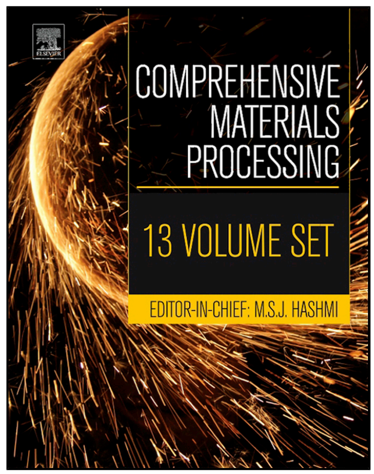

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8.04 Health Effects Associated with Welding

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8.04.1 Welding Process

Numerous metal-joining processes are used commercially, such as electric arc welding, resistance welding, oxyfuel gas welding, solid state welding, high energy density welding, and brazing and soldering. By far, electric arc welding is the most commonly used fusion process to join metals. By application of intense heat, metal at the joint between two parts is melted and caused to intermix with an intermediate molten filler metal (*1*). The extreme heat (>5000 °C) needed to melt metal is produced by an electric arc between the work to be welded and an electrode that is moved along the joint. Upon cooling and solidification, a metallurgical bond results. Because the joining is by intermixture of the substance of one part with the substance of another part, the final weldment at the joint displays the same strength properties as the metals of both parts. This is unlike nonfusion processes of joining (e.g., soldering, brazing, and adhesive bonding) in which the physical and mechanical properties of the base materials are not duplicated at the joint.

8.04.1.1 Arc Welding Processes

The American Welding Society has identified at least 20 different metal-joining processes that are currently used commercially (*2*). A majority of these processes are classified under electric arc welding, and taken together, these arc welding processes account for the greatest amount of welding and filler metal deposited commercially (*1*). The choice of a particular arc welding process is dependent on multiple factors, including the thickness and type of base metal to be welded, the size and strength of the weld desired, the speed or volume of welding, the position of the material to be welded (e.g., vertical or horizontal), and cost (*3*).

8.04.1.1.1 Gas Metal Arc Welding

Gas metal arc welding (GMAW) is a high-speed, economical process that is sometimes referred to as metal inert gas (MIG) welding (**Figure 1**). In this process, an arc is struck between the base metal and a continuously supplied consumable electrode, which provides filler metal for the weld (*2*). The electrode is bare, containing no coating or core. The shielding, to protect the molten metal from reacting with constituents of the atmosphere, is supplied by an external gas, usually containing one of a mixture of the following: helium, argon, or carbon dioxide. A significant amount of fume can be generated when welding with this process. Most of the fume generated during GMAW is derived from the consumption of the electrode and not from the base metal.

8.04.1.1.2 Shielded Metal Arc Welding

Shielded metal arc welding (SMAW) is the simplest, least expensive, and mostly widely used arc welding process (**Figure 2**). It is often referred to as 'stick welding' or manual metal arc welding. This process produces coalescence of metals by heating them with an arc between a covered metal electrode and the base metal work piece. Shielding is provided by decomposition of the electrode covering. The main function of the shielding is to protect the arc and the hot metal from chemical reaction with constituents of the atmosphere. The electrode covering contains fluxing agents, scavengers, and slag formers (*1*). Pressure is not used in the process, and the filler metal is obtained from the electrode. All ferrous metals can be welded in all positions using SMAW.

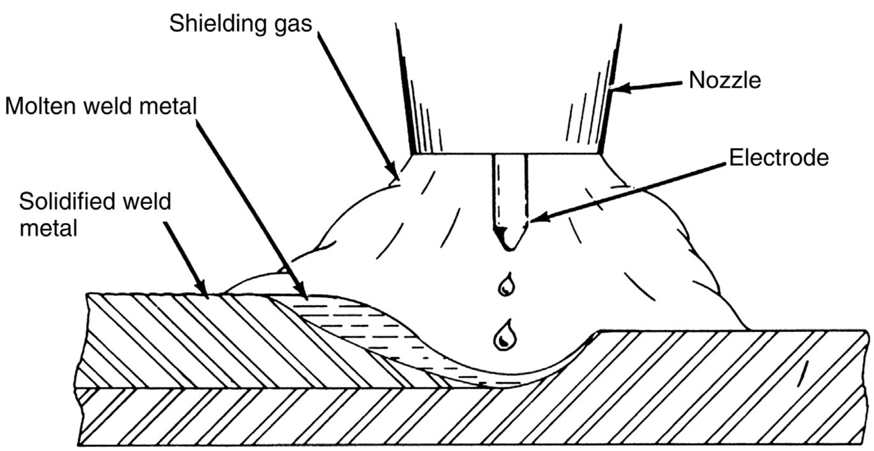

Figure 1 Gas metal arc welding (GMAW). The weld is produced by heating with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is obtained entirely from an externally supplied gas mixture. GMAW is sometimes referred to as metal inert gas (MIG) welding. The diagram is used by permission courtesy of Hobart Brothers Company. Technical Section. In *Pocket Welding Guide*, Troy, OH, 1997, pp 108–138.

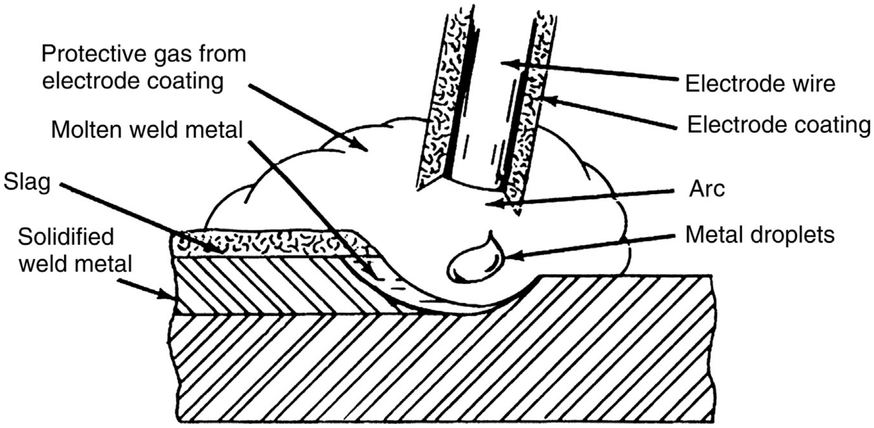

Figure 2 Shielded metal arc welding (SMAW). The weld is produced by heating with an arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. SMAW is sometimes referred to as stick welding. Filler metal is obtained from the electrode. The diagram is used by permission courtesy of Hobart Brothers Company. Technical Section. In *Pocket Welding Guide*, Troy, OH, 1997, pp 108–138.

8.04.1.1.3 Flux-Cored Arc Welding

Flux-cored arc welding (FCAW) produces coalescence of metals by heating them with an arc between a continuously supplied consumable electrode and the base metal work piece (**Figure 3**). Shielding is provided by a flux contained within the electrode. Additional shielding may or may not be obtained from an externally supplied inert gas or gas mixture. In addition, to flux, the central core of the electrodes may also contain deoxidizers, scavengers, slag formers, and other shielding agents (*1*). FCAW produces smooth sound welds of high quality.

8.04.1.1.4 Gas Tungsten Arc Welding

Gas tungsten arc welding (GTAW) is sometimes referred to as tungsten inert gas welding (**Figure 4**). In this process, coalescence of metals is produced by heating with an arc between the base metal and a nonconsumable tungsten electrode. The tungsten electrode serves only to maintain the arc. Shielding is obtained from a gas or gas mixture, usually helium, argon, or a combination of the two. Pressure and a filler metal may or may not be used depending on the joint configuration. This process can produce top quality welds using all metals and alloys. Compared to GMAW and SMAW, significantly less fume is generated during GTAW. The fume that is generated during GTAW mostly originates from base metal and the external filler metal if used (*2*).

8.04.1.1.5 Submerged Arc Welding

Submerged arc welding (SAW) is widely used to weld relatively thick plates at high metal deposition rates (*2*). Heat for this process is derived from an arc between a bare metal electrode and the work. SAW differs from other arc welding processes in that the arc is not visible (**Figure 5**). It is shielded by a blanket of granular fusible material called flux, which is placed over the joint area ahead of the arc (*1*). Pressure is not used, and filler metal is obtained primarily from the bare electrode wire that is continuously fed through the blanket of flux into the arc and the pool of molten flux. A unique feature of SAW is that the granular flux material covers the weld

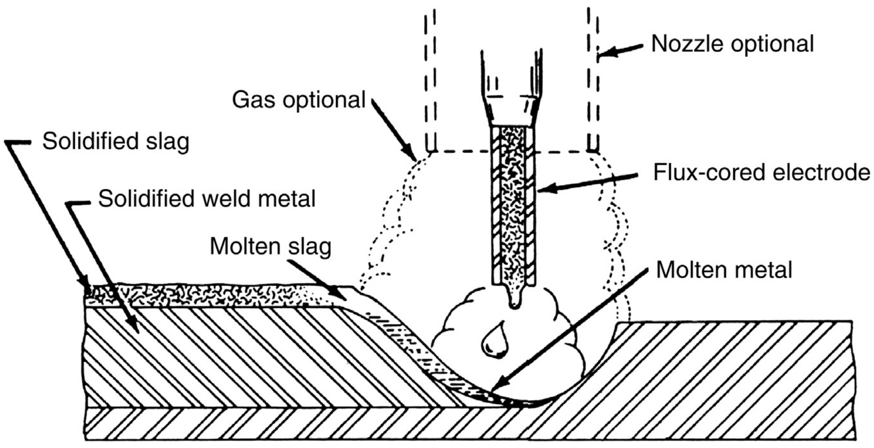

Figure 3 Flux-cored arc welding (FCAW). The weld is produced by heating with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is obtained from a flux contained within the electrode. The diagram is used by permission courtesy of Hobart Brothers Company. Technical Section. In *Pocket Welding Guide*, Troy, OH, 1997, pp 108–138.

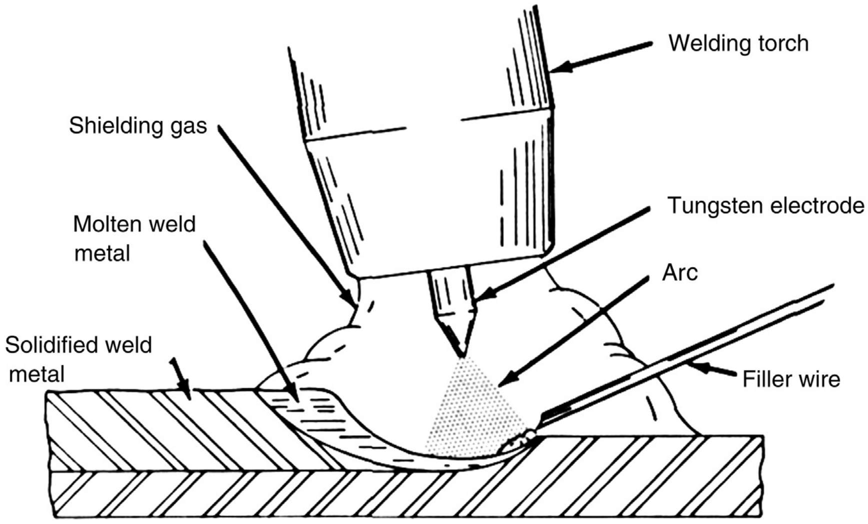

Figure 4 Gas tungsten arc welding (GTAW). The weld is produced by heating with an arc between a single tungsten (nonconsumable) electrode and the work. Shielding is obtained from an inert gas mixture. No weld spatter or slag is produced. This process is sometimes referred to as tungsten inert gas (TIG) welding. The diagram is used by permission courtesy of Hobart Brothers Company. Technical Section. In *Pocket Welding Guide*, Troy, OH, 1997, pp 108–138.

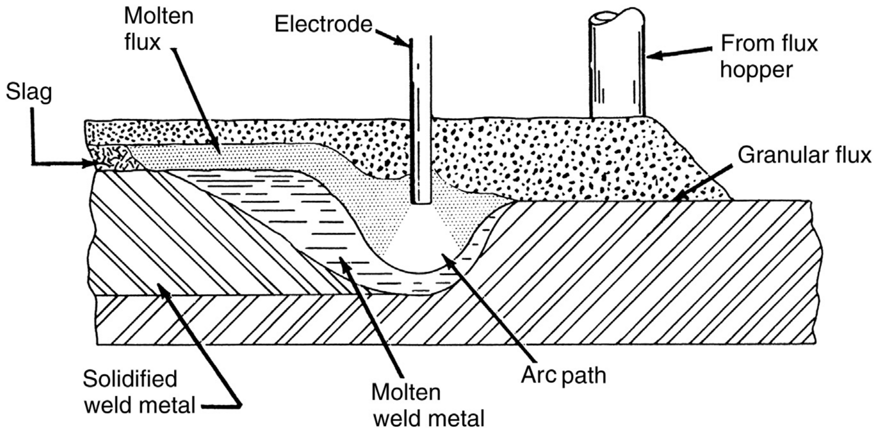

Figure 5 Submerged arc welding (SAW). The weld is produced by heating with an arc between a bare metal electrode and the work. The arc is shielded by a blanket of granular, fusible material on the work. The diagram is used by permission courtesy of Hobart Brothers Company. Technical Section. In *Pocket Welding Guide*, Troy, OH, 1997, pp 108–138.

area and prevents emission of arc radiation, sparks, spatter, and fumes. In addition to shielding the arc from view, the flux produces a slag that protects the weld metal, reducing the cooling rate and helping shape the weld contour.

8.04.1.1.6 Plasma Arc Welding

Plasma arc welding (PAW) is an extension of GTAW in which coalescence is obtained by heating with a plasma or constricted arc established between a nonconsumable electrode and the base metal. The heat in PAW originates in the arc, but this arc is not diffused as in an ordinary welding arc (*1*). Instead, it is constricted by being forced through a relatively small orifice. The orifice or plasma gas may be supplemented by an auxiliary source of shielding gas. This process is often used as a substitute for GTAW and, in some applications, offers greater welding speeds and better weld quality.

8.04.1.2 Other Joining Processes

8.04.1.2.1 Resistance Welding

Resistance welding is a group of welding processes in which coalescence is produced by the heat obtained from resistance of the work to the flow of electric current in a circuit and by the application of pressure (*4*). Examples of resistance welding include spot welding, induction welding, and flash welding. The most common type is spot welding. Resistance spot welding is a process that produces coalescence of metals at surfaces which are made to fit closely together for the purposes of making a joint. In a structure, a resistance spot weld has mechanical characteristics much like those of a rivet, although its soundness and strength are oftentimes many folds greater. Resistance spot welding processes are very effective for fabricating sheet metal articles where high rates of production are necessary. For this reason, spot welding has been particularly valuable in the automotive, aircraft, and appliance industries where high speed, repetitive welds are needed and relatively thin section sizes are welded.

8.04.1.2.2 Oxyfuel Gas Welding

Oxyfuel gas welding is a process that joins metals by combustion of a fuel gas, oxygen, and air mixed in a nozzle and directed at the work surface (*5*). The most common fuel gas used is acetylene. The fumes generated in this type of welding originate from the base metal, filler metal, and fluxes. However, the fume levels are minimal and the temperatures produced are much lower than during arc welding. This process is often used for auto body and home repair because the cost of equipment is low. It is not used to a large extent commercially because the weld quality is inferior to that of arc welding processes. The technique also may be applied to cutting rather than joining of metal (e.g., oxyfuel cutting).

8.04.1.2.3 Solid State Welding

Solid state welding includes friction welding, diffusion welding, hot and cold pressure welding, explosive welding, and ultrasonic welding. The common feature of these processes is that no melting occurs but the metal pieces are joined by the application of pressure and/or heat (*1*). These processes are often used for industrial applications where production rates are high, but the high cost of the equipment needed for the procedures prohibit their use for small production jobs.

