Metal Fumes from Welding Processes and Health Impact

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Abstract

Welding processes generate significant occupational and environmental pollutants and hazards. The common pollutants from the welding processes include metal fumes, particulate matter and gas by-products. Epidemiological studies have shown a number of health effects on welders from short-term and long-term exposure to welding fumes. This article is the first to integrate scientific results, mainly from epidemiological studies, focusing on metals from different welding processes associated with well-studied and emerging diseases/health conditions. An understanding of possible adverse health effects of exposure to welding metal fumes is important to develop prevention strategies that benefit and impact workers' health.

Introduction

Welding joins materials together by melting a metal work piece along with a filler metal to form a strong joint. Welding provides a powerful manufacturing tool for the high-quality joining of metallic components. Common welding processes include shielded manual metal arc

Welding (MMAW), gas metal arc welding (GMAW), flux-cored arc welding (FCAW), gas tungsten arc welding (GTAW) and others such as submerged, arc welding, plasma arc welding, and oxy-gas welding.

Depending on process and metals, gas or alloy used, all welding processes produce visible smog, fume, aerosols, particulate matter, and nanoparticles that contains harmful metal fume and toxic gas by-products. Most of the materials in the welding fume come from the consumable electrode. A small fraction of the fume is derived from spattered particles and the molten welding pool. Welding fumes could be partially volatilized in the welding process. The composition and the rate of generation of welding fumes are affected by the welding current, shielding gases and the technique and skill of the welder. As shown in Table 1, the generated fumes and dusts ranged from 0.2 to 45 mg/m^3 in welders breathing zone depending on the process type. However, fume concentrations generated during welding were much higher, for example, it was 95.07 mg/m^3 in ventilation exhausts (Mansouri et al., 2008). This shows the importance of a well-ventilated workplace, personal protective equipment and respirators for welders. The sizes of the particles in the fumes and dusts could be smaller than 0.50 µm in aerodynamic diameter (Jarnuszkiewicz et al., 1966; Lannefors & Akselsson, 1977). Recent studies also showed that many of the individual particles were in the ultrafine size range (0.01 to 0.10 µm). When mass-size distribution of welding fumes was studied during SMAW and GTAW techniques, it was found that 60% of total welding fumes consist of particulate matter size greater than 10 µm and 39.7% of the fume consists of PM<10 µm (Yang, Lin, Young, & Chang, 2018).

Table1. Fume or dust levels in the ambient air of welder's workplace

Concentrations (mg/m^3)	Process type	Reference
0.63 − 5.90	Shielded Metal Arc Welding	Boelter, Simmons, Berman, & Scheff, 2009; Schoonover, Conroy, Lacey, & Plavka, 2011; Boelter et al., 2009
2.1 − 45	Gas Metal Arc Welding	Cena, Chisholm, Keane, & Chen, 2015; Cena, Chen, & Keane, 2016; Mansouri et al., 2008; Vandenplas et al., 1995
0.12 − 24.3	Flux Cored Arc Welding	Matczak & Przybylska-Stanislawska, 2004; Goller & Paik, 1985
1.8 − 19.0	Electric Arc Welding (Iron oxide fumes concentration)	Liu, Wong, Quinlan, & Blanc, 1995; Mansouri et al., 2008
8.67	Plasma cutters	Dryson & Rogers, 1991
0.474 − 35.2	Metal Arc welding	Pourtaghi G. et al.,2009; Bertram et al., 2015; Schoonover et al., 2011, Olivera Popovic et al., 2014
0.5 − 4.29	Soldering fumes	Matczak, 2002; Hartmann et al., 2014
0.14 − 10.7	Stainless steel welding	Stanislawska, Janasik, & Trzcinka-Ochocka, 2011
0.2-23.4	Manual Metal Arc welding	Golbabaei et al., 2012; Matczak & Chmielnicka, 1993
0.8-17.8	Metal Inert Gas welding (Aluminium)	Matczak & Gromiec, 2002

Welding fumes and dust are particularly known for the inclusion of metals and metal oxides.

Welding fumes are derived from combustion and contain a mixture of metal oxide particles. Mild steel generates welding fumes mainly consisting of iron and manganese but stainless steel generates fumes that also contain chromium and nickel (Leonard et al., 2010). In addition, some other metals are also found in welding fumes: aluminum (Al), antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), molybdenum (Mo), nickel (Ni), silver (Ag), tin (Sn), titanium (Ti), vanadium (V) and zinc (Zn). Gas flame, electric arc, laser, an electron beam, friction and ultrasound are used as the source of energy for welding. Some of the metal products formed in welding when metals or electrodes get melted are: Al, Sb, As, Be, Cd, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, Ag, Sn, Ti, V and Zn. Table 2 summarizes metal concentrations in biological specimens and in the air collected in the working areas and personal breathing zone.

Aluminum. A study performed by (Hanninen, and colleagues, 1994) analyzed the aluminum in serum (S-Al) and urine (U-Al) of shipyard aluminum workers. The results of the study showed the mean S-Al concentration was 0.21 (range 0.03-0.64) umol/L and the mean U-Al was 2.8 (range 0.9-6.1) umol/L.

Antimony. A study performed by Matczak (2002), focused on air samples including personal eight-hour samples. The quantitative analysis revealed that time-weighted average (TWA) of fume concentrations for Antimony were: soldering fume < 0.035 mg/m^3. For this study, it shows the levels were safe on the day of sampling.

Cadmium. Cadmium is an element used in the manufacture of fluxes found in flux-cored electrodes. Despite its use in the welding process, however, there is a little literature information about its concentrations yielded from welding processes. A study performed by Arrandale and colleagues (2015) showed that female workers at a welding plant had urinary cadmium ranging from 0.05–0.93 μg/g.

Chromium. Chromium (Cr) commonly occurs in the fume since it is found in stainless steels and high alloy steels for welding. Cr can exit in various oxidation states when it is partly oxidized to Cr (VI) and Cr (III) during manual metal arc stainless steel welding. Both trivalent (Cr^{+3}) and hexavalent (Cr^{+6}) have been quantified in significant quantities in welding fumes. Arrandale et al., (2015), reported that female workers at a welding plant had urinary Cr concentrations in the range of 0.03–7.71 µg/g. Another study was conducted by (Cena et al., 2015), to estimate the amount of specific metals deposited into the respiratory system of workers at two facilities. The workers wore a nanoparticle respiratory deposition sampler while performing their duties. Cr concentrations were 40-105 µg/m^3, Cr (VI) ranged from 0.5-1.3 µg/m^3. A study by Ellingsen and colleagues (2017) studied whole blood, serum, urine and blood cells. The results for chromium were: whole blood <DL-6.8 µg/L, serum <DL-6.2 µg/L and urine 0.2-19 µg/g cr.

