exposure parameters would inevitably have adverse effects on the results of health risk assessment. In addition, the toxicity values of some pollutants, such as the Reference Concentration (RfC) standard value of PM_{10}, had not been found as suitable reference values, which affected the subsequent research on health risk assessment. Furthermore, the health risk protection measures taken by workers, such as wearing a KN100 dust mask, were not taken into account in this study, which could result in the calculated values of workers' health risk indicators being higher than the actual values. Finally, the content of this study is only a small fraction of health issues in welding and grinding, viz. respiratory problems in welding and grinding, skin cancer issues in welding, metal fume fever in welders and mill grinding noise. For example, harmful gases such as ozone and NO_x are inevitably generated during the welding process of aluminum alloys [44], but the concentration of these gases was not monitored in this study.

Based on the above analysis results, the following research is recommended as follows: firstly, from the perspective of basic research, extensive investigation and research on exposure parameters of welding and grinding workers should be conducted, and the corresponding databases should be established. Extensive research should be conducted on the physicochemical properties of aerosols, the anatomical structure of the respiratory tract, and the physiology of the respiratory tract in order to further investigate the deposition patterns of particles in the respiratory tract [36]. Then, from the perspective of the research object, similar research work should be conducted on the health risk assessment of different subway manufacturing plants in China (the world's factory). Furthermore, from the perspective of research methods, it is necessary to explore the application of artificial intelligence modeling methods in human health risk assessment, such as the artificial-

intelligence-based risk assessment of older adults [45]. Finally, from the perspective of health risk assessment, a comprehensive evaluation index system for health issues in welding and grinding should be established based on existing research results.

4. Conclusions

The quantitative assessment of the health risks of inhalable exposure to welding fumes and grinding particles in an aluminum alloy body workshop of subway factory industries is an indispensable part of the occupational health and safety management system. In this study, the dust mass concentration, exposure parameters for workers and health risk assessment of inhalable aluminum dust and $PM_{2.5}$ were investigated and studied. The research results showed that the mass concentration of $PM_{2.5}$ in the welding area was higher, while the mass concentrations of PM_{10} and total suspended particulate matter in the grinding area were higher. The geometric means of the non-carcinogenic Hazard Quota (HQ) of aluminum dust in the welding and grinding areas were 0.697 and 1.37, respectively, and the probability of their HQ exceeding 1 was approximately 17% and 68%, respectively. Therefore, workers should pay more attention to the protection against the non-carcinogenic risks of inhalable aluminum dust, especially grinding workers. The geometric mean carcinogenic risk (CR) of $PM_{2.5}$ in the welding and grinding areas was 8.90×10^{-3} and 3.11×10^{-3}, respectively. Both exceeded the acceptable upper limit value of $PM_{2.5}$ CR (1.0×10^{-4}), which meant that $PM_{2.5}$ in the working environment has a significant CR to workers, especially welders. Aluminum dust concentration with a sensitivity of more than 89% is the most significant cause of the non-carcinogenic health risks of aluminum dust in welding and grinding areas. Dust concentration and exposure duration have a considerable impact on the $PM_{2.5}$ CRs of workers. The remaining exposure parameters have relatively little sensitivity. Therefore, managers need to develop different measures and effective health risk management methods to reduce the dust health risks based on the sensitivity analysis results. These findings may provide valuable information for a better understanding of the contamination level and health risk assessment of inhalable welding fumes and grinding particles in subway factory industries.

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