8.04.1.2.4 High Energy Density Welding

High energy density welding processes include electron beam and laser beam welding (*4*). Electron beam welding produces coalescence by firing a stream of electrons at the work within a vacuum chamber. The laser in laser beam welding allows reaching temperatures sufficiently high to melt and vaporize any material and is often used to join metals with very high melting points. These processes can be used for a wide variety of applications and materials and produce high-quality welds. The commercial use of these processes is limited because of the high cost of the equipment.

8.04.1.2.5 Soldering/Brazing

Soldering and brazing are joining processes that produce coalescence of two or more metal pieces by melting and flowing a filler metal into the joint, with the filler metal having a lower melting point than the work piece. Soldering and brazing differ from welding in that they do not involve melting the work pieces. The difference between soldering and brazing is based on the melting temperature of the filler alloy. Brazing is performed at temperatures above 450 °C, whereas soldering processes use temperatures below 450 °C.

8.04.2 Welding Exposure

Approximately 340 000 workers were employed full time as welders, cutters, solderers, and brazers in the United States in 2010 (*6*). Estimates indicate that millions of more workers worldwide perform duties related to welding operations but are not classified as full-time welders, such as boilermakers, pipefitters, construction workers, shipbuilders, automotive workers, and farmers. Employment of full-time welders in the United States is expected to grow 15% to nearly 400 000 workers by 2020. Employment growth reflects the need for welders in the manufacturing industry because of the importance and versatility of welding as a manufacturing process. In addition, the aging workforce and the nation's deteriorating infrastructure will provide additional jobs to help in the repair and rebuilding of bridges, highways, and buildings. The basic skills of welding are mostly the same across industries, so welders can easily shift from one industry to another, depending on the needs of the workforce. Industries employing the most welders in 2010 were as follows: 61% manufacturing, 11% construction, 5% wholesale trade, and 5% maintenance and repair (*6*).

Due to the many different types of industries that utilize joining processes, welders are a heterogeneous workforce. Welders work in a number of settings, such as confined, poorly ventilated spaces (e.g., boilers, underground mines, ship hulls, pipelines, and building crawl spaces) or in well-ventilated indoor and outdoor open-air sites. Because of this, the exposure of welders can vary. Currently, no threshold limit value-time weighted average (TLV-TWA) exists for welding fume. The previous TLV-TWA of 5 mg m^{-3} for welding fume was retracted in 2004 by the American Conference of Governmental Industrial Hygienists (*7*). It is recommended that workplace exposure concentrations be kept at the lowest possible levels and be maintained below limits of specific metal constituents (e.g., chromium, manganese, or nickel) of the fume that may pose the greatest risk to health.

A wide range of welding fume concentrations have been measured in workplaces where welding occurs. Personal exposure measurements of nearly 200 workers from different work settings throughout the United States indicated that total welding particulate levels ranged from 1.02 to 37.3 mg m^{-3} in 1995 and 0.10–18.0 mg m^{-3} in 1996 (*8*). Meeker et al. (*9*) observed total welding particulate concentrations at a construction site to vary from 2.65 to 11.6 mg m^{-3} in work areas with no local exhaust ventilation compared to 3.15–5.44 mg m^{-3} in areas with local exhaust ventilation. Workplace fume concentrations of two common metals, iron and manganese, generated during welding were measured in eight welding companies by the Workplace Safety and Health Branch in Manitoba, Canada (*10*). Personal exposures for iron ranged from 0.04 to 16.29 mg m^{-3}, whereas manganese levels ranged from 0.01 to 4.93 mg m^{-3}. Vocational students training to be welders also may be at risk of overexposure to airborne fume and metal concentrations. Welding fume concentrations were observed to range from 3.1 to 10.8 mg m^{-3} at a welding shop in a vocational school, with manganese levels exceeding established workplace exposure limits (11).

8.04.3 Health and Safety Hazards in Welding

Although each arc welding process has a particular metallurgical and operational advantage, each may present its own potential health and safety hazard. Welding processes produce aerosol byproducts composed of a mixture of metal oxides volatilized from the welding electrode/rod or the flux material incorporated within the electrode (12). The formed welding fume is the vaporized metal that has reacted with air to form particles that are respirable in size (<5.0 μm in diameter), or in other words, small enough to be inhaled into the deepest regions of the lungs. Thus, welding fume is considered a potential respiratory hazard. The composition and the rate of generation of welding fumes are characteristic of the various welding processes, and are affected by the welding current, shielding gases, and the technique and skill of the welder. The concentration of the fume in the welder's breathing zone is a function of the volume of the space in which the welding is performed and the efficiency of fume removal by ventilation (13). The use of fluxes or surface coatings on the electrode and base metal pieces also influence the composition of the welding fumes and gases formed. Arc welding processes may generate complex aerosols that are composed of potentially hazardous metals (e.g., manganese, hexavalent chromium (Cr^{6+}), and nickel) and gases (e.g., carbon monoxide (CO) and ozone (O_3)). Welders also may be subjected to a number of physical hazards (unrelated to the inhalation of fumes and gases) that may affect health, such as heat, electricity, noise, ultraviolet (UV) light, and awkward working positions.

8.04.3.1 Fumes

8.04.3.1.1 Particle Morphology and Size

The basic mechanism of welding fume generation is believed to consist of vaporization of the elements and oxides from the welding area where the electrode is consumed, with rapid condensation of the vapors to form particles (14). This formation of particles is referred to as nucleation, a process by which high-temperature metal vapors are transformed into primary particles (15). Nucleation is followed by coagulation, a dynamic aerosol growth process where smaller primary particles collide to form larger, chainlike agglomerates. This agglomeration is enhanced by the turbulent conditions resulting from the extreme heat generated by the arc during the welding process, thus increasing particle movement and chances for particle collision. The primary particles formed during welding have been observed to be in the ultrafine size range, <0.10 μm (16), and varying welding process parameters (e.g., voltage) can affect the number of ultrafine welding particles generated (17). The agglomerates are formed after collisions between primary particle with primary particle, primary particle with agglomerate, and agglomerate with agglomerate (15). After these collisions, the agglomerates are believed to be held together by van der Waals, electrostatic, and magnetic forces. Multiple studies have used electron microscopy to image collected welding fume (12,18,19) and depict the characteristic chainlike particle agglomerate structure that is composed of much smaller, spherical primary particles (Figure 6). Particle size distribution resulting from arc welding has been observed to be multimodal and dynamically changes with respect to time (12,19). The choice of welding process and alloys used can have a marked effect on particle size and distribution. Three modes of particle sizes during welding have been described: (1) a nucleation mode (~0.01–0.10 μm) of individual primary particles, (2) an accumulation mode

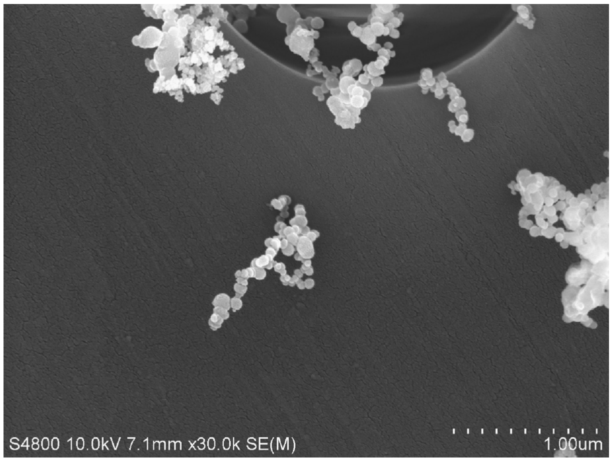

Figure 6 Scanning electron micrograph of stainless steel welding fume collected onto a filter during FCAW using a flux-cored electrode. Note the chainlike particles agglomerates that are composed of much smaller, spherical primary particles. The deposited welding particles were viewed using a JEOL 6400 scanning electron microscope (JEOL, Inc., Tokyo, Japan).

(0.10–1.0 μm) of agglomerated and coalesced particles formed from the nucleation mode, and (3) a coarse mode (~1–20 μm) of nonagglomerated, more spherical particles (*12*).

The potential health effects of welding fumes are dependent on the sites of deposition of the inhaled particles in the respiratory tract as well as the clearance mechanisms involved in removing the particles from the lungs. The respiratory tract is divided into three major subdivisions: (1) nasal/head airways, (2) tracheobronchial region (upper airways), and (3) alveolar region (lower airways). Several investigators have measured the mass median aerodynamic diameter of most welding fumes to be in the fine size particle range between 0.20 and 0.50 μm (*12,16,18,19*). The majority of particles in this size range would deposit in the alveolar lung region, the deepest region of the lungs, where rapid clearance mechanisms are not as effective. Inhaled particles such as welding fumes that reach the alveolar regions are most likely engulfed and cleared by a mobile, phagocytic white blood cell called the alveolar macrophage (AM) (see Figure 7) (*20*). Particles can remain in macrophages in the lungs and body's lymphatic systemic for extended periods of time. The retention half-time of solid, mostly insoluble particles (e.g., welding fume) in the alveolar region has been estimated to be up to 700 days in humans (*21*).

A significant portion of particles that are <0.1 μm can deposit in the tracheobronchial and the nasal/head airway regions (*20*). Because a fraction of generated welding fume is in the ultrafine size range, it is likely that some of the inhaled welding particles deposit in these regions as well. Particles that deposit in the tracheobronchial region have a short half-time in the respiratory tract as they are quickly removed by a lung clearance mechanism referred to as the mucociliary escalator. Inhaled particulates that have deposited in this region encounter a layer of mucus and become entrapped. The entrapped particles are moved by beating cilia up the mucociliary escalator and out of the trachea, where the material is swallowed and excreted from the body via the gastrointestinal tract. Importantly, welding particles that deposit in the nasal/head airways may have access to the central nervous system and the brain. A potential route of delivery of metals and ultrafine particles is uptake by olfactory neurons in the nose that can directly transport inhaled material to specific areas of the central nervous system. This may be one mechanism by which manganese, a potentially neurotoxin metal commonly present in most welding fume, may gain access to brain.

8.04.3.1.2 Elemental Composition

Welding produces complex metal oxide particles that are volatilized from the consumption of the welding electrode and/or from the flux material added to the electrode. The generated fume may be chemically distinct, depending on the selection of the welding process and materials. Due to the presence of fluxes, fumes formed during SMAW are physically and chemically more complex than fumes generated during GMAW (*12,18,22*). Because of the presence of alkali metals (e.g., potassium and sodium) in the fluxes, the fumes from SMAW processes tend to be highly water soluble, whereas fumes generated during GMAW processes are mostly water insoluble and closely mimic the metal composition of the welding wire that is consumed during the process (*23*). Recent studies indicate that the oxidation state of specific metals in welding fume is highly dependent on the selection of the shielding gas (*24,25*). The concentrations of Cr^{6+}, a known human carcinogen, and manganese were observed to vary significantly depending on the

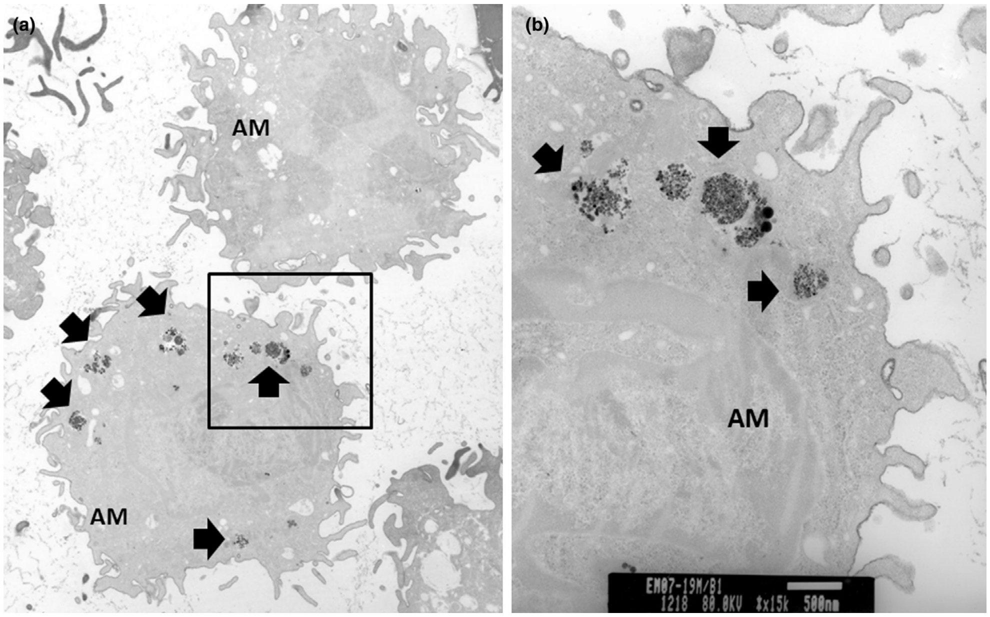

Figure 7 Transmission electron micrographs of mild steel welding particles (arrows) within a mobile, phagocytic white blood cell called an AM. The AM functions primarily to keep the lung airspaces sterile and free of debris that has been inhaled into the lungs. The AMs in this figure were recovered from a laboratory animal that had been exposed to mild steel welding fume for 3 days by inhalation. The image in (a) depicts multiple macrophages, whereas the image in (b) is a higher magnification of the boxed, highlighted area from image (a).

shielding gas composition. Base metal composition and coating, paint, and the presence of degreasing, cleaning, or antislag chemicals may also influence the chemical composition of the generated fume.

Approximately 90% of all welding is performed using mild or carbon and low alloy steels, whereas welding using stainless steel, aluminum, nickel, and all other metals accounts for less than 10% of all welding (*13*). Mild steel electrodes are composed of predominately iron with low and varying amounts of manganese. Stainless steel electrodes contain significant amounts of chromium, in addition to iron, manganese, and nickel. Depending on the process and materials used, many other elements may be present in generated welding aerosols (see **Table 1**). The most common welding fume components are discussed as follows.

8.04.3.1.2.1 Iron

Iron oxide is the principal alloying element in steel manufacture and the primary component of fumes generated from most welding processes. Fumes that contain iron oxide are considered a nuisance dust with little likelihood of causing chronic lung disease after inhalation. However, iron from welding particles has been observed to accumulate in the lungs. Diffuse, small rounded opacities, usually without the presence of complicated lesions or progressive pulmonary fibrosis, are observed on chest radiographs after long-term exposure to welding fumes (*5*). This is a common, but relatively benign condition in long-time welders referred to as siderosis (*26,27*). Using magnetometry to study the fate of the metallic iron particles from the lungs of shipyard arc welders, Kalliomaki et al. (*28*) estimated that approximately 70 mg of iron was deposited in the lungs of full-time welders per year, with an average lung burden of ferrous metal particles to be 1 g after 10 years of welding. Retired welders were determined to clear only 10–20% of the accumulated iron burden per year. Even after removal from the welding exposure, significant amounts of iron can persist in the lungs of exposed workers for long periods of time.

8.04.3.1.2.2 Chromium

The welding of stainless steel and high alloy steels produce fumes that contain chromium. Chromium in welding fumes can exist in different oxidation states such as Cr^{6+} and trivalent chromium (Cr^{3+}). Cr^{3+} has been considered to be of a low-order toxicity because it does not enter the cells of the body, whereas Cr^{6+} can enter cells and has been found to be quite toxic (*29,30*). Significant quantities of Cr^{6+} have been measured in fumes during stainless steel welding. The selection of the type of shielding gas and weld process can influence the concentration of Cr^{6+} produced (*24*). Cr^{6+} has been classified as a human carcinogen (*31*), and welding fumes that contain chromium have been shown to be mutagenic in cell-based studies (*32,33*). Epidemiology studies have indicated a possible increase in mortality from lung cancer among stainless steel welders (*34–36*). Because of the carcinogenic potential of stainless steel welding fumes, federal legislation in 2006 reduced the permissible workplace exposure limit (PEL) for chromium by an order of magnitude from 52 to 5 $\mu g\, m^{-3}$ (*37*). The decision to lower the exposure limit was based on the finding that employees exposed to Cr^{6+} faced an increased risk for significant health effects.