Copper. The sources of copper include copper-coated GMAW electrodes and Cu alloys. Vaporized copper has been implicated as one of the metals present in welding fumes that causes metal fume fever. Thus, most studies include air samples of fume and the air. A study performed by Matczak and team (2002), focused on air samples including personal eight-hour samples. The quantitative analysis revealed that TWA of fume concentrations for Cu were: soldering fumes <0.003-0.034 mg/m^3, brazing fume <0.003-0.038 mg/m^3. Balkhyour & colleagues (2010) looked at the total fume and metal concentrations in the breathing zone (within 0.5M) of workers during an eight-hour shift. The mean value for Cu was 0.001–0.080 mg/m^3.

Lead. A study performed by Matczak and team (2002), focused on air samples including personal eight-hour samples. The quantitative analysis revealed that TWA of fume concentrations for Pb were: soldering fumes <0.014-0.037 mg/m^3, brazing fume <0.014-0.023 mg/m$^{3.}$ For this study, it shows the levels were safe on the day of sampling.

Manganese. Manganese (Mn) commonly occurs in most welding fumes as manganese oxide is used as a flux agent in the coatings of shielded metal arc electrodes, in the flux-cored arc electrodes, and as an alloying element used in electrodes (Villaume et al., 1979). A study performed by Matczak and team (2002) focused on air samples including personal eight-hour samples. The quantitative analysis revealed that TWA of fume concentrations for manganese were: brazing fumes <0.07-0.12 mg/m^3. Cena and colleagues (2015) conducted a study to estimate the amount of specific metals deposited into the respiratory system of workers at two facilities. They reported that manganese concentrations were 2.8-199 µg/m^3. Balkhyour & Goknil (2010), looked at the total fume and metal concentrations in the breathing zone (within 0.5M) of workers during an eight-hour shift. The mean value for Manganese was 0.010 –0.477 mg/m^3.

Molybdenum. Balkhyour & Goknil (2010) looked at the total fume and metal concentrations in the breathing zone (within 0.5M) of workers during an eight-hour shift. The mean value for molybdenum (Mo) was 0.001–0.058 mg/m^3. A study by Ellingsen and team (2017), studied whole blood, serum, urine and blood cells. The results for Mo were: whole blood 0.28-5.7 µg/L, serum 0.50-3.3 µg/L, blood cells 1.1-2.4 µg/L and urine 12-93 µg/g cr.

Nickel. Nickel (Ni) is present in stainless steel welding fumes and in Ni alloys. Currently, Ni is classified as a human carcinogen (NIOSH, 1977). A study was conducted by Cena and colleagues (2014) to estimate the amount of specific metals deposited into the respiratory system of workers at two facilities. Ni concentrations ranged 0.05-0.11 mg/m^3.

Silver. A study performed by Matczak in 2002, focused on air samples including personal eight-hour samples. The quantitative analysis revealed that TWA of fume concentrations for Ag were: brazing fumes < 0.014 mg/m^3. For this study, it shows the levels were safe on the day of sampling.

Tin. A study performed by Matczak in 2002, focused on air samples including personal eight-hour samples. The quantitative analysis revealed that TWA of fume concentrations for Sn were: soldering fume <0.15 mg/m^3, brazing fume < 0.15 mg/m^3. For this study, it shows the levels were safe on the day of sampling.

Zinc. Zinc (Zn) is present in the galvanized coating on metal. Metal fume fever occurs when the galvanized metal is heated sufficiently to vaporize zinc, thus creating a fume high in zinc oxide. A study performed by Matczak (2002), focused on air samples including personal eight-hour samples and reported the TWA of fumes contained Zn concentrations ranging from 0.003-0.025 mg/m^3.

Table 2. Metal concentrations detected in welding processes

Metals	Concentration	Sample type	Sampling location	Source
Aluminum	4-53 µg Al/L	Blood	Fumes	Elinder, Ahrengart, Lidums, Pettersson, & Sjogren, 1991
	18-29 µg Al/g	Bone	Fumes	Elinder et al., 1991
	0.3-10.2 mg/m^3	Air sample	Fumes breathing zone	Sjogren & Elinder, 1992
	15-414 µg/L	Urine	Fumes breathing zone	Sjogren, Lidums, Hakansson, & Hedstrom, 1985; Sjogren, Elinder, Lidums, & Chang, 1988
Antimony	0.035 mg/m^3	Air sample	Fumes	Matczak, 2002
Cadmium	0.05-0.93 µg/g cr	Urine	Various	Arrandale et al., 2015
	0.2–12.5 mg/m^3	Air sample	Particles breathing zone	Golbabaei et al., 2012
Chromium	0.002-0.34 µg/L	Serum	Ambient air	Ulfvarson & Wold, 1977
	40–105 µg/m^3	Air sample	Particles breathing zone	Cena, Keane, et al., 2014
	0.01-1.4 mg/m^3	Air sample	Fumes	Ulfvarson & Wold, 1977
	0.03-7.71 µg/g cr	Urine	Various	Arrandale et al., 2015
	1.2 µg/L	Blood cells	Particles breathing zone	Ellingsen et al., 2017
	0.45 µg/L	Whole blood	Particles breathing zone	Ellingsen et al., 2017
	0.35 µg/L	Serum	Particles breathing zone	Ellingsen et al., 2017
	0.024 µg/g cr	Urine	Particles breathing zone	Ellingsen et al., 2017
	140 µg/m^3	Air sample	Particles breathing zone	Golbabaei et al., 2012
Cobalt	0.04-1.44 µg/g cr	Urine	Various	Arrandale et al., 2015