8.04.3.1.2.3 Manganese

Manganese is an important ingredient in the welding of steel because it increases hardness and strength, prevents steel from cracking during manufacture, improves metallurgical properties, and acts as a deoxidizing agent to remove iron oxide from the

Table 1 Potential elements present in fume from welding and joining processes

Fume	*Uses*	*Potential hazard concern*
Aluminum	Alloy and filler metal	Conducive to ozone production
Barium	Fluxing agent	Eye, nose, and throat irritant
Cadmium	Plating and brazing alloy	Respiratory irritant, metal fume fever, carcinogen
Chromium	Stainless steel alloy	Lung carcinogen
Copper	Alloy and coating material	Respiratory irritant, metal fume fever
Fluorine	Fluxing agent	Respiratory irritant
Iron	Most common fume component when welding steel	Siderosis
Lead	Brass, bronze, and steel alloy	Nervous system and kidney effects
Magnesium	Light metal alloy	Respiratory irritant, metal fume fever
Manganese	Steel alloy	Nervous system effects, respiratory irritant
Molybdenum	Steel alloy	
Nickel	Stainless steel alloy	Lung carcinogen
Silicon	Fluxing agent	
Tin	Bronze and solder alloy	Metal fume fever
Titanium	Fluxing agent	
Zinc	Galvanized steel, paint coatings	Metal fume fever

weld pool to form a stable weld (38). The amount of manganese in welding rods can vary, but most welders are exposed to mixed metal fumes that contain a small percentage of manganese (<5% per total metal present). However, some welders are exposed to aerosols generated from hard-surfacing electrodes that contain higher percentages of manganese (10–20%). The most common reason for using hard-surfacing electrodes in welding is to increase equipment's resistance to abrasion and impact in order to extend its service life. The use of hard-surfacing electrodes is becoming more common in many industries (e.g., power, railroad, mining, cement, and chemical) for mechanical process engineering such as in crushing, conveying, mixing, and separating (39).

Manganese is an essential element in the body that is found in all brain regions and is necessary for proper brain function. The inhalation of excess manganese can cause a neurodegenerative disorder characterized by both central nervous system abnormalities and neuropsychiatric disturbances. Overexposure to manganese in occupational setting, such as mining, smelting, and ferroalloy and dry battery industries has been observed to cause a Parkinson's diseaselike neurological condition called manganism (40–43). Individual cases of manganism have been reported in welders who have been exposed to high concentrations of manganese-containing welding fumes due to work in poorly ventilated areas (44).

8.04.3.1.2.4 Nickel

Nickel is present in stainless steel welding fumes and in nickel alloys. Achieving the new PEL for chromium has not always been practical during repair or fabrication of stainless steel components in certain U.S. industries (e.g., shipbuilding), where welding in confined spaces is common (45). There is an initiative in the welding industry to develop new welding consumables that have the same weldability characteristics of stainless steel consumables but would not contain chromium. New and alternative consumables (nickel-based alloys) have been developed. Initial laboratory studies indicate that the weld mechanical properties and weldability performance were similar in nature when comparing stainless steel and a specific nickel-based consumable (45). Importantly, the levels of airborne chromium were reduced by two orders of magnitude when welding with a nickel-based welding consumable as opposed to stainless steel welding. However, nickel is classified as a human carcinogen (31). Inhalation of particulate matter that contains Ni has caused lung irritation, inflammation, and adverse immune responses in humans and laboratory animals (46). *In vitro* cell studies have indicated that stainless steel welding fumes containing nickel are potentially mutagenic (47,48). Epidemiologic studies suggest that stainless steel welders have an increased risk for developing lung cancer due to elevations in nickel (49,50). However, this elevated risk has not been definitively shown to be associated with exposure to specific fume components and processes of welding (31).

8.04.3.1.2.5 Zinc

Exposure to zinc by welders most often occurs during the welding or cutting of galvanized steel (5). The inhalation of fumes that contain zinc oxides oftentimes causes metal fume fever, a common respiratory complaint among full-time welders. Metal fume fever is a self-limited condition that is characterized by an acute onset and flulike symptoms. Metal fume fever has also been caused by the inhalation of other metal oxides that may be present in welding fumes, such as copper, magnesium, or cadmium.

8.04.3.1.2.6 Aluminum

Aluminum is sometimes used as an additive in steels or as a nonferrous alloy in welding electrodes. Aluminum can be present in base metal coatings after paint, electroplated or sprayed, and hot dip treatment of materials to be welded (51). GMAW welding of aluminum alloys oftentimes uses aluminum–magnesium filler wire and produces relatively high fume rates due to the relative ease with which magnesium vaporizes. Also, the welding of aluminum is especially conducive to the production of the potentially toxic gas, O_3.

8.04.3.1.2.7 Cadmium

Cadmium is oftentimes used as a rust-preventive coating on steel and as an alloying element. Exposure to high levels of cadmium in welding fumes can produce severe lung irritation, pulmonary edema, and, in some cases, death (52,53). Inhalation of cadmium fume is one of the few specific welding-associated exposures for which a fatal outcome has been described (54). The presence of cadmium in welding fume has also been implicated in the development of metal fume fever (55). Importantly, cadmium has been classified as a human carcinogen (56).

8.04.3.1.2.8 Fluorides

Fluorides are present in the coatings of many types of fluxes used in SMAW and FCAW. Exposure to fumes that contain fluorides may cause eye, nose, and throat irritation (53). Repeated inhalation of fluorides over long periods of time may lead to pulmonary edema. In addition, fluoride inhalation has been shown to suppress lung antibacterial defense mechanisms, which may increase the susceptibility to infection (57).

8.04.3.2 Gases

A number of potentially hazardous gases can be generated that have several origins, depending on the specific welding process and condition.

8.04.3.2.1 Ozone

O_3 is a severe pulmonary irritant and is produced by a photochemical reaction between atmospheric oxygen and UV radiation emitted by the welding arc. The reaction occurs in two steps (see eqns [1] and [2]):

$$O_2 + \text{UV light} \rightarrow 2O \qquad [1]$$

$$O + O_2 \rightarrow O_3 \qquad [2]$$

The rate of formation of O_3 depends upon the wavelengths and the intensity of UV light generated in the welding arc, which is in turn is affected by the material being welded, the type of electrode used, the shielding gas, the welding process, and other welding variables such as voltage, current, and arc length (*2*). O_3 is unstable in air, and its decomposition is accelerated by metal oxide fumes (*58*). Therefore, the generation of O_3 is minimal with welding processes (e.g., FCAW and SMAW) that produce the greatest amounts of metal fume. Exposure to O_3 levels as low as 0.3 ppm may cause respiratory discomfort, whereas inhalation of O_3 above 10 ppm for several hours may lead to pulmonary edema, a condition characterized by fluid accumulation in the lungs (*59*).

8.04.3.2.2 Carbon Monoxide

Carbon monoxide (CO) is an odorless, colorless gas that can cause sudden illness and death if inhaled. CO is formed by the decomposition of organic compounds such as calcium carbonate ($CaCO_3$) in electrode coatings during SMAW or by the reduction of carbon dioxide (CO_2) when used in shielding gases during GMAW. At high temperatures within the welding arc, CO_2 is reduced to the more chemically stable CO. Exposure to CO can cause loss of consciousness and death. The most common symptoms of CO poisoning are headache, dizziness, weakness, nausea, vomiting, chest pain, and confusion (*60*). CO toxicity is caused by the formation of carboxyhemoglobin, which decreases the ability of the blood to carry oxygen to various tissues.

8.04.3.2.3 Nitrogen Oxides

Nitrogen oxides are formed during welding processes by direct oxidation of atmospheric nitrogen at high temperatures produced by the arc. First, nitric oxide (NO) is formed from nitrogen and oxygen (see eqn [3]):

$$N_2 + O_2 + \text{heat} \rightarrow 2NO \qquad [3]$$

The rate of formation of NO is not significant below a temperature of 1200 °C, but increases with rising temperatures (*2*). After dilution with air, NO can react further with oxygen to form nitrogen dioxide (NO_2; see eqn [4]):

$$2NO + O_2 \rightarrow 2NO_2 \qquad [4]$$

Nitrogen oxide gases can be irritating to the eyes, mucus membranes, and lungs when inhaled (*61*). Exposure to very high concentrations can cause severe pulmonary irritation and edema.

8.04.3.2.4 Chlorinated Hydrocarbons

Chlorinated hydrocarbons are often used to degrease base metal pieces prior to welding. Trichloroethylene ($ClCH{=}CCl_2$) is one of the more commonly used agents and has a high vapor pressure at room temperatures (*51*). The airborne vapors formed near the welding arc are subject to oxidation in a process that is enhanced by UV radiation from the arc to produce the irritant gas phosgene ($COCl_2$; see eqn [5]).

$$ClCH{=}CCl_2 + O_2 + \text{UV light} \rightarrow COCl_2 + HCl + CO \qquad [5]$$

$COCl_2$ gas may appear colorless or as a white to pale yellow cloud. At low concentrations, it has a pleasant odor of newly mown hay, but at high concentrations, the odor may be strong and unpleasant (*62*). $COCl_2$ is irritating to skin, eyes, nose, throat, and lungs. Overexposure to $COCl_2$ may cause coughing, burning sensation in eyes and throat, difficulty breathing, watery eyes, blurred vision, nausea and vomiting, and pulmonary edema.

8.04.3.3 Ventilation and Respiratory Control

The respiratory hazards associated with welding are caused by the inhalation of metal fumes and gases. Adequate ventilation is the key to preventing or minimizing the respiratory hazards of welding fume. Clean air for welding operations is provided by the use of ventilation systems, which usually include local exhaust systems and general ventilation supply systems. A cleaner workplace may also improve employee productivity. Lyttle (*63*) observed that decreased fume formation increased worker productivity, and that proper selection and utilization of welding consumables led to an improved worker environment, reduced welding costs, and ultimately provided greater protection for the welder. The most efficient and economical method of welding contaminant control in the breathing zone of the welder is local exhaust that captures the contaminants at or near the source (*64*). In a review of the literature that examined the use of local exhaust ventilation during welding, Flynn and Susi (65) report that local exhaust ventilation can reduce fume exposure to total particulate, manganese, and Cr^{6+} to levels below relevant workplace standards. In addition, field studies suggest that 40–50% or more reduction in exposure is possible with a portable or fixed local exhaust ventilation system, if used properly, relative to natural ventilation. However, it is important to note that no local exhaust ventilation system is 100% effective in capturing the generated welding fume (64). Also, because of the size or mobility of the welding zone, there will be working conditions where the use of local exhaust ventilation may not be possible. In such situations, general ventilation is needed to dilute the welding contaminants not captured by the local exhaust ventilation system.

8.04.3.3.1 Local Exhaust Ventilation

Local exhaust systems capture welding air contaminants near their source. Both stationary and mobile local exhaust ventilation systems exist, and they consist of a capture hood, duct system, air-cleaning device, fan, and outlet discharge ductwork (64). Local exhaust ventilation systems need to remove the welding contaminants without disturbing the welding process (e.g., the fume-capture velocity at the weld zone must not disturb the shielding gas). The use of local exhaust ventilation as a primary engineering control for welding fume is well established and design guidelines exist. Recommended capture velocities for exterior hoods designed to control welding fumes are in the range of 100–170 fpm (66). The local exhaust ventilation configurations for welding vary depending on whether a fixed site for the work exists or whether a mobile hood is required for work conducted at changing locations. See Table 2 for a description of commonly used local ventilation systems for welding operations.

8.04.3.3.2 General Ventilation

General ventilation systems, consisting of both supply and exhaust, can be mechanical, natural, or a mixture of both (64). Mechanical supply systems are normally used for contaminant dilution and thermal comfort in the work zone and complement local exhaust ventilation systems by removing air contaminated by welding fumes and gases not captured by local exhausts. Because the welding plume rises during welding operations, general ventilation exhaust inlets are primarily located in the upper areas of a welding shop. When there is no need for thermal comfort conditions in the building during the cooling and heating season, natural ventilation through windows, doors, or fixed air vents may be used, provided that the welding contaminant concentrations in the breathing zone do not exceed standard workplace exposure limits.

8.04.3.3.3 Personal Respiratory Protection

When ventilation controls fail to reduce the air contaminants produced by welding to allowable levels or when the use of ventilation is not feasible (e.g., welding confined spaces), personal respiratory protective equipment should be used to protect the welder from overexposure to hazardous levels of airborne contaminants (67). Another recommendation as a method to reduce the risk of overexposure to hazardous fumes and gases is for the welder to keep their face out of the welding plume. In a study by Ludwig et al. (68), it was concluded that although ventilation controls significantly reduced total fume exposure, the position of the worker's head in relation to the emission source greatly influenced the amount of exposure of the welder.

8.04.3.3.4 Welding in Confined Spaces

When welding in a confined space, all the hazards that are associated with normal welding are amplified. Hazardous gases and fumes may accumulate rapidly, thus causing a reduction in safe, breathable air. A confined space is characterized as an area with poor ventilation that has limited space, entry, or exit (69). Examples of confined spaces are storage tanks, holds of ships, boilers, furnaces, tunnels, ventilation and exhaust ducts, silos, sewers, pipelines, reactor vessels, and underground utility vaults. Before work, the atmosphere of the confined space needs to be tested for adequate oxygen levels and the presence of any flammables. If flammables are present, there is a greater threat that flammable gases could accumulate in a small space and cause an explosion. During welding, the area needs to be continuously ventilated and monitored to ensure that fumes and gases do not exceed established workplace exposure limits. A National Institute for Occupational Safety and Health/Mine Safety and Health Administration

Table 2 Local exhaust ventilation systems for welding operations[a]

Ventilation system type	*Description*
Welding gun with integral fume extraction system	Extracts fume at weld area through GMAW and FCAW guns; studies have shown a successful implementation of extraction guns in GMAW and FCAW welding, indicating a successful balance between fume extraction maintaining shielding gas requirements[b]
High vacuum source capture nozzle	Captures fume through high-velocity, low-volume extraction nozzle, usually positioned by the welder
Flexible fume extraction arm	Draws high air volume, easily positioned and repositioned by the welder
Cross-draft welding table	For controlling fume in a fixed location for welding of small parts
Fixed exhaust hood	For overhead capture of fume in fixed locations
Canopy hood	Uses larger air volumes to control fume in an area where source capture is impractical

[a]*Adapted from American Welding Society.* Ventilation Guide for Weld Fume, *Miami, FL, 2001, pp 3–8.*

[b]*Flynn, M. R.; Susi, P. Local Exhaust Ventilation for the Control of Welding Fumes in the Construction Industry – A Literature Review. Ann. Occup. Hyg. 2012; http://dx.doi.org/10.1093/annhyg/mes018.*

approved breathing device should be used when welding in a confined space when required by code and good work practice. Oftentimes, supplied air is required to maintain sufficient oxygen content and prevent possible suffocation. Importantly, welding in confined spaces should never be performed alone. A coworker or watchperson is required to be outside the confined area who is in constant communication with the welder inside, properly trained to handle emergencies, and has a means to disconnect power to the welding equipment if danger arises.