Metals	Concentration	Sample type	Sampling location	Source
Copper	0.35-1.4 µg/L	Serum	Ambient Air	Ulfvarson & Wold, 1977
	0.003-0.034 mg/m^3	Air sample	Fumes	Matczak, 2002
	0.003-0.038 mg/m^3	Air sample	Fumes	Matczak, 2002
	0.001–0.080 mg/m^3	Air sample	Particles breathing zone	Balkhyour & Goknil, 2010
Lead	0-1.870 µg/L	Serum	Ambient air	Ulfvarson & Wold, 1977
	0.014-0.037 mg/m^3	Air sample	Fumes	Matczak, 2002
	0.014-0.023 mg/m^3	Air sample	Fumes	Matczak, 2002
Manganese	5–9300 µg/m^3	Air sample	Fumes	Bailey, Kerper, & Goodman, 2018; Hanley, Andrews, Bertke, & Ashley, 2015
	0.010 –0.477 mg/m^3	Air sample	Particles breathing zone	Balkhyour & Goknil, 2010
	2.8–199 µg/m^3	Air sample	Particles breathing zone	Cena et al., 2015
	0.07-0.12 mg/m^3	Air sample	Fumes	Matczak, 2002
	0.009-0.37 µg/L	Serum	Ambient air	Ulfvarson & Wold, 1977
	0.60-11.33 µg/g cr	Urine	Various	Arrandale et al., 2015
Molybdenum	0.001 –0.058 mg/m^3	Air sample	Particles breathing zone	Balkhyour & Goknil, 2010
	0.2-58 µg/m^3	Air sample	Particles breathing zone	Ellingsen et al., 2017
	0.097 µg/L	Blood cells	Particles breathing zone	Ellingsen et al., 2017
	0.088 µg/L	Whole blood	Particles breathing zone	Ellingsen et al., 2017
	0.042 µg/L	Serum	Particles breathing zone	Ellingsen et al., 2017
	0.048 µg/g cr	Urine	Particles breathing zone	Ellingsen et al., 2017
Nickel	0.0007-0.16 mg/ m^3	Air sample	Fumes	Ulfvarson & Wold, 1977
	10–51 µg/m^3	Air sample	Particles breathing zone	Cena, Keane, et al., 2014; L. G. Cena et al.,2015
	50 µg/m^3	Air sample	Particles breathing zone	Golbabaei et al., 2012
Silver	0.014 mg/m^3	Air sample	Fumes	Matczak, 2002
Tin	0.15 mg/m^3	Air sample	Fumes	Matczak, 2002
Vanadium	0.02-0.68 µg/m^3	Air sample	Particles breathing zone	Kucera et al., 2001; Ellingsen et al., 2017
	0.025 µg/L	Blood cells	Particles breathing zone	Ellingsen et al., 2017
	0.035 µg/L	Whole blood	Particles breathing zone	Ellingsen et al., 2017
	0.025 µg/L	Serum	Particles breathing zone	Ellingsen et al., 2017
Zinc	0.003-0.025 mg/m^3	Air sample	Fumes	Matczak, 2002; Matczak & Chmielnicka, 1988
	76.12-621.34 µg/g cr	Urine	Various	Arrandale et al., 2015

Health effects of metals from welding fumes

Exposure to welding fumes has been associated with both short-term and long-term health effects. The degree of health risk from welding fumes depends on the composition, concentration and length of exposure. Common short-term effects which occur after four to twelve hours of exposure are eyes, nose, chest and respiratory tract irritation, thirst, fever, muscle ache, fatigue, nausea, coughing, and gastrointestinal effects. Welders experience problems like sensitive skin, as well as eye and ear morbidity symptoms due to a lack of proper use of PPE and training (Alexander et al., 2016). A high dose of cadmium in welding fumes can be dangerous for short-term exposure. Long-term metal fumes exposure effects may cause respiratory, reproductive and neurological diseases (Nemery, 1990). Long-term exposure to welding may lead to risk of skin cancer or other dermatological problems on exposed skin areas (Heltoft et al., 2017).

Respiratory effects: Over the last several decades, numerous studies have addressed and studies have been done on the effects of welding fumes on respiratory systems. The effects include pulmonary function, metal fume fever, bronchitis, pneumoconiosis and fibrosis, lung cancer, respiratory infection and immunity. Metal fume fever, caused by the inhalation of freshly formed zinc oxide fumes, is the most frequently observed welders' acute respiratory illness, a relatively common febrile illness of short duration that may occur during and after welding duties. Hassaballa and colleagues (2005), reported a 25-year-old person's metal fume fever case raised concerns that the welder could develop several respiratory complications within a few days after inhalation of metal fumes. Another study conducted by Vogelmeier and team (1987) reported that during the exposure to metal fumes, Zn levels and peripheral leukocytes were elevated as body temperature rose. Also, significant alteration in lung function occurred as evidenced by a fall in respiratory vital capacity and arterial oxygen partial pressure (Vogelmeier et al., 1987). A later study suggested that pulmonary responses of inflammatory cells may play a large role in metal fume fever (Blanc et al., 1993).

Welders are at higher risk for respiratory infections (Marongiu et al., 2016). There is increased chance of pneumococcal infection in welders (Grigg et al., 2017), and the risk is higher in welders who smoke (Wong et al., 2010). Also, excess mortality rate due to pneumonia has been reported among welders in several studies. For example, Coggon and team found a significant increase in mortality from pneumonia among welders (Coggon et al., 1994). Such increased mortality associated with respiratory infections could be due to cell-mediated immunity deficiencies and cytotoxic activity of immune cells caused by welding fume exposure (Tuschl et al., 1997; Boshnakova et al., 1989).

The effects of welding fumes on the pulmonary function of workers has been commonly examined over the last two decades. Sobaszek and team (2000) examined the acute respiratory effects of 144 stainless steel welders and 223 controls at the start and end of a work shift. The welders had experienced a significant decrease in forced vital capacity due to a sensitization of the respiratory tract by Cr. A more recent study examined lung function of 1982 workers during 2002-2010 occupational health check-ups and reported that a decrease in lung function was caused by occupational exposure to welding fumes and smoking habit (Haluza et al., 2014). Smoking habit may confound the results of pulmonary function tests in welders (Chinn et al., 1990).

Welding fumes have been categorized as a possible human carcinogen (Group 2B) [IARC, 1990, 1993], as the fumes contain dangerous carcinogenic metals, e.g. Cd, Ni and Cr(VI) ("Chromium, nickel and welding," 1990). Rachelle Beveridge and colleagues conducted case-control studies among two populations from 1979 to 1986 and 1996 to 2001 with 1598 cases and 1965 controls. They collected detailed job histories to identify their occupational exposure to metals including nickel, chromium and cadmium (Beveridge et al., 2010). They reported that lung cancer risk was increased only to former smokers or non-smokers.

However, a recent random trial by Wong and colleagues on 2034 participants shows that longer working years in the welding field and foundry work are related to an increase in risk of lung cancer among heavy smokers (Wong et al., 2017). 2,034 lung cancer cases had incident lung cancer out of a random trial among 53,454 heavy smokers. Medically/histologically confirmed cases from 2002-2009 along with duration of exposure to metal fumes were accessed by questionnaires. This study supports the evidence of exposure to metal fumes or welding may be related to an increase in lung cancer risk. Similarly, in a cohort study by Siew et al. of all working age-group Finnish men who took part in a census in 1970 were followed by the Finnish cancer registry for lung cancer cases (1,971-1,995). This study supported that cumulative exposure to welding fumes and iron is related to increased lung cancer risk, mainly squamous cell carcinoma (Siew et al, 2012). Metals, e.g. Cd and Ni in welding fumes could induce the formation of DNA-protein cross-links, which could influence the initiation and promotion of cancer. Also, inappropriate covalent DNA-protein cross-links can disrupt gene expressions and chromatin structure and may lead to the deletion of DNA sequences (Costa et al., 1993).

Renal disease: If chronic exposure to metals from welding fumes can induce nephrotoxic effects is still controversial. Epidemiological studies have not consistently suggested an adverse effect on renal function (Vyskocil et al., 1992; Verschoor et al., 1988). However, increasing reports have shown an association between certain metals from welding fumes and nephrotoxicity. For example, a total of 103 Chinese welders had significantly increased urinary b2-microglobulinaemia levels, a biomarker of renal tubular dysfunction, after exposure to airborne cadmium from 5 to 86 mg/m^3 in the personal breathing zones (Ding et al., 2011). Also, exposure to metal fumes increased renal intestinal alkaline phosphatase expression and oxidative stress in welders (Hambach et al., 2013). A recent study, which used ECM-receptor interaction-related biomarkers for renal injury, kidney injury molecule (KIM)-1 and neutrophil gelatinase-associated lipocalin (NGAL) to assess nephrotoxicity, reported that the levels of those biomarkers increased in welding worker post-exposure and were significantly associated with urinary Al, Cr, Mn, Fe, Co and Ni levels in welders (Chuang et al., 2015).

Reproductive system: Sexual dysfunction is also one of the major complains of welders. A cross-sectional study on 35 stainless steel welders, 46 mild steel welders and 54 non-welding metal workers showed that sperm count and motility were significantly decreased in mild steel workers (Bonde, 1990a). Another study (conducted before and after three weeks of non-exposure among metal workers and welders) by Bonde warns us that welding may cause non-reversible effect on semen quality (Bonde, 1990b). Questionnaires from 242 congenital malformation cases and 270 controls revealed that the chance of congenital malformation was higher in the child if the father was exposed to welding fumes during periconceptional period (El-Helaly et al., 2011). However, a longitudinal, multi-country study of parents of 24,168 offspring aged 2-51 years found that the father's pre-conception welding was independently associated with non-allergic asthma in their offspring and the father's smoking habit before conception may be a factor for the increased risk of offspring asthma (Svanes et al., 2017). Also, radiant heat exposure for a long time during welding could be a confounding factor for decreased sperm quality and fertility of male welders (Bonde, 1992). Male workers exposed to manganese also have symptoms of sexual dysfunction (Bowler et al., 2007).

Emerging health issues

Central nervous system: Welders may be at increased risk of neurological and neurobehavioral health effects when exposed to metals such as Pb, Fe, Al, and Mn. For example, welders with long time exposure to Mn, Al or Pb experienced neuropsychiatric symptoms (Sjogren et al., 1990). 12 welders with exposure to Al had decreased motor function, including reaction time, finger tapping speed and endurance, vocabulary, and tracking (Sjogren et al., 1996). In addition, aluminum from welding fumes associated with symptoms of decrease in memory and concentration problems along with fatigue and depressions too (Riihimaki et al., 2000). However, short time exposure to Al showed no neurological system effect even if the concentration was higher. Psychomotor function abnormalities have been observed in hemodialysis patients who had a history of welding and exposure to Al (Sjogren & Elinder, 1992). Recent studies indicate neurological and neurobehavioral deficits may occur when workers are exposed to low levels of Mn (<0.2 mg/m^3) in welding fumes (Bowler et al., 2007). These effects include changes in mood and short-term memory, altered reaction time, and reduced hand-eye coordination (Bowler et al., 2007; Antonini et al., 2006).

The mechanisms of the effects of metals from welding fumes on the central nervous system is still unclear. However, recent animal studies reported that Mn can reach the brain through brain microvascular endothelial cell, olfactory and trigeminal nerve and crossing choroid plexuses to cerebrospinal fluid and final up-to brain (Yokel, 2009).

There is a complaint about sleep disorders by welders exposed to heavy metal fumes in comparison to office workers who have less awake time throughout the night (Chuang et al., 2018). There is a behavioral change in long term welders (Lee et al., 2016) and fatigue, mild depression, and memory and concentration problems (Riihimaki et al., 2000). Some research indicates that there may be an effect of heavy metals like aluminum on short-term memory, learning and attention (Hanninen et al., 1994), along with decrease in other cognitive performance (Akila et al., 1999). Increase in welding fume exposure causes increase in Cd levels in urine and can cause renal tubular dysfunction (Ding et al., 2011). Increase in manganese exposure during the welding process can also be a strong link for decrease in memory, attention, concentration, learning abilities, cognitive abilities and visual problems (Bowler et al., 2007). Additionally, participants present symptoms like sleep disorders, headache, sexual dysfunction, insomnia, slurred speech, tremors, etc. (Bowler et al., 2007). A case study of a 5-year-old boy with symptoms of anorexia, irritability, vomiting, mental confusion, insomnia and abnormal movements warns us about not only occupational exposure but also environmental exposure to welding fumes (Cury et al., 2017). The boy had a history of three months in a new house adjacent to a welding garage, and he had blood Pb level of 27 µg/dL. However, this case study does not discuss previous environmental exposure, if any, but his symptoms lasted 15 days and a neurological examination along with MRI showed right hemiparesis, generalized myoclonus, impaired swallowing and grasp reflex.

Sleep disorders and depression: There is increasing attention on the effect of pulmonary exposure to metal fumes fine (<2.5 µm) particulate matter ($PM_{2.5}$) on sleep disorders (Bureau of Labor Statistics U.S. Department of Labor, 2015; Shen et al., 2018). Earlier studies showed an association between welding fumes and sleep disorders. For example, a case report showed that workers exposed to welding fumes containing Mn presented with symptoms of sleep disturbances, olfactory, extrapyramidal and mood disturbances (Bowler et al., 2011; Bowler et al., 2007a). Furthermore among 43 bridge welders, 79% had sleep disturbances (Bowler et al., 2007b). According to Bowler and team (2007), TWA of Mn in air ranged from 0.11-0.46 mg/m^3 in a study of 43 welders working in confined spaces with indicated symptoms like excessive fatigue, sleep disorders, toxic hallucinations, depression and anxiety. More recent studies have further advanced our understanding of metals in welding fumes playing a critical role in sleep disorders. Chuang and colleagues (2018) reported that welding workers had greater awake times than did office workers. They further suggested that exposure to heavy metals in metal fume $PM_{2.5}$ may disrupt sleep quality in welding workers and an imbalance of serotonin by personal $PM_{2.5}$ with metals could be the cause for sleep disorders. Serotonin is one of the most important brain chemicals regulating the sleep/wake cycle (Portas et al, 2000). An increase in 1 µg/m^3 of personal $PM_{2.5}$ exposure was found to associate with a decrease of 0.001 ng/mL in serotonin in welding workers. Lower levels of serotonin were reported to result in sleepiness and to cause sleep disturbances, depression, and chronic fatigue syndrome (Portas et al., 2000). However, more studies are needed to confirm the cause.