8.04.3.4 Nonrespiratory Hazards

There are multiple nonrespiratory hazards that a welder may encounter, such as radiation, electricity, heat, noise, and even the uncomfortable postures involved in the work. The primary means of skin protection are the welding helmet or hood, gloves, and work clothes (*70*). This personal protective equipment serves to protect the welder's skin from heat and UV radiation. The welder's hood is equipped with specific filter plates to shield the eyes from different wavelengths of UV light that are given off by the welding arc. Caps are commonly worn under the helmet to protect the scalp from flying sparks. Importantly, the welder's hood is not designed to provide impact protection for the eyes. Therefore, safety glasses are required behind the hood to provide impact protection when the hoods are lifted. Welders should always wear heavy, flame-resistant gloves, such as leather, to protect hands from burns and cuts. In addition, as long as the gloves are dry and in good condition, they will offer some insulation against electric shock. Leather capes and sleeves, aprons, and chaps may be required for processes that generate flying molten metal or spatter. In some cases, leather shirts and trousers may be required, particularly in restricted spaces when performing overhead work. Welders should avoid pant cuffs, pants tucked inside boots, rolled-up sleeves, and garments with pockets that do not have flaps. Sparks and molten metals may become lodged in the crevices and burn through clothing.

8.04.3.4.1 Radiation

Radiation is electromagnetic energy produced by the welding arc and needs to be controlled to protect the welder. The effects of radiation depend on the wavelength, intensity, and length of time of exposure by the welder. Arc welding processes produce intense visible and invisible (e.g., UV and infrared) light rays that can burn both eyes and skin. Each type of welding emits a different and continually changing spectrum and intensity of optical radiation (*71*). The intensity and wavelength of the radiant energy produced depends on the welding process and parameters, electrode and base metal composition, fluxes, and any coating on the base material to be welded (*72*). Welding processes that use argon in the shielding gas mixture generate greater amounts of UV radiation than those using other shielding gases.

One of the most common nonrespiratory complaints of welders is an inflammatory eye condition that is caused by exposure to UV light referred to as 'arc eye' or 'welder's flash' (*5*). Reports also indicate that welders may have an elevated risk for ocular melanoma or eye cancer, likely due to a long duration of exposure to UV light (*73,74*). Welding helmets should be fitted with a proper filter shade to protect the welder's eyes and face. Tenkate and Collins (*75*) estimated that the average ocular exposure (inside the welding helmet) was 4–5 times higher than the maximum permissible exposure (MPE) limit for UV light for welders and nearly 9 times higher than the UV-light MPE for nonwelders working in the area. Thus, safety glasses with UV-protective side shields should also be worn under the welder's helmet. Interestingly, studies have indicated that there is a marked difference in the concentration of contaminants when simultaneous samples are obtained inside and outside the eye protection helmet worn by the welder. Goller and Paik (*76*) indicated that fume concentrations at the breathing zone inside the welding helmet were reduced by 36–71% from concentrations outside the helmets. Curtains and screens should be used to protect other workers in the area from the flash and glare produced during welding.

8.04.3.4.2 Heat

The possibility of burns and fires is a concern during welding operations. Temperatures in the welding arc have been measured to be greater than 5000 °C. Thus, workpieces and equipment may become very hot. Sparks, hot metal, and spatter also can be produced during welding and have been observed to spray up to 35 feet from the work area (*1*). Not only must welders be protected with flame-resistant and insulated protective garments and gloves, consumable materials need to be removed from the welding area and noncombustible screens, and barriers need to be erected to protect other workers in the area (*77*). In addition, due to the extreme heat produced during welding, the room temperature within a work area may rise very rapidly to unhealthy conditions. Acute exposure to high temperatures may lead to heat stress, heat exhaustion, and heat stroke.

8.04.3.4.3 Noise

In welding and cutting operations, excessive noise may be produced by arc welding equipment, power sources, air carbon arc cutting and plasma arc cutting processes, and engine-driven generators (*78*). As with radiation exposure, the length and number of times that a worker is exposed to high levels of noise will determine the potential damage to one's hearing (*1*). If it is not possible to reduce the level of noise at the source during a welding operation by shielding or acoustic and engineering control methods, it is recommended that adequate ear protection be worn at all times.

8.04.3.4.4 Ergonomics

Ergonomics involves designing the workplace to fit the needs of the worker rather than trying to make the worker adjust to the workplace. Good ergonomic design has been shown to increase work quality and production as well as worker well-being. Welders can be subjected to ergonomic stresses caused by the dimensions and weight of the welding equipment and by the awkward body positions they must often assume to perform the work (59). Limited studies have examined the ergonomic aspects of welding. It has been shown that welders have a high prevalence of musculoskeletal symptoms due to static loading of the shoulders, neck, and low back (79,80). Schneider and Susi (81) concluded that awkward postures, occasional high-force requirements, static postures, repetitive movements, and lifting were potential ergonomic stresses for structural steel workers. The selection of the welding process may also influence muscle fatigue and discomfort during work in confined spaces. SMAW was observed to cause more muscle discomfort than FCAW, likely due to differences in weight of the welding gun and electrode assemblies for the specific process (82).

8.04.4 Health Effects of Welding

Thousands of studies have evaluated the health effects associated with welding. As mentioned previously, the health of welders is oftentimes difficult to assess because of differences in worker populations, work area ventilation, welding processes and materials used, and other occupational exposures besides welding fumes. The majority of published studies have evaluated the pulmonary responses of welding fume (Table 3). Most long-time welders have experienced some type of respiratory disorder during their time of employment (3,5,83). Pulmonary effects have included siderosis, bronchitis, metal fume fever, lung function changes, a susceptibility to upper and lower respiratory infections, and the possible development of lung cancer. Much less information exists concerning the nonpulmonary effects of welding fume inhalation on other organ systems in the body such as the skin, brain, heart, and reproductive system (Table 4).

Table 3 Summary of pulmonary effects of welding

Effect	*Comment*
Metal fume fever	● Frequent acute respiratory complaint ● Usually caused by fumes that contain zinc oxides ● Presents with flulike symptoms ● Self limiting, short duration
Bronchitis	● Common chronic respiratory complaint ● Confounding effects with tobacco smoking
Siderosis and pulmonary fibrosis	● Siderosis: significant lung accumulation of iron; benign pneumoconiosis ● Fibrosis: few reports; mostly due to exposure to exceedingly high fume exposures
Lung function and asthma	● Transient effects on lung function and respiratory symptoms with a return to normal when removed from exposure ● Uncertain association in the development of occupational asthma ● Some welders in specific industries may be at increased risk
Lung infection and immunotoxicity	● Increased mortality due to pneumonia ● Evidence of immunosuppression in welders ● Increase in frequency, duration, and severity of upper and lower respiratory tract infections
Lung cancer	● Classified as 'possibly carcinogenic' to humans due to the presence of chromium and nickel in stainless steel welding fumes by the International Agency for Research on Cancer ● Not a definitive association of lung cancer with welding fume exposure ● Confounding effects with tobacco smoking and exposure to other occupational carcinogens ● Whole animal carcinogenicity studies limited

Table 4 Summary of nonpulmonary effects of welding

Effect	*Comment*
Dermal	● Due to exposure to UV light ● Sunburnlike response ● Generally localized to unprotected areas of the body and common in the neck area
Neurological	● Most likely due to the presence of manganese in the fumes ● Cases of neurological disease have been reported in welders ● Most cases are because of exposure to very high levels of welding fumes, where welding has taken place in confined spaces or during welding that has used electrodes high in manganese content ● No large-scale, well-controlled epidemiology study that includes complete and accurate workplace exposure data examining neurotoxicity in welders currently exists
Cardiovascular	● Recent reports indicate that welders are at an increased risk for cardiovascular disease ● Changes in cardiovascular parameters in welders include effects on heart rate variability, arterial vessel stiffness, and vascular inflammation and oxidative stress
Reproductive	● Multiple studies suggest an association with welding fume exposure and reproductive impairments ● Specific metals common in welding fumes and possibly UV radiation may cause adverse effects on reproduction function

8.04.4.1 Pulmonary Effects of Welding

8.04.4.1.1 Metal Fume Fever

A common acute respiratory complaint of welders is a flulike condition referred to as metal fume fever. It is primarily caused by the inhalation of freshly formed zinc oxide fumes or other metal fumes that may contain a portion of zinc oxide. Metal fume fever occurs most frequently in welders joining or cutting through galvanized-coated steels. The condition may also be called other names, including 'Monday morning syndrome,' 'foundry fever,' 'smelter's chills,' 'welder's ague,' and 'galvanizer's poisoning' (*3,84*). It may develop after the inhalation of other metal oxides, such as copper, magnesium, tin, or cadmium, that are generated during welding or other joining processes. The clinical features of metal fume fever are similar to those caused by respiratory viruses such as influenza and the common cold, and because of this, can be frequently misdiagnosed if an occupational history is not taken (*84*). The symptoms include thirst, dry cough, chills, malaise, muscle aches, headaches, nausea, fever, and a metallic taste in the mouth and present within 48 h of exposure before resolving by 1–2 days after onset. An interesting feature of metal fume fever is the development of short-term tolerance in which workers are asymptomatic with repeated exposure, and episodes of metal fume fever often occur on Mondays after a weekend break from exposure (*3*).

Metal fume fever is a poorly understood illness. Development of the condition is connected to exposure levels, but very little data are available regarding the zinc concentrations that are needed to trigger the syndrome (*85*). It is believed that proinflammatory mediators called cytokines (e.g., tumor necrosis factor-α, interleukin-1, interleukin-6, and interleukin-8) are released by lung leukocytes (white blood cells) after inhalation of specific metal fumes that cause an immune or allergic and inflammatory response throughout the body of the exposed worker (*86,87*). In 2009, there were 554 calls, a likely underestimation of actual cases in exposed workers, made to poison centers in the United States concerning metal fume fever (*88*). Earlier reports estimated that 1500–2500 cases of metal fume fever occur annually in the United States (*86*). Importantly, repeated episodes of metal fume fever, although self-limiting and acute, may indicate poor workplace hygiene practice and ultimately lead to the development of chronic respiratory diseases (*84*).

8.04.4.1.2 Bronchitis

A common respiratory complaint of welders is chronic bronchitis (*5*). Chronic bronchitis is defined as a productive cough occurring on most days for at least 3 months a year for 2 consecutive years (*89*). Epidemiological studies on the prevalence of chronic bronchitis in relation to occupational exposure are few (*90*). Confounding factors affecting the ability to detect chronic bronchitis in welders are the prevalence of cigarette smoking in welders and chronic bronchitis caused by smoking in control populations. Multiple studies have indicated that a higher percentage of welders smoke as compared to the general population (*91–93*). However, some studies have shown an association between welding fume exposure and the development of chronic bronchitis. Cotes et al. (*94*) studied shipyard welders and similarly exposed caulker/burners. Subjects over 50 years of age had a 40% prevalence of chronic bronchitis with a relative risk ratio of 2.8 when adjusted for age and smoking status. In a cross-sectional study, Bradshaw et al. (*95*) demonstrated that chronic bronchitis symptoms were greater than double in welders compared to nonwelding controls. In a population-based study as a follow-up to the European Community Respiratory Health Survey, an association was observed between welding and symptoms of chronic bronchitis (*96*). In agreement, Holm et al. (*90*) observed that smoking and exposure to welding fumes were both associated with an increased prevalence and incidence of chronic bronchitis in a large population-based survey of Northern Europe residents. Importantly, a dose–response trend was also found in the study, with elevated prevalence in subjects with high exposure compared to individuals with low exposures.

8.04.4.1.3 Siderosis and Pulmonary Fibrosis

The appearance of numerous opacities on chest X-rays of welders without any symptoms of pulmonary illness was reported early after the introduction of arc welding (*26,27*). This condition became known as siderosis and has been classified as a benign form of pneumoconiosis (an occupational lung condition associated with the inhalation of dusts or particles). Siderosis is caused by the accumulation of iron oxide in the lungs and is not usually associated with pulmonary fibrosis (lung scarring) and functional impairment of the lungs (*97*). Radiographic abnormalities are reversible and may resolve partially or completely after the worker is removed from the exposure. Pulmonary function in welders with siderosis has been observed within normal limits for age and height and not significantly different from matched, nonwelder controls (*98*). Most of the iron oxide particles that have deposited in the lungs are present in AMs, a mobile and phagocytic white blood cell type present in the airspaces, without any evidence of pulmonary inflammation and injury (*99*). The prevalence of siderosis in welders increases with age and length of exposure. It has been observed that the development of siderosis was rare before 15 years of exposure to welding fume, but the presence of siderosis increased to 30% in welders who had greater than 45 years of exposure (*100*).

Pulmonary fibrosis has been reported in welders. These cases were believed to result only from nonwelding inhalation exposures of mixed dusts with fibrogenic potential (e.g., silica, asbestos, and coal dust) encountered in the welder's working area (*101*). However, Funahashi et al. (*102*) demonstrated that it was possible for welders to develop pulmonary fibrosis after exposure to only welding fumes. They measured the elemental composition of biopsied lung tissue from 10 symptomatic welders and observed the presence of iron deposits in areas where fibrotic areas were present. Silicon levels in the lung tissue of these welders were no different from controls, ruling out the likelihood of exposure to highly fibrogenic dust, silica. In addition, Buerke and colleagues (*103*) examined the lungs of 15 welders who had been exposed to extremely high levels of welding fumes over long periods of time (mean duration of exposure for 28 years) while working in poorly ventilated work areas. Pulmonary testing of the welders revealed significant decrements in numerous lung function tests. Also, areas of fibrosis were observed in close proximity with deposits of iron oxide accumulations. They concluded that siderosis in the welders that they examined had progressed into pulmonary fibrosis, and this was attributed to exposure to high levels of welding fumes in confined spaces. More recent case reports have confirmed these observations that in some specific working conditions pulmonary fibrosis may develop secondary to siderosis and cause symptomatic respiratory disease in welders (*104,105*).

8.04.4.1.4 Lung Function and Asthma

Numerous studies have examined the effects of welding fume inhalation on lung function of exposed workers. Differing results have been observed because some studies have been conducted during actual workplace conditions, others in more controlled work environments, and some in laboratories. Also, lung function tests of welders may vary due to differences in welding processes and materials, duration of exposure, ventilation of the exposure area, or exposure to confounding factors, such as tobacco smoking. After a review of the literature, Sferlazza and Beckett (*5*) concluded that exposure to welding fume alone had little to no measurable effects on lung function and that groups of susceptible welders who are exposed to high concentrations of welding fume may account for the differences in lung function observed between welders and control populations in some studies. It has been documented that shipyard welders, who are exposed to higher fume conditions because of work in confined, poorly ventilated areas, had greater decrements in lung function than welders who worked in well-ventilated places (*106–109*). Welders who are exposed to stainless steel welding fumes using SMAW processes have been observed to be more susceptible to lung function impairment compared to welders exposed to other certain types of fume using different welding processes (*110–112*). Exposure to the aerosols generated during resistance spot welding has been reported to decrease lung function, increase respiratory symptoms, and potentially induce occupational asthma (*113–115*).

The effects of welding fume exposure on pulmonary function may be transient, occurring at the time of welding fume exposure, which then return to normal during unexposed nonworking periods. In a study examining the respiratory symptoms of welders over a 3-year period, Beckett et al. (*116*) observed a slight but significant reduction in some parameters of lung function at the time of welding when compared with measurements on nonwelding days. In addition, welders reported excesses in cough, phlegm production, wheezing, and chest tightness during the work week, which improved on weekends. These symptoms were significantly more frequent among welders as compared with controls throughout the study, but the complaints subsided as welding exposure diminished during the course of the 3-year period. The authors concluded that welding was associated with reversible, work-related respiratory symptoms and small, transient across-shift reductions in lung function. However, they observed no increase in airway reactivity (e.g., asthma) among welders over the 3-year period, indicating that exposure to welding fumes is unlikely to cause significant chronic effects on lung function.