Parkinson’s disease: Recent studies on how welding fumes affect neurological systems suggested that welding fumes could increase the risk for Parkinson’s disease. Exposure to welding fumes may damage dopaminergic neurons in the brain, raising the welders' risk for Parkinson's disease. A longitudinal cohort study of 886 welders followed up to 9.9 years after baseline measurements showed the progression of Parkinson’s disease increased with cumulative Manganese exposure. The exposure was associated with hands bradykinesia (slow movement), limb rigidity and impairment of facial expression and speech (Racette et al., 2017). Another study supports the finding by demonstrating that in a study of healthy welders exposed to Mn, positron emission tomography imaging showed reduced uptake of the tracer F-18-fluoro-L-dopa, a sign of dysfunction in nigrostriatal neurons in welders who may have had occupational exposure to high levels of manganese (Criswell et al., 2011).

Cardio-vascular diseases: Evidence accumulating from epidemiological studies indicates an association between the exposure to welding fumes and increased risks of cardiovascular events, e.g. cardiac arrhythmia, myocardial ischemia and atherosclerosis (Cavallari et al., 2007; Chinn et al., 1990). A study by Brook et al. shows that even short-term inhalation of fine particulate matter causes arterial vasoconstriction on healthy adults (Brook et al., 2002). This warns us about the cardiovascular risks to welders as they get continuously exposed to metal fumes. Cavallari and colleagues showed that metal fumes exposure of boilermaker construction workers to $PM_{2.5}$ caused alterations in heart rate variability (Cavallari et al., 2008). Fang and colleagues did a study on 26 males after exposure to welding metal fumes and their results showed that exposure to $PM_{2.5}$ evokes adverse vascular changes (Fang et al., 2008). Umukoro and colleagues observed that long-term metal particulate exposure can decrease cardiac accelerations and decelerations in welding workers (Umukoro et al., 2016). In a cross-sectional study, interviews and biological sampling conducted on 101 welders and 127 controls in southern Sweden, it was found that there was an increase in blood pressure among welders in comparison to the control group (Li et al., 2015). A longitudinal study from 2001-2010 in Rome suggested that long-term exposure to metal PM2.5 μm is found to contribute to mortality mainly from ischemic heart disease (Badaloni et al., 2017).

Conclusions

Epidemiological studies have generated some scientific data revealing health effects of fumes from welding processes on welders' health. However, scientific data on metal in welding fumes is still limited. Those epidemiological studies performed in different worker populations, industrial settings, and welding techniques. Also, most of those studies lack a well-defined exposure assessment to determine duration of metal exposure and to quantify inhalable and biological response doses. Epidemiological results have consistently shown an association between exposure to metal fumes and respiratory effects, including bronchitis, airway irritation, lung function changes and a possible increased risk of lung cancer. However, possible underlying mechanisms and causality remain less clear regarding inhalation of metal welding fumes. Also, determination of dose-response of metals in fumes has posed a challenge due to a mixture of toxicants in welding fumes and availability of well-defined populations. Finally, few studies have addressed the non-respiratory effects of metals in welding fumes, although increasing results over recent years have become available showing the reproductive, renal and dermal effects. A few specific metals in welding fumes, such as Mn and Al have been found to associate with neurological effects when inhaled in high concentrations. However, whether those metals can cause neurological problems remains unanswered. Some emerging health effects have been examined including Parkinson's disease, cardiovascular disease, sleep disorders and depression. Health impacts caused by metals in welding fumes remain an important health issue for welders. More epidemiology studies are needed to provide a better understanding of health effects caused by exposure to metals in welding fumes.

References:

Akila, R., Stollery, B. T., & Riihimaki, V. (1999). Decrements in cognitive performance in metal inert gas welders exposed to aluminium. Occup Environ Med, 56(9), 632-639.

Alexander, V., Sindhu, K. N., Zechariah, P., Resu, A. V., Nair, S. R., Kattula, D., . . . Alex, T. R. (2016). Occupational safety measures and morbidity among welders in Vellore, Southern India. Int J Occup Environ Health, 22(4), 300-306. doi: 10.1080/10773525.2016.1228287

Antonini, J. M., Santamaria, A. B., Jenkins, N. T., Albini, E., & Lucchini, R. (2006). Fate of manganese associated with the inhalation of welding fumes: potential neurological effects. Neurotoxicology, 27(3), 304-310. doi: 10.1016/j.neuro.2005.09.001

Arrandale, V. H., Beach, J., Cembrowski, G. S., & Cherry, N. M. (2015). Urinary metal concentrations among female welders. Ann Occup Hyg, 59(1), 52-61. doi: 10.1093/annhyg/meu079

Badaloni, C., Cesaroni, G., Cerza, F., Davoli, M., Brunekreef, B., & Forastiere, F. (2017). Effects of long-term exposure to particulate matter and metal components on mortality in the Rome longitudinal study. Environ Int, 109, 146-154. doi: 10.1016/j.envint.2017.09.005

Bailey, L. A., Kerper, L. E., & Goodman, J. E. (2018). Derivation of an occupational exposure level for manganese in welding fumes. Neurotoxicology, 64, 166-176. doi: 10.1016/j.neuro.2017.06.009

Balkhyour, M. A., & Goknil, M. K. (2010). Total fume and metal concentrations during welding in selected factories in Jeddah, Saudi Arabia. Int J Environ Res Public Health, 7(7), 2978-2987. doi: 10.3390/ijerph7072978

Bertram, J., Brand, P., Hartmann, L., Schettgen, T., Kossack, V., Lenz, K., . . . Kraus, T. (2015). Human biomonitoring of aluminium after a single, controlled manual metal arc inert gas welding process of an aluminium-containing worksheet in non-welders. Int Arch Occup Environ Health, 88(7), 913-923. doi: 10.1007/s00420-015-1020-7

Beveridge, R., Pintos, J., Parent, M. E., Asselin, J., & Siemiatycki, J. (2010). Lung cancer risk associated with occupational exposure to nickel, chromium VI, and cadmium in two population-based case-control studies in Montreal. Am J Ind Med, 53(5), 476-485. doi: 10.1002/ajim.20801

Blanc, P. D., Boushey, H. A., Wong, H., Wintermeyer, S. F., & Bernstein, M. S. (1993). Cytokines in metal fume fever. Am Rev Respir Dis, 147(1), 134-138. doi: 10.1164/ajrccm/147.1.134

Boelter, F. W., Simmons, C. E., Berman, L., & Scheff, P. (2009). Two-zone model application to breathing zone and area welding fume concentration data. J Occup Environ Hyg, 6(5), 298-306. doi: 10.1080/15459620902809895

Bonde, J. P. (1990a). Semen quality and sex hormones among mild steel and stainless steel welders: a cross sectional study. Br J Ind Med, 47(8), 508-514.

Bonde, J. P. (1990b). Semen quality in welders before and after three weeks of non-exposure. Br J Ind Med, 47(8), 515-518.

Bonde, J. P. (1992). Semen quality in welders exposed to radiant heat. Br J Ind Med, 49(1), 5-10.

Boshnakova, E., Divanyan, H., Zlatarov, I., Marovsky, S., Kisyova, K., Zanev, D., . . . Marinova, T. (1989). Immunological screening of welders. J Hyg Epidemiol Microbiol Immunol, 33(4), 379-382.

Bowler, R. M., Gocheva, V., Harris, M., Ngo, L., Abdelouahab, N., Wilkinson, J.,…Roels, H. A. (2011). Prospective study on neurotoxic effects in manganese-exposed bridge construction welders. Neurotoxicology, 32(5), 596-605. doi: 10.1016/j.neuro.2011.06.004

Bowler, R. M., Nakagawa, S., Drezgic, M., Roels, H. A., Park, R. M., Diamond, E., . . . Koller, W. (2007). Sequelae of fume exposure in confined space welding: a neurological and neuropsychological case series. Neurotoxicology, 28(2), 298-311. doi: 10.1016/j.neuro.2006.11.001

Bowler, R. M., Roels, H. A., Nakagawa, S., Drezgic, M., Diamond, E., Park, R., Doty, R. L. (2007). Dose-effect relationships between manganese exposure and neurological, neuropsychological and pulmonary function in confined space bridge welders. Occup Environ Med, 64(3), 167-177. doi: 10.1136/oem.2006.028761

Brook, R. D., Brook, J. R., Urch, B., Vincent, R., Rajagopalan, S., & Silverman, F. (2002). Inhalation of fine particulate air pollution and ozone causes acute arterial vasoconstriction in healthy adults. Circulation, 105(13), 1534-1536.

Cavallari, J. M., Eisen, E. A., Chen, J. C., Fang, S. C., Dobson, C. B., Schwartz, J., & Christiani, D. C. (2007). Night heart rate variability and particulate exposures among boilermaker construction workers. Environ Health Perspect, 115(7), 1046-1051. doi: 10.1289/ehp.10019

Cavallari, J. M., Eisen, E. A., Fang, S. C., Schwartz, J., Hauser, R., Herrick, R. F., & Christiani, D. C. (2008). PM2.5 metal exposures and nocturnal heart rate variability: a panel study of boilermaker construction workers. Environ Health, 7, 36. doi: 10.1186/1476-069x-7-36

Cena, L. G., Chen, B. T., & Keane, M. J. (2016). Evolution of Welding-Fume Aerosols with Time and Distance from the Source: A study was conducted on the spatiotemporal variability in welding-fume concentrations for the characterization of first- and second-hand exposure to welding fumes. Weld J, 95(Suppl), 280s-285s.

Cena, L. G., Chisholm, W. P., Keane, M. J., & Chen, B. T. (2015). A Field Study on the Respiratory Deposition of the Nano-Sized Fraction of Mild and Stainless Steel Welding Fume Metals. J Occup Environ Hyg, 12(10), 721-728. doi: 10.1080/15459624.2015.1043055

Cena, L. G., Chisholm, W. P., Keane, M. J., Cumpston, A., & Chen, B. T. (2014). Size Distribution and Estimated Respiratory Deposition of Total Chromium, Hexavalent Chromium, Manganese, and Nickel in Gas Metal Arc Welding Fume Aerosols. Aerosol Sci Technol, 48(12), 1254-1263. doi: 10.1080/02786826.2014.980883

Cena, L. G., Keane, M. J., Chisholm, W. P., Stone, S., Harper, M., & Chen, B. T. (2014). A novel method for assessing respiratory deposition of welding fume nanoparticles. J Occup Environ Hyg, 11(12), 771-780. doi: 10.1080/15459624.2014.919393

Chinn, D. J., Stevenson, I. C., & Cotes, J. E. (1990). Longitudinal respiratory survey of shipyard workers: effects of trade and atopic status. Br J Ind Med, 47(2), 83-90.

Chromium, nickel and welding. (1990). IARC Monogr Eval Carcinog Risks Hum, 49, 1-648.

Chuang, H. C., Su, T. Y., Chuang, K. J., Hsiao, T. C., Lin, H. L., Hsu, Y. T., Lai, C. H. (2018). Pulmonary exposure to metal fume particulate matter cause sleep disturbances in shipyard welders. Environ Pollut, 232, 523-532. doi: 10.1016/j.envpol.2017.09.082

Chuang, K. J., Pan, C. H., Su, C. L., Lai, C. H., Lin, W. Y., Ma, C. M., Chuang, H. C. (2015). Urinary neutrophil gelatinase-associated lipocalin is associated with heavy metal exposure in welding workers. Sci Rep, 5, 18048. doi: 10.1038/srep18048

Coggon, D., Inskip, H., Winter, P., & Pannett, B. (1994). Lobar pneumonia: an occupational disease in welders. Lancet, 344(8914), 41-43.

Costa, M., Zhitkovich, A., & Toniolo, P. (1993). DNA-protein cross-links in welders: molecular implications. Cancer Res, 53(3), 460-463.

Criswell, S. R., Perlmutter, J. S., Videen, T. O., Moerlein, S. M., Flores, H. P., Birke, A. M., & Racette, B. A. (2011). Reduced uptake of [(1)(8)F]FDOPA PET in asymptomatic welders with occupational manganese exposure. Neurology, 76(15), 1296-1301. doi: 10.1212/WNL.0b013e3182152830

Cury, R. G., Marin, J. H., & Contreras Lopez, W. O. (2017). Lead Poisoning: Myoclonus Following Welding Exposure. Acta Med Port, 30(12), 889. doi: 10.20344/amp.9398

Ding, X., Zhang, Q., Wei, H., & Zhang, Z. (2011). Cadmium-induced renal tubular dysfunction in a group of welders. Occup Med (Lond), 61(4), 277-279. doi: 10.1093/occmed/kqr034

Dryson, E. W., & Rogers, D. A. (1991). Exposure to fumes in typical New Zealand welding operations. N Z Med J, 104(918), 365-367.

El-Helaly, M., Abdel-Elah, K., Haussein, A., & Shalaby, H. (2011). Paternal occupational exposures and the risk of congenital malformations--a case-control study. Int J Occup Med Environ Health, 24(2), 218-227. doi: 10.2478/s13382-011-0019-x

Elinder, C. G., Ahrengart, L., Lidums, V., Pettersson, E., & Sjogren, B. (1991). Evidence of aluminium accumulation in aluminium welders. Br J Ind Med, 48(11), 735-738.