Other studies have indicated that exposure to welding fumes may be a possible cause of occupational asthma (*117–119*). More recently, case reports of occupational asthma have been reported in welders (*111,120*). El-Zein et al. (*121*) examined the incidence of occupational asthma in apprentice welders over a 15-month training period. They observed that the incidence of airway hyperresponsiveness increased 11.9% from the time of baseline lung function tests taken at the start of the apprenticeship to when follow-up tests were taken at the end of their training. Banga et al. (*122*) reported that welding fumes were among the top-five workplace exposures associated with the development of occupational asthma among Michigan workers, with a large majority of subjects suffering chronic respiratory symptoms.

8.04.4.1.5 Lung Infection and Immunotoxicity

Severity, frequency, and duration of upper and lower respiratory tract infections have been reported by a scientific panel to be increased among welders (*51*). Wergeland and Iversen (*123*) warned all Norwegian physicians about the possible lethal risk of an association of pneumonia with the inhalation of metal fumes. The warning advised physicians who diagnose pneumonia to consider occupational exposure and work history of the patient. It was suggested that pneumonia after exposure to fumes from welding, cutting, or grinding may require hospitalization and that the inhalation of metal fumes may seriously aggravate the prognosis of pneumonia. Unfortunately, the determination of the mechanisms that cause these observations is lacking.

Data from the national databases of occupational mortality for England and Wales have consistently demonstrated that welders have an increased mortality from pneumonia (*124–126*). Coggon et al. (*127*) confirmed these observations using UK data from 1979 to 1980 and 1982 to 1990 that indicated an excess of pneumonia in men below retirement age of 65 years. Because a similar mortality pattern was found in other metal fume–exposed workers, it was concluded that the primary causative agent could be the metallic fume components or possibly O_3 or NO gases. Studies from the United States associating increased mortality from pneumonia due to welding fume exposure mostly support these findings (*128–131*).

In a hospital-based case–control study in males (mean age of 46 years), Palmer et al. (*132*) determined that inhalation of metal fumes renders the worker susceptible to infectious pneumonia, and that this was a reversible phenomenon after exposure ceased. Further, the study identified pneumonia of pneumococcal as well as *Legionella*, *Mycoplasma*, and *Haemophilus influenza* origin in the subjects. Also, inhalation of ferrous metals was found to be associated with a higher risk of pneumonia than exposure to nonferrous materials. Importantly, the study eliminated other workplace hazards such as coal dust, wood dust, cement dust, and asbestos as contributing to the increased risk in the metal dust–exposed subjects. These results led Palmer and colleagues to postulate that ferrous metal fumes may cause oxidative damage to lung host defenses or that they may provide an enriched free-iron environment for microorganisms to temporarily prosper.

Case studies of rapidly progressing, fatal pneumonia were reported in four healthy male welders residing in Texas and Louisiana (*133,134*). All four cases exhibited symptoms of *Bacillus anthracis* respiratory disease, and the welders succumbed to the illness 5–8 days after their initial onset of symptoms. The causative agent was determined to be *Bacillus cereus*, an organism occasionally associated with foodborne illness and merely considered a contaminant in clinical laboratory specimens. In healthy individuals, *B. cereus* poses no health concern, but could cause a variety of infections in those who are immunocompromised or possess an underlying illness (*135*). In all cases, including another similar nonfatal case involving the same organism, the men were linked only by their metal-working profession (*133,134,136,137*). This association further raises the possibility that exposure to metal fumes may lead to periods of increased susceptibility to lung infection, even to ubiquitous, relatively harmless infectious agents.

8.04.4.1.6 Lung Cancer

An association between welding and the development of lung cancer has been extensively studied. Multiple studies have reported an elevated risk for the development of lung cancer among welders (*34–36*), whereas others have not (*138–141*). Some studies have indicated an increased risk of lung cancer in welders as high as 20–40% (*142,143*). The interpretation of an excess lung cancer risk in welders has been proven to be difficult because of uncertain workplace exposure assessment and inadequate information on smoking habits and coexposure to other potential occupational carcinogens, such as asbestos and silica. In a multinational study that pooled data from 21 case–control and 27 cohort studies of 11 092 welders in Europe, Simonato et al. (*144*) observed a significantly greater mortality rate due to lung cancer among welders, but asbestos exposure was implicated as a confounding factor. Despite these issues as well as limited evidence in humans and inadequate evidence in animals, the International Agency for Research on Cancer (*31*) concluded that welding fumes were 'possibly carcinogenic' to humans due to the presence of chromium and nickel in stainless steel welding fumes. Experimental animal studies are suggestive, but not conclusive, of lung carcinogenicity (*145,146*).

It has been hypothesized that welding with mild steel electrodes/rods, which accounts for ∼90% of all welding, poses little risk for the development of lung cancer because of a lack of chromium and nickel in the generated mild steel fumes, and the risk of lung cancer is confined to stainless steel welding (*147*). Moreover, *in vitro* cell culture studies have indicated that chromium-containing stainless steel, but not mild steel, welding fumes are mutagenic and induce cellular DNA damage (*31,148*). However, epidemiological studies have been unable to correlate the development of lung cancer solely with exposure to stainless steel welding fumes as compared to mild steel fumes (*34,50,149*). Despite the number of studies that have examined the risk of lung cancer and welding fume exposure, many questions still remain. New directions in research on this topic have been suggested and include reexamination of existing cohorts and establishing new cohorts with accurate workplace exposure assessment (e.g., the type of welding process, the type of metal being welded, the types of rods and fluxes being used, and coexposure to other agents being used in the work environment, like abrasives, cleaners, and degreasers) and improved smoking data (*150*). In addition, experimental animal studies are needed on inhalation exposure to different types of welding fumes, including ultrafine-sized particles, and on epigenetic mechanisms, gene expression pathways, and functional level changes related to welding fume exposure.

8.04.4.2 Nonpulmonary Effects of Welding

8.04.4.2.1 Dermal Effects

The skin can readily absorb UV radiation from the welding arc. Burns from UV light are quite common among welders. It has been observed that localized cutaneous erythema (redness of the skin) occurs frequently in welders and sometimes in other exposed workers (*151*). The erythema was generally localized and confined to unprotected areas of the body and common in the neck area of welders. The severity of radiation injury to the skin depends on protective clothing, exposure time, intensity of radiation, distance from radiation source, wavelength, sensitivity of the subject, and the presence of skin-sensitizing agents in the body that are activated by the radiation (*2*). Skin-sensitizing substances generated during welding include chromium, nickel, zinc, cobalt, cadmium, molybdenum, and tungsten. Exposure to UV light produced during welding has been hypothesized to be a potential cause of skin cancer; however, the incidence of skin cancer in welders is largely unknown (*152*). Currie and Monk (*153*) observed five cases of nonmelanoma skin cancer in welders, which was possibly due to nonsolar UV radiation. Donoghue and Sinclair (*154*) reported a case of skin cancer (basal cell carcinoma) in a boilermaker who repeatedly developed cutaneous erythema in an unprotected area of skin between his chest and neck (when the V neck of his shirt was open) after periods of welding. They concluded that it is possible that episodes of cutaneous erythema due to welding and cumulative UV radiation exposure are risk factors for the development of skin cancer in welders.

8.04.4.2.2 Neurological Effects

There is an emerging concern among occupational health officials about the potential neurological effects associated with the exposure to manganese in welding fumes (*44*). Most welding fumes contain a small percentage of manganese. Manganese overexposure is a well-documented distinct clinical neurotoxic syndrome in workers that resembles Parkinson's disease. It is caused by the accumulation of elevated manganese levels in a specific region of the brain, the basal ganglia, and associated with irreversible brain disease. In its early stages, manganese toxicity may be detected as neurofunctional alterations in groups of exposed persons. Later it appears as subclinical signs in individuals who seek medical attention. It ends with development of the chronic neurological condition known as 'manganism' (*155*). This condition is characterized by tremor, muscle weakness and rigidity, extreme slowness of movements, a propensity to fall backward, and a distinct 'cock-walk,' in which patients walk on their toes with elbows flexed and spine erect (*156*).

A limited number of studies have examined the potential neurological effects associated with welding fume inhalation. Neurobehavioral changes have been reported in exposed welders (*157–163*). However, most of these studies are limited due to incomplete or inaccurate workplace exposure data, little or no information on exposures to other potential workplace neurotoxicants (e.g., CO, iron, and organic solvents), and evaluation of very small exposure population groups. Several case reports of neurological disease in welders have been described. Airborne manganese levels in most of the cases were excessive as the affected welders had worked in railroad industries where the manganese content of the welding rods was high (*164,165*), in confined spaces (*166*), where workplace hygiene was poor (*167*), or where welding tasks were associated with an excessive risk of exposure (*168*). Also, a positive brain magnetic resonance imaging T1 hyperintensity signal in a specific brain region, indicative of manganese poisoning, was observed during examination in several of the cases (*164,166,168*). In addition, some studies have described a potential link between welding and Parkinsonism, and suggest the possibility of an early onset Parkinsonism among welders (*169,170*), whereas other studies have not (*171–173*). Recent animal studies indicate that repeated exposure to manganese-containing welding fumes modulated molecular factors associated with neurotoxicity and neuroinflammation in specific regions of rat brains (*174,175*).

To date, questions still exist as to whether the risk of neurotoxicity is dependent on the welding process or industry, where fume concentrations may be potentially higher or more hazardous. It appears that the case reports of manganese intoxication in welders are mostly limited to exposure to very high levels of welding fumes, where welding has taken place in confined spaces or during welding that has used electrodes high in manganese content. Furthermore, it needs to be determined whether or not exposure to long-term, low levels of manganese in welding fumes can lead to neurotoxicity in welders. Lucchini et al. (*43*) have shown in ferroalloy workers that cumulative exposure to low levels of manganese oxides may cause neurofunctional changes. However, no large-scale, well-controlled epidemiology study that includes complete and accurate workplace exposure data examining this issue in welders currently exists.

8.04.4.2.3 Cardiovascular Effects

Epidemiological studies suggest a link between environmental pulmonary exposure to particulate matter air pollution and adverse cardiovascular outcomes (*176*). Hospitalizations for cardiovascular events have been shown to increase on high population days when levels of particulate matter are elevated, and specific susceptible populations (e.g., elderly, very young, and individuals with preexisting cardiopulmonary disease) have been found to be at the greatest risk to such exposure. Welding represents a unique occupational particulate matter exposure because of the generation of inhalable metal fumes. Thus, welders are a possible at-risk population with the potential for the development of adverse cardiovascular effects. Until recently, few reports on the study of cardiovascular health in welders existed. It is believed that a minimal number of adverse cardiovascular events occur in welders during or after exposure to high concentrations of particulates because of a 'healthy worker effect.' In other words, welders exhibit lower cardiovascular morbidity and mortality than the general population after periods of high particulate exposure because severely ill and susceptible individuals do not likely work as welders and are not employed in environments where active welding takes place.

A few early epidemiological studies have indicated that welders are at an increased risk for cardiovascular disease (*131,177,178*). More recently, using two large cohorts from the Swedish National Censuses of 1970 and 1990, Sjogren et al. (*179*) observed a significant increase in mortality among welders due to ischemic heart disease. Importantly, the increase could not be explained by different smoking habits. In a prospective cohort study, Ibfelt et al. (*180*) sampled over 10 000 metal workers in 75 welding companies in Denmark and observed a significant increase in hazard rate ratio for chronic ischemic heart disease in welders with increasing exposure to metal particles after adjustment for tobacco smoking, alcohol intake, and use of antihypertension medications. Multiple recent studies of welders have suggested potential mechanisms related to cardiovascular disease. Changes in cardiovascular parameters in welders include effects on heart rate variability, aortic augmentation index (a marker of arterial stiffness), and markers of systemic inflammation and oxidative stress (*181–186*). The results of an animal study by Erdely et al. (*187*) complement the epidemiological and functional human studies that suggest welding may result in adverse cardiovascular effects. It was observed that exposure to stainless steel welding fumes increased the development of atherosclerotic lesions in the heart using an atherosclerosis mouse model. These effects were accompanied by lung inflammation and indications of systemic inflammation and oxidative stress.

8.04.4.2.4 Reproductive Effects

Multiple studies have suggested an association with welding fume exposure and impairments in reproductive function. Using a questionnaire combined with semen analysis, Mortensen (*188*) sampled 1255 male workers and reported a twofold increase in the risk of fertility abnormalities in welders. The risk was even higher for stainless steel welders. In a cross-sectional study, Bonde (*189*) observed decrements in sperm quality in both stainless steel and mild steel welders. Later, Bonde (*190*) studied welders who were sufficiently protected from fume exposure by exhaust ventilation and compressed air respirators. It was concluded that a significant reversible decrease in semen quality was observed in the welders, but it was suspected to be due to radiant heat exposure and not inhalation of welding fumes.

In a review of the literature examining the effect of occupational exposures on male reproduction function, Tas et al. (*191*) indicated that specific metals that are common in welding fumes may have toxic effects on reproduction function. Wu et al. (*192*) examined the effects of exposure to manganese and welding fumes on semen quality in 63 manganese miners, 110 shipyard welders, 38 machine shop welders, and 99 control subjects in China. It was concluded that manganese may have a toxic effect on sperm quality. The semen quality of 57 stainless steel welders in South India was monitored (*193*). It was observed that sperm concentration and motility decreased in the welders, and semen abnormalities correlated with the number of years of exposure to welding fumes containing nickel and chromium. In a cross-sectional study of 96 welders, Ellingsen et al. (*194*) compared serum concentration of potential biomarkers that may predict alterations in reproductive function. A significantly lower concentration of inhibin B was observed in the welders compared to controls, suggesting a possible functional impairment of testicular cells that may be caused by welding fume exposure.