Ellingsen, D. G., Chashchin, M., Berlinger, B., Fedorov, V., Chashchin, V., & Thomassen, Y. (2017). Biological monitoring of welders' exposure to chromium, molybdenum, tungsten and vanadium. J Trace Elem Med Biol, 41, 99-106. doi: 10.1016/j.jtemb.2017.03.002

Fang, S. C., Eisen, E. A., Cavallari, J. M., Mittleman, M. A., & Christiani, D. C. (2008). Acute changes in vascular function among welders exposed to metal-rich particulate matter. Epidemiology, 19(2), 217-225. doi: 10.1097/EDE.0b013e31816334dc

Golbabaei, F., Seyedsomea, M., Ghahri, A., Shirkhanloo, H., Khadem, M., Hassani, H., . . . Dinari, B. (2012). Assessment of welders exposure to carcinogen metals from manual metal arc welding in gas transmission pipelines, iran. Iran J Public Health, 41(8), 61-70.

Goller, J. W., & Paik, N. W. (1985). A comparison of iron oxide fume inside and outside of welding helmets. Am Ind Hyg Assoc J, 46(2), 89-93. doi: 10.1080/15298668591394455

Grigg, J., Miyashita, L., & Suri, R. (2017). Pneumococcal infection of respiratory cells exposed to welding fumes; Role of oxidative stress and HIF-1 alpha. PLoS ONE, 12(3), e0173569. doi: 10.1371/journal.pone.0173569

Haluza, D., Moshammer, H., & Hochgatterer, K. (2014). Dust is in the air. Part II: Effects of occupational exposure to welding fumes on lung function in a 9-year study. Lung, 192(1), 111-117. doi: 10.1007/s00408-013-9529-6

Hambach, R., Lison, D., D'Haese, P., Weyler, J., Francois, G., De Schryver, A., . . . van Sprundel, M. (2013). Adverse effects of low occupational cadmium exposure on renal and oxidative stress biomarkers in solderers. Occup Environ Med, 70(2), 108-113. doi: 10.1136/oemed-2012-100887

Hanley, K. W., Andrews, R., Bertke, S., & Ashley, K. (2015). Manganese Fractionation Using a Sequential Extraction Method to Evaluate Welders' Shielded Metal Arc Welding Exposures During Construction Projects in Oil Refineries. J Occup Environ Hyg, 12(11), 774-784. doi: 10.1080/15459624.2015.1047022

Hanninen, H., Matikainen, E., Kovala, T., Valkonen, S., & Riihimaki, V. (1994). Internal load of aluminum and the central nervous system function of aluminum welders. Scand J Work Environ Health, 20(4), 279-285.

Hartmann, L., Bauer, M., Bertram, J., Gube, M., Lenz, K., Reisgen, U., . . . Brand, P. (2014). Assessment of the biological effects of welding fumes emitted from metal inert gas welding processes of aluminium and zinc-plated materials in humans. Int J Hyg Environ Health, 217(2-3), 160-168. doi: 10.1016/j.ijheh.2013.04.008

Hassaballa, H. A., Lateef, O. B., Bell, J., Kim, E., & Casey, L. (2005). Metal fume fever presenting as aseptic meningitis with pericarditis, pleuritis and pneumonitis. Occup Med (Lond), 55(8), 638-641. doi: 10.1093/occmed/kqi141

Heltoft, K. N., Slagor, R. M., Agner, T., & Bonde, J. P. (2017). Metal arc welding and the risk of skin cancer. Int Arch Occup Environ Health, 90(8), 873-881. doi: 10.1007/s00420-017-1248-5

Jarnuszkiewicz, I., Knapik, A., & Kwiatkowski, B. (1966). Particles size distribution of welding fume depending on the microclimatic conditions of the welders working places. Biul Inst Med Morsk Gdansk, 17(1), 73-76.

Kucera, J., Bencko, V., Papayova, A., Saligova, D., Tejral, J., & Borska, L. (2001). Monitoring of occupational exposure in manufacturing of stainless steel constructions. Part I: Chromium, iron, manganese, molybdenum, nickel and vanadium in the workplace air of stainless steel welders. Cent Eur J Public Health, 9(4), 171-175.

Lannefors, H. O., & Akselsson, K. R. (1977). Ambient air contamination by micron and submicron particles from welding operations. Bull Environ Contam Toxicol, 17(5), 521-527.

Lee, E. Y., Flynn, M. R., Du, G., Lewis, M. M., Herring, A. H., Van Buren, E., . . . Huang, X. (2016). Editor's Highlight: Lower Fractional Anisotropy in the Globus Pallidus of Asymptomatic Welders, a Marker for Long-Term Welding Exposure. Toxicol Sci, 153(1), 165-173. doi: 10.1093/toxsci/kfw116

Leonard, S. S., Chen, B. T., Stone, S. G., Schwegler-Berry, D., Kenyon, A. J., Frazer, D., & Antonini, J. M. (2010). Comparison of stainless and mild steel welding fumes in generation of reactive oxygen species. Part Fibre Toxicol, 7, 32. doi: 10.1186/1743-8977-7-32

Li, H., Hedmer, M., Karedal, M., Bjork, J., Stockfelt, L., Tinnerberg, H., . . . Broberg, K. (2015). A Cross-Sectional Study of the Cardiovascular Effects of Welding Fumes. PLoS ONE, 10(7), e0131648. doi: 10.1371/journal.pone.0131648

Liu, D., Wong, H., Quinlan, P., & Blanc, P. D. (1995). Welding helmet airborne fume concentrations compared to personal breathing zone sampling. Am Ind Hyg Assoc J, 56(3), 280-283. doi: 10.1080/15428119591017123

Mansouri, N., Atbi, F., Moharamnezhad, N., Rahbaran, D. A., & Alahiari, M. (2008). Gravimetric and analytical evaluation of welding fume in an automobile part manufacturing factory. J Res Health Sci, 8(2), 1-8.

Marongiu, A., Hasan, O., Ali, A., Bakhsh, S., George, B., Irfan, N., . . . Cullinan, P. (2016). Are welders more at risk of respiratory infections? Findings from a cross-sectional survey and analysis of medical records in shipyard workers: the WELSHIP project. Thorax, 71(7), 601-606. doi: 10.1136/thoraxjnl-2015-207912

Matczak, W. (2002). [Assessment of exposure to toxic metals released during soldering and grazing processes]. Med Pr, 53(6), 473-480.

Matczak, W., & Chmielnicka, J. (1988). [Evaluation of exposure to fumes arising during welding of non-alloyed and low-alloyed steel by various methods]. Med Pr, 39(4), 253-261.

Matczak, W., & Chmielnicka, J. (1993). Relation between various chromium compounds and some other elements in fumes from manual metal arc stainless steel welding. Br J Ind Med, 50(3), 244-251.

Matczak, W., & Gromiec, J. (2002). Evaluation of occupational exposure to toxic metals released in the process of aluminum welding. Appl Occup Environ Hyg, 17(4), 296-303. doi: 10.1080/10473220252826600

Matczak, W., & Przybylska-Stanislawska, M. (2004). [Determination of fumes and their elements from flux cored arc welding]. Med Pr, 55(6), 481-489.

Nemery, B. (1990). Metal toxicity and the respiratory tract. Eur Respir J, 3(2), 202-219.

Portas, C. M., Bjorvatn, B., & Ursin, R. (2000). Serotonin and the sleep/wake cycle: special emphasis on microdialysis studies. Prog Neurobiol, 60(1), 13-35.

Racette, B. A., Searles Nielsen, S., Criswell, S. R., Sheppard, L., Seixas, N., Warden, M. N., & Checkoway, H. (2017). Dose-dependent progression of parkinsonism in manganese-exposed welders. Neurology, 88(4), 344-351. doi: 10.1212/wnl.0000000000003533

Riihimaki, V., Hanninen, H., Akila, R., Kovala, T., Kuosma, E., Paakkulainen, H., . . . Engstrom, B. (2000). Body burden of aluminum in relation to central nervous system function among metal inert-gas welders. Scand J Work Environ Health, 26(2), 118-130.

Schoonover, T., Conroy, L., Lacey, S., & Plavka, J. (2011). Personal exposure to metal fume, NO2, and O3 among production welders and non-welders. Ind Health, 49(1), 63-72.

Shen, Y. L., Liu, W. T., Lee, K. Y., Chuang, H. C., Chen, H. W., & Chuang, K. J. (2018). Association of PM2.5 with sleep-disordered breathing from a population-based study in Northern Taiwan urban areas. Environ Pollut, 233, 109-113. doi: 10.1016/j.envpol.2017.10.052

Siew, S. S., Kauppinen, T., Kyyronen, P., Heikkila, P., & Pukkala, E. (2012). Occupational exposure to wood dust and formaldehyde and risk of nasal, nasopharyngeal, and lung cancer among Finnish men. Cancer Manag Res, 4, 223-232. doi: 10.2147/cmar.s30684

Sjogren, B., & Elinder, C. G. (1992). Proposal of a dose-response relationship between aluminium welding fume exposure and effect on the central nervous system. Med Lav, 83(5), 484-488.

Sjogren, B., Elinder, C. G., Lidums, V., & Chang, G. (1988). Uptake and urinary excretion of aluminum among welders. Int Arch Occup Environ Health, 60(2), 77-79.

Sjogren, B., Gustavsson, P., & Hogstedt, C. (1990). Neuropsychiatric symptoms among welders exposed to neurotoxic metals. Br J Ind Med, 47(10), 704-707.

Sjogren, B., Iregren, A., Frech, W., Hagman, M., Johansson, L., Tesarz, M., & Wennberg, A. (1996). Effects on the nervous system among welders exposed to aluminium and manganese. Occup Environ Med, 53(1), 32-40.

Sjogren, B., Lidums, V., Hakansson, M., & Hedstrom, L. (1985). Exposure and urinary excretion of aluminum during welding. Scand J Work Environ Health, 11(1), 39-43.

Sobaszek, A., Boulenguez, C., Frimat, P., Robin, H., Haguenoer, J. M., & Edme, J. L. (2000). Acute respiratory effects of exposure to stainless steel and mild steel welding fumes. J Occup Environ Med, 42(9), 923-931.

Stanislawska, M., Janasik, B., & Trzcinka-Ochocka, M. (2011). [Assessment of occupational exposure of welders based on determination of fumes and their components produced during stainless steel welding]. Med Pr, 62(4), 359-368.

Svanes, C., Koplin, J., Skulstad, S. M., Johannessen, A., Bertelsen, R. J., Benediktsdottir, B., . . . Gomez Real, F. (2017). Father's environment before conception and asthma risk in his children: a multi-generation analysis of the Respiratory Health In Northern Europe study. Int J Epidemiol, 46(1), 235-245. doi: 10.1093/ije/dyw151

Tuschl, H., Weber, E., & Kovac, R. (1997). Investigations on immune parameters in welders. J Appl Toxicol, 17(6), 377-383.

Ulfvarson, U., & Wold, S. (1977). Trace-element concentrations in blood samples from welders of stainless steel or aluminium and a reference group. Scand J Work Environ Health, 3(4), 183-191.

Umukoro, P. E., Fan, T., Zhang, J., Cavallari, J. M., Fang, S. C., Lu, C., . . . Christiani, D. C. (2016). Long-Term Metal PM2.5 Exposures Decrease Cardiac Acceleration and Deceleration Capacities in Welders. J Occup Environ Med, 58(3), 227-231. doi: 10.1097/jom.0000000000000661

Vandenplas, O., Dargent, F., Auverdin, J. J., Boulanger, J., Bossiroy, J. M., Roosels, D., & Vande Weyer, R. (1995). Occupational asthma due to gas metal arc welding on mild steel. Thorax, 50(5), 587-588: discussion 589.

Verschoor, M. A., Bragt, P. C., Herber, R. F., Zielhuis, R. L., & Zwennis, W. C. (1988). Renal function of chrome-plating workers and welders. Int Arch Occup Environ Health, 60(1), 67-70.

Vogelmeier, C., Konig, G., Bencze, K., & Fruhmann, G. (1987). Pulmonary involvement in zinc fume fever. Chest, 92(5), 946-948.

Vyskocil, A., Smejkalova, J., Tejral, J., Emminger, S., Vincentova, M., Ettlerova, E., . . . Bernard, A. (1992). Lack of renal changes in stainless steel welders exposed to chromium and nickel. Scand J Work Environ Health, 18(4), 252-256.

Wong, A., Marrie, T. J., Garg, S., Kellner, J. D., & Tyrrell, G. J. (2010). Welders are at increased risk for invasive pneumococcal disease. Int J Infect Dis, 14(9), e796-799. doi: 10.1016/j.ijid.2010.02.2268

Wong, J. Y. Y., Bassig, B. A., Seow, W. J., Hu, W., Ji, B. T., Blair, A., . . . Lan, Q. (2017). Lung cancer risk in welders and foundry workers with a history of heavy smoking in the USA: The National Lung Screening Trial. Occup Environ Med, 74(6), 440-448. doi: 10.1136/oemed-2016-104168

Yang, S. Y., Lin, J. M., Young, L. H., & Chang, C. W. (2018). Mass-size distribution and concentration of metals from personal exposure to arc welding fume in pipeline construction: a case report. Ind Health. doi: 10.2486/indhealth.2017-0197

Yokel, R. A. (2009). Manganese flux across the blood-brain barrier. Neuromolecular Med, 11(4), 297-310. doi: 10.1007/s12017-009-8101-2