References

1. The James F. Lincoln Arc Welding Foundation. Arc-Welding Fundamentals, *The Procedure Handbook of Arc Welding,* 14th ed; The James F. Lincoln Arc Welding Foundation: Cleveland, OH, 2000; p 1.3–16.1.
2. Villaume, J. E.; Wasti, K.; Liss-Suter, D.; Hsiao, S. *Effects of Welding on Health*; American Welding Society: Miami, FL, Vol. 1, 1979.
3. Martin, C. J.; Guidotti, T. L.; Langard, S. Respiratory Hazards of Welding. *Clin. Pulm. Med.* **1997,** *4,* 194–204.
4. Stout, R. D. The Welding Processes in Relation to Weldability, *Weldability of Steels,* 4th ed.; Welding Research Council: New York, 1987; pp 20–22.
5. Sferlazza, S. J.; Beckett, W. S. The Respiratory Health of Welders. *Am. Rev. Respir. Dis.* **1991,** *143,* 1134–1148.
6. Bureau of Labor Statistics. *Occupational Outlook Handbook Employment: Welders, Cutter, Solders, and Brazers*; U.S. Department of Labor. http://www.bls.gov/ooh (accessed on 05 August 2012).
7. American Conference of Governmental Industrial Hygienists. *TLVs and BEIs Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices;* Cincinnati, OH, 2004; p 36.
8. Susi, P.; Goldberg, M.; Barnes, P.; Stafford, E. Use of Task-Based Exposure Assessment Model (TBEAM) for Assessment of Metal Fume Exposures during Welding and Thermal Cutting. *Appl. Occup. Environ. Hyg.* **2000,** *15,* 26–38.
9. Meeker, J. D.; Susi, P.; Flynn, M. R. Manganese and Welding Fume Exposure and Control in Construction. *J. Occup. Environ. Hyg.* **2007,** *4,* 943–951.
10. Korczynski, R. E. Occupational Health Concerns in the Welding Industry. *Appl. Occup. Environ. Hyg.* **2000,** *15,* 936–945.
11. Wallace, M. E.; Lentz, T. J.; Fajen, J. M.; Palassis, J. Assessment of Students' Exposure to Welding Fumes in a Vocational School Welding Shop. *Appl. Occup. Environ. Hyg.* **1997,** *12,* 712–715.
12. Zimmer, A. T.; Biswas, P. Characterization of the Aerosols Resulting from Arc Welding Processes. *J. Aerosol. Sci.* **2001,** *32,* 993–1008.
13. Beckett, W. S. Welding. In *Occupational and Environmental Respiratory Disease;* Harber, P., Schenker, M. B., Balmes, J. R., Eds.; Mosby-Year Book, Inc.: St. Louis, MO, 1996; pp 704–717.
14. Harris, M. K. Fume and Gas Generation, *Welding Health and Safety: A Field Guide for OEHS Professionals;* American Industrial Hygiene Association: Fairfax, VA, 2002; p 214.
15. Zimmer, A. T. The Influence of Metallurgy on the Formation of Welding Aerosols. *J. Environ. Monit.* **2002,** *4,* 628–632.
16. Sowards, J. W.; Ramierz, A. J.; Dickinson, D. W.; Lippold, J. C. Characterization of Welding Fume from SMAW Electrodes. *Weld J.* **2010,** *89,* 82s–90s.
17. Antonini, J. M.; Keane, M.; Chen, B. T.; Stone, S.; Roberts, J. R.; Schwegler-Berry, D.; Andrews, R. N.; Frazer, D. G.; Sriram, K. Alterations in Welding Process Voltage Affect the Generation of Ultrafine Particles, Fume Composition, and Pulmonary Toxicity. *Nanotoxicology* **2011,** *5,* 700–710.
18. Jenkins, N. T.; Pierce, W. M.-G.; Eagar, T. W. Particle Size Distribution of Gas Metal and Flux Cored Arc Welding Fumes. *Weld J.* **2005,** *84,* 156s–163s.
19. Antonini, J. M.; Afshari, A. A.; Stone, S.; Chen, B.; Scwegler-Berry, D.; Fletcher, W. G.; Goldsmith, W. T.; Vandestouwe, K. H.; McKinney, W.; Castranova, V.; Frazer, D. G. Design, Construction, and Characterization of a Novel Robotic Welding Fume Generator and Inhalation Exposure System for Laboratory Animals. *J. Occup. Environ. Hyg.* **2006,** *3,* 194–203.
20. McClellan, R. O. Particle Interactions with the Respiratory Tract. In *Particle-Lung Interactions;* Lenfant, C., Ed.; Marcel Dekker, Inc.: New York, 2000; pp 3–56.
21. Oberdorster, G. Kinetics of Inhaled Ultrafine Particles in the Organism. In *Effects of Air Contaminants on the Respiratory Tract - Interpretations from Molecular to Meta Analysis;* Heinrich, U., Ed.; Fraunhofer IRB Verlag: Hannover, 2004; pp 122–143.
22. Jenkins, N. T.; Eagar, T. W. Chemical Analysis of Welding Fume Particles. *Weld J.* **2005,** *84,* 87s–93s.
23. Antonini, J. M.; Lawryk, N. J.; Krishna Murthy, G. G.; Brain, J. D. Effect of Welding Fume Solubility on Lung Macrophage Viability and Function *In Vitro. J. Toxicol. Environ. Health, Part A* **1999,** *58,* 343–363.
24. Keane, M.; Stone, S.; Chen, B.; Slaven, J.; Schwegler-Berry, D.; Antonini, J. Hexavalent Chromium Content in Stainless Steel Welding Fumes is Dependent on the Welding Process and Shield Gas Type. *J. Environ. Monit.* **2009,** *11,* 418–424.
25. Keane, M.; Stone, S.; Chen, B. Welding Fumes from Stainless Steel Gas Metal Arc Processes Contain Multiple Manganese Chemical Species. *J. Environ. Monit.* **2010,** *12,* 1133–1140.
26. Doig, A. T.; McLaughlin, A. G. X-ray Appearances of the Lungs of Electric Arc Welders. *Lancet* **1936,** *1,* 771–775.
27. Enzer, N.; Sander, O. A. Chronic Lung Changes in Electric Arc Welders. *J. Ind. Hyg.* **1938,** *20,* 333–350.
28. Kalliomaki, P.-L.; Kalliomaki, K.; Rahkonen, E.; Aittoniemi, K. Lung Retention of Welding Fumes and Ventilatory Lung Functions. A Follow-Up Study among Shipyard Welders. *Ann. Occup. Hyg.* **1983,** *27,* 449–452.
29. Cohen, M. D.; Kargacin, B.; Klein, C. B.; Costa, M. Mechanisms of Chromium Carcinogenicity and Toxicity. *Crit. Rev. Toxicol.* **1993,** *23,* 255–281.
30. Antonini, J. M.; Leonard, S. S.; Roberts, J. R.; Solano-Lopez, C.; Young, S.-H.; Shi, X.; Taylor, M. D. Effect of Stainless Steel Manual Metal Arc Welding Fume on Free Radical Production, DNA Damage, and Apoptosis Induction. *Mol. Cell. Biochem.* **2005,** *279,* 17–23.
31. International Agency for Research on Cancer. Chromium, Nickel, and Welding, *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans;* World Health Organization: Geneva, 1990; pp 447–525.
32. Maxild, J.; Andersen, M.; Kiel, P.; Stern, R. M. Mutagenicity of Fume Particles from Metal Arc Welding on Stainless Steel in the Salmonella/Microsome Test. *Mutat. Res.* **1978,** *56,* 235–243.
33. Costa, M.; Zhitkovich, A.; Toniolo, P. DNA-Protein Cross-Links in Welders: Molecular Implications. *Cancer Res.* **1993,** *53,* 460–463.
34. Sjogren, B.; Stragis Hansen, K.; Kjuus, H.; Persson, P.-G. Exposure to Stainless Steel Welding Fumes and Lung Cancer: A Meta-Analysis. *Occup. Environ. Med.* **1994,** *51,* 335–336.
35. Moulin, J. J. A Meta-Analysis of Epidemiologic Studies of Lung Cancer in Welders. *Scand. J. Work Environ. Health* **1997,** *23,* 104–113.
36. Becker, N. Cancer Mortality among Arc Welders Exposed to Fumes Containing Chromium and Nickel. *J. Occup. Environ. Med.* **1999,** *41,* 294–303.
37. Fiore, S. R. Reducing Exposure to Hexavalent Chromium in Welding Fumes. *Weld J.* **2006,** *85,* 38–42.
38. Harris, M. K. Health Effects of Metals, Gases, and Other Agents Commonly Encountered in Welding Processes, *Welding Health and Safety: A Field Guide for OEHS Professionals;* American Industrial Hygiene Association Press: Fairfax, VA, 2002; p 184.
39. Wahl, W. Exploring Trends in Hardfacing. *Weld J.* **2006,** *85,* 35–37.
40. Couper, J. On the Effects of Black Oxide of Manganese When Inhaled into the Lungs. *Brit. Ann. Med. Pharm.* **1837,** *1,* 41–42.

41. Wennberg, A.; Iregren, A.; Struwe, G.; Cizinsky, G.; Hagman, M.; Johansson, L. Manganese Exposure in Steel Smelters a Health Hazard to the Nervous System. *Scand. J. Work Environ. Health* **1991,** *17,* 255–262.
42. Mergler, D.; Baldwin, M. Early Manifestations of Manganese Neurotoxicity in Humans: An Update. *Environ. Res.* **1997,** *73,* 92–100.
43. Lucchini, R.; Apostoli, P.; Perrone, C.; Placidi, D.; Albini, E.; Migliorati, P.; Mergler, D.; Sassine, M. P.; Palmi, S.; Alessio, L. Long-Term Exposure to "Low Levels" of Manganese Oxides and Neurofunctional Changes in Ferroalloy Workers. *Neurotoxicology* **1999,** *20,* 287–297.
44. Antonini, J. M.; Santamaria, A. B.; Jenkins, N. T.; Albini, E.; Lucchini, R. Fate of Manganese Associated with the Inhalation of Welding Fumes: Potential Neurological Effects. *Neurotoxicology* **2006,** *27,* 304–310.
45. Sowards, J. W.; Liang, D.; Alexandrov, B. T.; Frankel, G. S.; Lippold, J. C. A New Chromium-Free Welding Consumable for Joining Austenitic Stainless Steels. *Weld J.* **2011,** *90,* 63s–76s.
46. Zhao, J. S.; Shi, X. L.; Castranova, V.; Ding, M. Occupational Toxicology of Nickel and Nickel Compounds. *J. Environ. Pathol. Toxicol. Oncol.* **2009,** *28,* 177–208.
47. Hedenstedt, A.; Jenssen, D.; Lidesten, B.; Ramel, C.; Rannug, U.; Stern, R. M. Mutagenicity of Fume Particles from Stainless Steel Welding. *Scand. J. Work Environ. Health* **1977,** *3,* 203–211.
48. Costa, M. Molecular Mechanisms of Nickel Carcinogenesis. *Annu. Rev. Pharmacol. Toxicol.* **1991,** *31,* 321–337.
49. Gerin, M.; Siemiatycki, J.; Richardson, L.; Pellerin, J.; Lakhani, R.; Dewar, R. Nickel and Cancer Associations from a Multi-Center Occupational Exposure Case-Referent Study. In *Nickel in the Human Environment;* Sunderman, Jr., F. W., Ed.; International Agency for Research on Cancer: Lyon, 1984. Scientific Publication No. 53.
50. Langard, S. Nickel-Related Cancer in Welders. *Sci. Total Environ.* **1994,** *148,* 303–309.
51. Lockey, J. E.; Schenker, M. B.; Howden, D. G.; Desmeules, M. J.; Saracci, R.; Sprince, N. L.; Harber, P. I. Current Issues in Occupational Lung Disease. *Am. Rev. Respir. Dis.* **1988,** *138,* 1047–1050.
52. Anthony, J. S.; Zamel, N.; Aberman, A. Abnormalities in Pulmonary Function after Brief Exposure Toxic Metal Fumes. *Can. Med. Assoc. J.* **1978,** *119,* 586–588.
53. Ashby, H. S. Welding Fume in the Workplace. *Prof. Saf.* **2002,** *47,* 55–60.
54. Patwardhan, J. R.; Finch, E. S. Fatal Cadmium Fume Pneumonitis. *Med. J. Aust.* **1976,** *29,* 962–964.
55. Ohshiro, H.; Nose, T.; Sugiyama, K.; Meshitsuka, S.; Kurozawa, Y.; Kuranobu, M.; Funakawa, K.; Yamasaki; Kinosita, K. A Case Study of Acute Cadmium Poisoning by Welding Work. *Jap. J. Ind. Health* **1988,** *30,* 210–211.
56. International Agency for Research. Beryllium, Cadmium, Mercury, and Exposures in Glass Manufacturing Industry. In *IARC Monographs Evaluating the Carcinogenic Risks to the Human, Lyon, France*, 1993, pp 119–237.
57. Yamamoto, S.; Katagiri, K.; Ando, M.; Chen, X.-Q. Suppression of Pulmonary Antibacterial Defense Mechanisms and Lung Damage in Mice Exposed to Fluoride Aerosol. *J. Toxicol. Environ. Health* **2001,** *62,* 485–494.
58. Maizlish, N.; Beaumont, J.; Singleton, J. Mortality among California Highway Workers. *Am. J. Ind. Med.* **1988,** *13,* 363–379.
59. Palmer, W. G.; Eaton, J. C. *Effects of Welding on Health*; American Welding Society: Miami, FL, Vol. X, 1998.
60. Centers for Disease Control and Prevention. *Emergency Preparedness and Response: Preventing Carbon Monoxide Poisoning after an Emergency*. http://emergency.cdc.gov/disasters/cofacts.asp (accessed on 05 October 2012).
61. Ichinose, F.; Hurford, W. E.; Zapol, W. M. Evaluation of Inhaled Nitric Oxide in Experimental Models of Lung Injury. In *Nitric Oxide and the Lung;* Zapol, W. M., Bloch, K. D., Eds.; Marcel Dekker, Inc.: New York, 1997; pp 251–270.
62. Centers for Disease Control and Prevention. *Emergency Preparedness and Response: Facts about Phosgene.* http://emergency.cdc.gov/agent/phosgene/basics/facts.asp (accessed on 05 October 2012).
63. Lyttle, K. A. Decrease Fume, Increase Productivity: Optimized Consumables Selection for an Improved Working Environment and Reduced Welding Costs. In *International Institute of Welding Conference ProceedingsThe Human Factor and Its Environment*; International Institute of Welding: Lisbon, Portugal, 1999; pp 75–84.
64. American Welding Society. *Ventilation Guide for Weld Fume*, Miami, FL, 2001, pp 3–8.
65. Flynn, M. R.; Susi, P. Local Exhaust Ventilation for the Control of Welding Fumes in the Construction Industry – A Literature Review. *Ann. Occup. Hyg.* **2012,** *56* (7), 764–776, http://dx.doi.org/10.1093/annhyg/mes018.
66. American Conference of Governmental Industrial Hygienists. *Industrial Ventilation – A Manual of Recommended Practice,* 27th ed; Cincinnati, OH, 2010.
67. American Welding Society. *Safety in Welding, Cutting, and Allied Process*, Miami, FL, 1999, p 10.
68. Ludwig, T.; Schwass, D.; Seitz, G.; Siekmann, H. Intakes of Thorium While Using Thoriated Tungsten Electrodes for TIG Welding. *Health Phys.* **1999,** *77,* 462–469.
69. American Welding Society. Confined Spaces. In *Safety and Health Fact Sheets*, Miami, FL, 1998, Fact Sheet No. 12.
70. Harris, M. K. Personal Protective Equipment, *Welding Health and Safety: A Field Guide for OEHS Professionals;* American Industrial Hygiene Association: Fairfax, VA, 2002; pp 191–199.
71. Tenkate, T. D. Optical Radiation Hazards of Welding Arc. *Rev. Environ. Health* **1998,** *13,* 131–146.
72. American Welding Society, Radiation. In *Safety and Health Fact Sheets*, Miami, FL, 1998, Fact Sheet No. 2.
73. Guenel, P. G.; Laforest, L.; Cyr, D.; Fevotte, J.; Sabroe, S.; Dufour, C.; Lutz, J.-M.; Lynge, E. Occupational Risk Factors, Ultraviolet Radiation, and Ocular Melanoma: A Case-Control Study in France. *Cancer Causes Control* **2001,** *12,* 451–459.
74. El Ghissassi, F.; Baan, R.; Straif, K.; Grosse, Y.; Secretan, B.; Bouvard, V.; Benbrahim-Tallaa, L.; Guha, N.; Freeman, C.; Galichet, L.; Cogliano, V. A Review of Human Carcinogens – Part D: Radiation. *Lancet Oncol.* **2009,** *10,* 751–752.
75. Tenkate, T. D.; Collins, M. J. Personal Ultraviolet Radiation Exposure of Workers in a Welding Environment. *Am. Ind. Hyg. Assoc. J.* **1997,** *58,* 33–38.
76. Goller, J. W.; Paik, N. W. A Comparison of Iron Oxide Fume Inside and Outside of Welding Helmets. *Am. Ind. Hyg. Assoc. J.* **1985,** *46,* 89–93.
77. American Welding Society. Burn Protection. In *Safety and Health Fact Sheets*, Miami, FL, 1998, Fact Sheet No. 7.
78. American Welding Society. Noise. In *Safety and Health Fact Sheets*, Miami, FL, 1998, Fact Sheet No. 3.
79. Herberts, P.; Kadedors, R.; Andersson, G. Shoulder Pain in Industry: An Epidemiology Study on Welders. *Acta Orthop. Scand.* **1981,** *52,* 299–306.
80. Torner, M.; Zetterberg, C.; Anden, U.; Hanson, T.; Lindell, V. Workload and Musculoskeletal Problems: A Comparison between Welders and Office Clerks. *Ergonomics* **1991,** *34,* 1179–1196.
81. Schneider, S.; Susi, P. Ergonomics and Construction: A Review of Potential Hazards in New Construction. *Am. Ind. Hyg. Assoc. J.* **1994,** *55,* 635–649.
82. Lowe, B. D.; Wurselbacher, S. J.; Shulman, S. A.; Hudock, S. D. Electromyographic and Discomfort Analysis of Confined-Space Shipyard Welding Processes. *Appl. Ergon.* **2001,** *32,* 255–269.
83. Antonini, J. M. Health Effects of Welding. *Crit. Rev. Toxicol.* **2003,** *33,* 61–203.
84. Wong, A.; Greene, S.; Robinson, J. Metal Fume Fever: A Case Review of Calls Made to the Victorian Poisons Information Centre. *Aust. Fam. Physician* **2012,** *41,* 141–144.
85. Plum, L. M.; Rink, L.; Haase, H. The Essential Toxin: Impact of Zinc on Human Health. *Int. J. Environ. Res. Public Health* **2010,** *7,* 1342–1365.
86. Blanc, P.; Boushey, H. A.; Wong, H.; Wintermeyer, S. F.; Bernstein, M. S. Cytokines in Metal Fume Fever. *Am. Rev. Respir. Dis.* **1993,** *147,* 134–138.
87. Gordon, T.; Fine, J. M. Metal Fume Fever. *Occup. Med.* **1993,** *8,* 505–517.
88. Bronstein, A. C.; Spyker, D. A.; Cantilena, L. R.; Green, J. L.; Rumack, B. H.; Giffin, S. L. 2009 Annual Report of the American Association of Poison Control Centers' National Poison Data System (NPDS): 27th Annual Report. *Clin. Toxicol.* **2010,** *48,* 979–1178.
89. American Thoracic Society. Standards for the Diagnosis and Care of Patients with Chronic Obstructive Pulmonary Disease. *Am. J. Respir. Crit. Care Med.* **1995,** *152,* S77–S121.
90. Holm, M.; Kim, J.-L.; Lillienber, L.; Storaas, T.; Jogi, R.; Svanes, C.; Schlunssen, V.; Forsbeg, B.; Gislason, T.; Janson, C.; Toren, K. Incidence and Prevalence of Chronic Bronchitis: Impact of Smoking and Welding. The RHINE Study. *Int. J. Tuberc. Lung Dis.* **2012,** *16,* 553–557.

91. Dunn, J. E.; Linden, G.; Breslow, L. Lung Cancer Mortality Experience of Men in Certain Occupations in California. *Am. J. Public Health* **1960,** *50,* 1475–1487.
92. Sterling, T. D.; Wenkham, J. J. Smoking Characteristics by Type of Employment. *J. Occup. Med.* **1976,** *18,* 743–754.
93. Menck, H. R.; Henderson, B. E. Occupational Differences in Rates of Lung Cancer. *J. Occup. Med.* **1976,** *18,* 797–801.
94. Cotes, J. E.; Feinman, E. L.; Male, V. J.; Remie, E. S.; Wickham, C. A. G. Respiratory Symptoms and Impairment in Shipyard Welders and Caulker Burners. *Br. J. Ind. Med.* **1989,** *46,* 292–301.
95. Bradshaw, L. M.; Fishwick, D.; Slater, T.; Pearce, N. Chronic Bronchitis, Work Related Respiratory Symptoms, and Pulmonary Function in Welders. *Occup. Environ. Med.* **1998,** *55,* 150–154.
96. Lillienberg, L.; Zock, J.-P.; Kromhout, H. A Population-Based Study on Welding Exposures at Work and Respiratory Symptoms. *Ann. Occup. Hyg.* **2008,** *52,* 107–115.
97. Flors, L.; Domingo, M. L.; Leiva-Salinas, C.; Mazon, M.; Rosello-Sastre, E.; Vilar, J. Uncommon Occupational Lung Diseases: High-Resolution CT Findings. *Am. J. Roentgenol.* **2010,** *194,* W20–W26.
98. Kleinfeld, M.; Messite, J.; Kooyman, O.; Spiro, J. Welders' Siderosis: A Clinical Roentgenographic and Physiological Study. *Arch. Environ. Health* **1969,** *19,* 70–73.
99. Morgan, W. K. C. On Welding, Wheezing, and Whimsy. *Am. Ind. Hyg. Assoc. J.* **1989,** *50,* 59–69.
100. Attfield, M. D.; Ross, D. S. Radiological Abnormalities in Electric Arc Welders. *Br. J. Ind. Med.* **1978,** *35,* 117–122.
101. Guidotti, T. L.; Abraham, J. L.; DeNee, P. B.; Smith, J. R. Arc Welders' Pneumoconiosis: Application of Advanced Scanning Electron Microscopy. *Arch. Environ. Health* **1978,** *33,* 117–124.
102. Funahashi, A.; Schlueter, D. P.; Pintar, K.; Bemis, E. L.; Siegesmund, K. A. Welder's Pneumoconiosis: Tissue Elemental Microanalysis by Energy Dispersive X-Ray Analysis. *Br. J. Ind. Med.* **1988,** *45,* 14–18.
103. Buerke, U.; Schneider, J.; Rosler, J.; Woitowitz, H.-J. Interstitial Pulmonary Fibrosis after Severe Exposure to Welding Fumes. *Am. J. Ind. Med.* **2002,** *41,* 259–268.
104. McCormick, L. M.; Goddard, M.; Madadeva, R. Pulmonary Fibrosis Secondary to Siderosis Causing Symptomatic Respiratory Disease: A Case Report. *J. Med. Case Reports* **2008,** *2,* 257–260.
105. Ji, C.; Chen, G.; Cai, H.; Meng, F.; Chen, Y.; Guo, L.; Hunag, J.; Ling, C. An Unusual Case of Welder's Siderosis with Local Massive Fibrosis: A Case Report. *Chin. Med. J.* **2012,** *125,* 552–554.
106. Oxhoj, H.; Bake, B.; Wedel, H.; Wilhelmsen, L. Effects of Electric Arc Welding on Ventilatory Function. *Arch. Environ. Health* **1979,** *34,* 211–217.
107. Akbar-Khanzadeh, F. Long-Term Effects of Welding Fumes upon Respiratory Symptoms and Pulmonary Function. *J. Occup. Med.* **1980,** *22,* 337–341.
108. Akbar-Khanzadeh, F. Short-Term Respiratory Function Changes in Relation to Work Shift Welding Fume Exposures. *Int. Arch. Occup. Environ. Health* **1993,** *64,* 393–397.
109. Mur, J. M.; Teculescu, D.; Pham, Q. T.; Gaertner, M.; Massin, N.; Meyer-Bisch, C.; Moulin, J. J.; Diebold, F.; Pierre, F. Lung Function and Clinical Findings in a Cross-Sectional Study of Arc Welders: An Epidemiological Study. *Int. Arch. Occup. Environ. Health* **1985,** *57,* 1–18.
110. Sobaszek, A.; Boulenguez, C.; Frimat, P.; Robin, H.; Haguenoer, J. M.; Edme, J.-L. Acute Respiratory Effects of Exposure to Stainless Steel and Mild Steel Welding Fumes. *J. Occup. Environ. Med.* **2000,** *42,* 923–931.
111. Hannu, T.; Piipari, R.; Kasurinen, H.; Keskinen, M.; Tuppurainen, M.; Tuomi, T. Occupational Asthma due to Manual Metal-Arc Welding of Special Stainless Steels. *Eur. Respir. J.* **2005,** *26,* 736–739.
112. Brand, P.; Gube, M.; Gerards, K.; Bertram, J.; Kaminski, H.; John, A. C.; Kuhibusch, T.; Wiemann, M.; Eisnebeis, C.; Winkler, R.; Kraus, T. Internal Exposure, Effect Monitoring, and Lung Function in Welders after Acute Short-Term Exposure to Welding Fumes from Different Welding Processes. *J. Occup. Environ. Med.* **2010,** *52,* 887–892.
113. Lee, H. S.; Chia, S. E.; Yap, J. C. H.; Wang, Y. T.; Lee, C. S. Occupational Asthma due to Spot-Welding. *Singapore Med. J.* **1990,** *31,* 506–508.
114. Luo, J.-C. J.; Hsu, K.-H.; Shen, W.-S. Pulmonary Function Abnormalities and Airway Irritation Symptoms of Metal Fume Exposure on Automobile Spot Welders. *Am. J. Ind. Med.* **2006,** *49,* 407–416.
115. Loukzadeh, Z.; Sharifian, S. A.; Aminian, O.; Shojaoddiny-Ardekani, A. Pulmonary Effects of Spot Welding in Automobile Assembly. *Occup. Med.* **2009,** *59,* 267–269.
116. Beckett, W. S.; Pace, P. E.; Sferlazza, S. J.; Perlman, G. D.; Chen, A. H.; Xu, X. P. Airway Reactivity in Welders: A Controlled Prospective Cohort Study. *J. Occup. Environ. Med.* **1996,** *38,* 1229–1238.
117. Wang, Z. P.; Larsson, K.; Malmberg, P.; Sjogren, B.; Hallberg, B. O.; Wrangskog, K. Asthma, Lung Function, and Bronchial Responsiveness in Welders. *Am. J. Ind. Med.* **1994,** *26,* 741–754.
118. Simonsson, B. G.; Nielsen, J.; Karlsson, S.-E.; Horstman, V.; Kronholm-Diab, K.; Skerfving, S. A Prospective Study on Bronchial Responsiveness in Newly Employed Workers Exposed to Substances Potentially Harmful to the Airways. *Eur. Respir. J.* **1995,** *8,* 194S.
119. Beach, J. R.; Dennis, J. H.; Avery, A. J.; Bromly, C. L.; Ward, R. J.; Walters, E. H.; Stenton, S. C.; Hendrick, D. J. An Epidemiologic Investigation of Asthma in Welders. *Am. J. Respir. Crit. Care Med.* **1996,** *154,* 1394–1400.
120. Munoz, X.; Cruz, M. J.; Freixa, A.; Guardino, X.; Morrell, F. Occupational Asthma Caused by Metal Arc Welding of Iron. *Respiration* **2009,** *78,* 455–459.
121. El-Zein, M.; Malo, J.-L.; Infante-Rivard, C.; Gautrin, D. Incidence of Probable Occupational Asthma and Changes in Airway Calibre and Responsiveness in Apprentice Welders. *Eur. Respir. J.* **2003,** *22,* 513–518.
122. Banga, A.; Reilly, M. J.; Rosenman, K. D. A Study of Characteristics of Michigan Workers with Work-Related Asthma Exposed to Welding. *J. Occup. Environ. Med.* **2011,** *53,* 415–419.
123. Wergeland, E.; Iversen, B. G. Deaths from Pneumonia after Welding. *Scand. J. Work Environ. Health* **2001,** *27,* 353.
124. Registrar General. Decennial Supplement England and Wales, 1951. In *Occupational Mortality*; Part II, No. 1, London, United Kingdom, 1958.
125. Registrar General. Decennial Supplement England and Wales, 1961. In *Occupational Mortality Tables*, London, United Kingdom, 1971.
126. Registrar General. Decennial Supplement England and Wales, 1971, Series DS, No. 1, London, United Kingdom, 1981.
127. Coggon, D.; Inskip, H.; Winter, P.; Pannett, B. Lobar Pneumonia: An Occupational Disease in Welders. *Lancet* **1994,** *344,* 41–43.
128. Beaumont, J. J.; Weiss, N. S. Mortality of Welders, Shipfitters, and Other Metal Trades Workers in Boilermakers Local No. 104, AFL-CIO. *Am. J. Epidemiol.* **1980,** *112,* 775–786.
129. Polednak, A. P. Mortality among Welders, Including a Group Exposed to Nickel Oxides. *Arch. Environ. Health* **1981,** *36,* 235–242.
130. McMillan, G. H.; Pethybridge, R. J. The Health of Welders in Naval Dockyards: Proportional Mortality Study of Welders and Two Control Groups. *J. Soc. Occup. Med.* **1983,** *33,* 75–84.
131. Newhouse, M. L.; Oakes, D.; Woolley, A. J. Mortality of Welders and Other Craftsmen at a Shipyard in NE England. *Br. J. Ind. Med.* **1985,** *42,* 406–410.
132. Palmer, K. T.; Poole, J.; Ayres, J. G.; Mann, J.; Burge, P. S.; Coggon, D. Exposure to Metal Fume and Infectious Pneumonia. *Am. J. Epidemiol.* **2003,** *157,* 227–233.
133. Miller, J. M.; Hair, J. G.; Hebert, M.; Hebert, L.; Roberts, F. J., Jr.; Weyant, R. S. Fulminating Bacteremia and Pneumonia due to *Bacillus cereus*. *J. Clin. Microbiol.* **1997,** *35,* 504–507.
134. Avashia, S. B.; Riggins, W. S.; Lindley, C.; Hoffmaster, A.; Drumgoole, R.; Nekomoto, T.; Jackson, P. J.; Hill, K. K.; Williams, K.; Lehman, L.; Libal, M. C.; Wilkins, P. P.; Alexander, J.; Tvaryanas, A.; Betz, T. Fatal Pneumonia among Metalworkers due to Inhalation Exposure to *Bacillus cereus* Containing *Bacillus anthracis* Toxin Genes. *Clin. Infect. Dis.* **2007,** *44,* 414–416.
135. Drobniewski, F. A. *Bacillus cereus* and Related Species. *Clin. Microbiol. Rev.* **1993,** *6,* 324–338.
136. Hoffmaster, A. R.; Ravel, J.; Rasko, D. A.; Chapman, G. D.; Chute, M. D.; Marston, C. K.; De, B. K.; Sacchi, C. T.; Fitzgerald, C.; Mayer, L. W.; Maiden, M. C.; Priest, F. G.; Barker, M.; Jiang, L.; Cer, R. Z.; Rilstone, J.; Peterson, S. N.; Weyant, R. S.; Galloway, D. R.; Read, T. D.; Popovic, T.; Fraser, C. M. Identification of Anthrax Toxin Genes in a *Bacillus cereus* Associated with an Illness Resembling Inhalation Anthrax. *Proc. Natl. Acad. Sci. USA* **2004,** *101,* 8449–8454.

137. Hoffmaster, A. R.; Hill, K. K.; Gee, J. E.; Marston, C. K.; De, B. K.; Popovic, T.; Sue, D.; Wilkins, P. P.; Avashia, S. B.; Drumgoole, R.; Helma, C. H.; Ticknor, L. O.; Okinaka, R. T.; Jackson, P. J. Characterization of *Bacillus cereus* Isolates Associated with Fatal Pneumonias: Strains are Closely Related to *Bacillus anthracis* and Harbor *B. anthracis* Virulence Genes. *J. Clin. Microbiol.* **2006,** *44,* 3352–3360.
138. Steenland, K.; Beaumont, J.; Elliot, L. Lung Cancer in Mild Steel Welders. *Am. J. Epidemiol.* **1991,** *133,* 220–229.
139. Hansen, K. S.; Lauritsen, J. M.; Skytthe, A. Cancer Incidence among Mild Steel and Stainless Steel Welders and Other Metal Workers. *Am. J. Ind. Med.* **1996,** *30,* 373–382.
140. Danielsen, T. E.; Langard, S.; Andersen, A. Incidence of Cancer among Welders and Other Shipyard Workers with Information on Previous Work History. *J. Occup. Environ. Med.* **2000,** *42,* 101–109.
141. Steenland, K. Ten-Year Update on Mortality among Mild Steel Welders. *Scand. J. Work Environ. Health* **2002,** *28,* 163–167.
142. Ambroise, D.; Wild, P.; Moulin, J. J. Update of a Meta-Analysis on Lung Cancer and Welding. *Scand. J. Work Environ. Health* **2006,** *32,* 22–31.
143. Siew, S. S.; Kauppinen, T.; Kyyronen, P.; Heikkilia, P.; Pukkala, E. Exposure to Iron and Welding Fumes and the Risk of Lung Cancer. *Scand. J. Work Environ. Health* **2008,** *34,* 444–450.
144. Simonato, L.; Fletcher, A. C.; Andersen, A.; Andersen, K.; Becker, N.; Chang-Claude, J.; Ferro, G.; Gerin, M.; Gray, C. N.; Hansen, K. S.; Kalliomaki, P.-L.; Kurppa, K.; Langard, S.; Merlo, F.; Moulin, J. J.; Newhouse, M. L.; Peto, J.; Pukkala, E.; Sjorgen, B.; Wild, P.; Winkelmann, R.; Saracci, R. A Historical Prospective Study of European Stainless Steel, Mild Steel, and Shipyard Welders. *Br. J. Ind. Med.* **1991,** *48,* 145–154.
145. Zeidler-Erdely, P. C.; Kashon, M. L.; Battelli, L. A.; Young, S.-H.; Erdely, A. D.; Roberts, J. R.; Reynolds, S. H.; Antonini, J. M. Lung Inflammation and Tumor Induction in Lung Tumor Susceptible A/J and Resistant C57BL/6J Mice Exposed to Welding Fume. *Particle Fibre Toxicol.* **2008,** *5,* 12.
146. Zeidler-Erdely, P. C.; Li, S.; Kashon, M. L.; Antonini, J. M. Response of the Mouse Lung Transcriptome to Welding Fume: Effects of Stainless and Mild Steel Fumes on Lung Gene Expression in A/J and C57 BL/6J Mice. *Respir. Res.* **2010,** *11,* 70.
147. Stern, R. M. Assessment of Risk of Lung Cancer for Welders. *Arch. Environ. Health* **1983,** *38,* 148–155.
148. Baker, R. S. U.; Arlauskas, A.; Tandon, R. K.; Crisp, P. T.; Ellis, J. Toxic and Genotoxic Action of Electric Arc Welding Fumes on Cultured Mammalian Cells. *J. Appl. Toxicol.* **1986,** *6,* 357–362.
149. Sorensen, A. R.; Thulstrup, A. M.; Hansen, J.; Ramlau-Hansen, C. H.; Meershon, A.; Skytthe, A.; Bonde, J. P. Risk of Lung Cancer According to Mild Steel and Stainless Steel Welding. *Scand. J. Work Environ. Health* **2007,** *33,* 379–386.
150. Ward, E. M.; Schulte, P. A.; Straif, K.; Hopf, N. B., et al. Research Recommendations for Selected IARC-Classified Agents. *Environ. Health Perspect.* **2010,** *118,* 1355–1362.
151. Emmett, E. A.; Buncher, C. R.; Suskind, R. B.; Rowe, K. W. Skin and Eye Diseases among Arc Welders and Those Exposed to Welding Operations. *J. Occup. Med.* **1981,** *23,* 85–90.
152. Dixon, A. J.; Dixon, B. F. Ultraviolet Radiation from Welding and Possible Risk of Skin and Ocular Malignancy. *Med. J. Aust.* **2004,** *181,* 155–157.
153. Currie, C. L.; Monk, B. E. Welding and Non-Melanoma Skin Cancer. *Clin. Exp. Dermatol.* **2000,** *25,* 28–29.
154. Donoghue, A. M.; Sinclair, M. J. Basal Cell Carcinoma after Frequent Episodes of Cutaneous Erythema and Peeling Induced by Welding. *Occup. Environ. Med.* **1999,** *56,* 646–648.
155. Mergler, D. Neurotoxic Effects of Low Level Exposure to Manganese in Human Populations. *Environ. Res.* **1999,** *80,* 99–102.
156. Olanow, C. W. Manganese-Induced Parkinsonism and Parkinson's Disease. *Ann. NY Acad. Sci.* **2004,** *1012,* 209–223.
157. Sjogren, B.; Gustavsson, P.; Hogstedt, C. Neuropsychiatric Symptoms among Welders Exposed to Neurotoxic Metals. *Br. J. Ind. Med.* **1990,** *47,* 704–707.
158. Sjogren, B.; Iregren, A.; Frech, W.; Hagman, M.; Johansson, L.; Tesarz, M.; Wennberg, A. Effects of the Nervous System among Welders Exposed to Aluminum and Manganese. *Occup. Environ. Med.* **1996,** *53,* 32–40.
159. Sinczuk-Walczak, H.; Jakubowski, M.; Matczak, W. Neurological and Neurophysiological Examinations of Workers Occupationally Exposed to Manganese. *Int. J. Occup. Med. Environ. Health* **2001,** *14,* 329–337.
160. Bowler, R. M.; Gysens, S.; Diamond, E.; Booty, A.; Hartney, C.; Roels, H. A. Neuropsychological Sequelae of Exposure to Welding Fumes in a Group of Occupationally Exposed Men. *Int. J. Hyg. Environ. Health* **2003,** *206,* 517–526.
161. Bowler, R. M.; Nakagawa, S.; Drezgic, M.; Roels, H. A.; Park, R. M.; Diamond, E.; Mergler, D.; Bouchard, M.; Bowler, R. P.; Koller, W. Sequelae of Fume Exposure in Confined Space Welding: A Neurological and Neuropsychological Case Series. *Neurotoxicology* **2007,** *28,* 298–311.
162. Bowler, R. M.; Roels, H. A.; Nakagawa, S.; Drezgic, M.; Diamond, E.; Park, R.; Koller, W.; Bowler, R. P.; Mergler, D.; Bouchard, M.; Smith, D.; Gwiazda, R.; Doty, R. L. Dose-Effect Relationships between Manganese Exposure and Neurological, Neuropsychological and Pulmonary Function in Confined Space Bridge Welders. *Occup. Environ. Med.* **2007,** *64,* 167–177.
163. Ellingsen, D. G.; Konstantinov, R.; Bast-Pettersen, R.; Merkurjeva, L.; Chashchin, M.; Thomassen, Y.; Chashchin, V. A Neurobehavioral Study of Current and Former Welders Exposed to Manganese. *Neurotoxicology* **2008,** *29,* 48–59.
164. Nelson, K.; Golnick, J.; Korn, T.; Angle, C. Manganese Encephalopathy: Utility of Early Magnetic Resonance Imaging. *Br. J. Ind. Med.* **1993,** *50,* 510–513.
165. Franek, B. Manganese Exposure during Welding Operations. *Appl. Occup. Environ. Hyg.* **1994,** *9,* 537–538.
166. Sadek, A. H.; Rauch, R.; Schulz, P. E. Parkinsonism due to Manganism in a Welder. *Int. J. Toxicol.* **2003,** *22,* 393–401.
167. Rasmussen, K. H.; Jepsen, J. R. The Organic Psychosyndrome in Electric Arc Welders. A Possible Sequela of Manganese Toxicity. *Ugeskr Laeger* **1987,** *149,* 3497–3498.
168. Discalzi, G.; Pira, E.; Hernandez, E. H.; Valentina, C.; Turbiglio, M.; Meliga, F. Occupational Manganese Parkinsonism: Magnetic Resonance Imaging and Clinical Patterns Flowing $CaNa_2$-EDTA Chelation. *Neurotoxicology* **2000,** *21,* 863–866.
169. Racette, B. A.; McGee-Minnich, L.; Moerlein, S. M.; Mink, J. W.; Videen, T. O.; Perlmutter, J. S. Welding-Related Parkinsonism: Clinical Features, Treatment, and Pathophysiology. *Neurology* **2001,** *56,* 8–13.
170. Racette, B. A.; Tabbal, S. D.; Jennings, D.; Good, L.; Perlmutter, J. S.; Evanoff, B. Prevalence of Parkinsonism and Relationship to Exposure in a Large Sample of Alabama Welders. *Neurology* **2005,** *64,* 230–235.
171. Goldman, S. M.; Tanner, C. M.; Olanow, C. W.; Watts, R. L.; Field, R. D.; Langston, J. W. Occupation and Parkinsonism in Three Movement Disorders Clinics. *Neurology* **2005,** *65,* 1430–1435.
172. Stampfer, M. J. Welding Occupations and Mortality from Parkinson's Disease and Other Neurodegenerative Diseases among United States Men, 1985–1999. *J. Occup. Environ. Hyg.* **2009,** *6,* 267–272.
173. Tanner, C. M.; Ross, G. W.; Jewell, S. A.; Hauser, R. A.; Jankovic, J.; Factor, S. A.; Bressman, S.; Deligtisch, A.; Marras, C.; Lyons, K. E.; Bhudhikanok, G. S.; Roucoux, D. F.; Meng, C.; Abbott, R. D.; Langston, J. W. Occupation and Risk of Parkinsonism: A Multicenter Case-Control Study. *Arch. Neurol.* **2009,** *66,* 1106–1113.
174. Sriram, K.; Lin, G. X.; Jefferson, A. M.; Roberts, J. R.; Chapman, R. S.; Chen, B. T.; Soukup, J. M.; Ghio, A. J.; Antonini, J. M. Dopaminergic Neurotoxicity Following Pulmonary Exposure to Manganese-Containing Welding Fumes. *Arch. Toxicol.* **2010,** *84,* 521–540.
175. Sriram, K.; Lin, G. X.; Jefferson, A. M.; Roberts, J. R.; Wirth, O.; Hayashi, Y.; Krajnak, K. M.; Soukup, J. M.; Ghio, A. J.; Reynolds, S. H.; Castranova, V.; Munson, A. E.; Antonini, J. M. Mitochondrial Dysfunction and Loss of Parkinson's Disease-Linked Proteins Contribute to Neurotoxicity of Manganese-Containing Welding Fumes. *FASEB J.* **2010,** *24,* 4989–5002.
176. Brook, R. D.; Rajagopalan, S.; Pope, C. A., 3rd; Brook, J. R.; Bhatnagar, A.; Diez-Roux, A. V.; Holguin, F.; Hong, Y.; Luepker, R. V.; Mittleman, M. A.; Peters, A.; Siscovick, D.; Smith, S. C., Jr.; Whitsel, L.; Kaufman, J. D. Particulate Matter Air Pollution and Cardiovascular Disease: An Update to Scientific Statement from the American Heart Association. *Circulation* **2010,** *121,* 2331–2378.

177. Moulin, J. J.; Wild, P.; Haguenoer, J. M.; Faucon, D.; De Gaudemaris, R.; Mur, J. M.; Mereau, M.; Gary, Y.; Toamain, J. P.; Birembaut, Y.; Blanc, M.; Debiolles, M. P.; Jegaden, D.; Laterriere, B.; Leonard, M.; Marini, F.; Massardier, C.; Moulin, M.; Reure, M.; Rigal, L.; Robert, G.; Viossat, M. A Mortality Study among Mild Steel and Stainless Steel Welders. *Br. J. Ind. Med.* **1993,** *50,* 234–243.
178. Hilt, B.; Qvenild, T.; Romyhr, O. Morbidity from Ischemic Heart Disease in Workers at a Stainless Steel Welding Factory. *Nor. Epidemiol.* **1999,** *9,* 21–26.
179. Sjogren, B.; Fossum, T.; Lindh, T.; Weiner, J. Welding and Ischemic Heart Disease. *Int. J. Occup. Environ. Health* **2002,** *8,* 309–311.
180. Ibfelt, E.; Bonde, J. P.; Hansen, J. Exposure to Metal Welding Fume Particles and Risk for Cardiovascular Disease in Denmark: A Prospective Cohort Study. *Occup. Environ. Med.* **2010,** *67,* 772–777.
181. Kim, J. Y.; Chen, J. C.; Boyce, P. D.; Christiani, D. C. Exposure to Welding Fumes is Associated with Acute Systemic Inflammatory Responses. *Occup. Environ. Med.* **2005,** *62,* 157–163.
182. Scharrer, E.; Hessel, H.; Kronseder, A.; Guth, W.; Rolinski, B.; Jorres, R. A.; Radon, K.; Schierl, R.; Angerer, P.; Nowak, D. Heart Rate Variability, Hemostatic and Acute Inflammatory Blood Parameters in Healthy Adults after Short-Term Exposure to Welding Fume. *Int. Arch. Occup. Environ. Health* **2007,** *80,* 265–272.
183. Cavallari, J. M.; Fang, S. C.; Eisen, E. A.; Schwartz, J.; Hauser, R.; Herrick, R. F. Time Course of Heart Rate Variability Decline Following Particulate Matter Exposure in an Occupational Cohort. *Inhal. Toxicol.* **2008,** *20,* 415–422.
184. Fang, S. C.; Eisen, E. A.; Cavallari, J. M.; Mittleman, M. A.; Christiani, D. C. Acute Changes in Vascular Function among Welders Exposed to Metal-Rich Particulate Matter. *Epidemiology* **2008,** *19,* 217–225.
185. Fang, S. C.; Cavallari, J. M.; Eisen, E. A.; Chen, J. C.; Mittleman, M. A.; Christiani, D. C. Vascular Function, Inflammation, and Variations in Cardiac Autonomic Responses to Particulate Matter among Welders. *Am. J. Epidemiol.* **2009,** *169,* 848–856.
186. Fang, S. C.; Eisen, E. A.; Cavallari, J. M.; Mittleman, M. A.; Christiani, D. C. Circulating Adhesion Molecules after Short-Term Exposure to Particulate Matter among Welders. *Occup. Environ. Med.* **2010,** *67,* 11–16.
187. Erdely, A.; Hulderman, T.; Salmen-Muniz, R.; Liston, A.; Zeidler-Erdely, P. C.; Chen, B. T.; Stone, S.; Frazer, D. G.; Antonini, J. M.; Simeonova, P. P. Inhalation Exposure of Gas-Metal Arc Stainless Steel Welding Fume Increased Atherosclerotic Lesions in Apolipoprotein E Knockout Mice. *Toxicol. Lett.* **2011,** *204,* 12–16.
188. Mortensen, J. T. Risk for Reduced Sperm Quality among Welders Workers, with Special Reference to Welders. *Scand. J. Work Environ. Health* **1988,** *14,* 27–30.
189. Bonde, J. P. Semen Quality and Sex Hormones among Mild Steel and Stainless Steel Welders: A Cross Sectional Study. *Br. J. Ind. Med.* **1990,** *47,* 508–514.
190. Bonde, J. P. Semen Quality in Welders Exposed to Radiant Heat. *Br. J. Ind. Med.* **1992,** *49,* 5–10.
191. Tas, S.; Lauwerys, R.; Lison, D. Occupational Hazards for the Male Reproductive System. *Crit. Rev. Toxicol.* **1996,** *26,* 261–307.
192. Wu, W.; Zhang, Y.; Zhang, F. Studies on Semen Quality in Workers Exposed to Manganese and Electric Welding. *Chin. J. Prev. Med.* **1996,** *30,* 266–268.
193. Danadevi, K.; Rozati, R.; Reddy, P. P.; Grover, P. Semen Quality of Indian Welders Occupationally Exposed to Nickel and Chromium. *Reprod. Toxicol.* **2003,** *17,* 451–456.
194. Ellingsen, D. G.; Chashchin, V.; Haug, E.; Chashchin, M.; Tkachenko, V.; Lubnina, N.; Bast-Pettersen, R.; Thomassen, Y. An Epidemiological Study of Reproductive Function Biomarkers in Male Welders. *Biomarkers* **2007,** *12,* 497–509.
195. Hobart Brothers Company. Technical Section. In *Pocket Welding Guide*, Troy, OH, 1997, pp 108–138.