1. EXPOSURE DATA

1.1 Description of major welding processes and materials

Welding is a broad term for the process of joining metals through coalescence (AWS, 2010). Welding techniques tend to be broadly classified as arc welding or gas welding. Arc welding uses electricity to generate an arc, whereas gas or oxyfuel welding (ISO 4063:2009 process numbers 3, 31, 311, 312, and 313) uses fuel gases such as acetylene or hydrogen to generate heat. Welding results in concurrent exposures including welding fumes, gases, and ionizing and non-ionizing radiation, and coexposures from other sources such as asbestos and solvents (Table 1.1).

Welding fumes are produced when metals are heated above their melting point, vapourize and condense into fumes. The fumes consist of predominantly fine solid particles with an aerodynamic diameter of less than 1 µm, and are a complex mixture of particles from the wire or electrode, base metal, or any coatings on the base metal. They consist mainly of metal oxides, silicates, and fluorides. Exposure to various gases also occurs during welding, such as nitrogen oxides (NO_x), carbon monoxide (CO), or ozone (O_3). Welding fumes and welding gases are distinct in that fumes contain solid particles that are temporarily suspended in the air due to a solid material being heated (such as metals), whereas gases are molecules in a gaseous state in the ambient air that have been generated by or are used as part of the welding process (e.g. the shielding gas) (ISO, 2009).

While there are many welding processes routinely employed in occupational settings, the most common arc welding processes are manual metal arc (MMA, ISO No. 111), gas metal arc (GMA, ISO No. 13), flux-cored arc (FCA, ISO Nos 114 and 136), gas tungsten arc (GTA, ISO No. 14), and submerged arc (SA, ISO No. 12) (Table 1.2 and Table 1.3). Electric resistance welding (ER, ISO Nos 21 and 22) is also commonly used for spot or seam welding, and uses electric currents and force to generate heat. In occupational settings, these processes are most commonly used to weld mild steel (MS, low carbon) or stainless steel (SS). Flame cutting (ISO No. 81), the process of using oxygen (O) and a fuel to cut a metal, is a closely related process that is often grouped occupationally with welding (ISO, 2009). Other processes closely related to welding, and often performed by welders, include gouging, brazing, carbon arc or plasma arc cutting, and soldering (broadly described by ISO Nos 8 and 9) (Burgess, 1995). An overview of all welding and allied processes is given in ISO standard 4063 (ISO, 2009).

1.1.1 History of welding processes

With epidemiological studies of welders spanning the 20th and 21st centuries, a brief mention of how welding has changed during this period and when welding processes became used commercially is warranted. A carbon arc torch was patented in 1881, and gas welding and

Table 1.1 Occupational exposures of welders that have been evaluated by the *IARC Monographs*

Agent	Evidence for carcinogenicity		Overall evaluation	Most recent volume (year)	Occurrence	Welding types	Organ sites (sufficient or limited evidence in humans)
	Humans	Animals					
Arsenic and inorganic arsenic compounds	Sufficient	Sufficient	1	100C (2012)	Impurity in some mild SS welding fumes	All	Lung, skin, urinary bladder, prostate, kidney, liver
Asbestos	Sufficient	Sufficient	1	100C (2012)	Insulation material and in heat-protective equipment of welders and the weld	Shipyard welding	Mesothelioma, larynx, lung, ovary, pharynx, stomach, colon, rectum
Beryllium and beryllium compounds	Sufficient	Sufficient	1	100C (2012)	Hardening agent in copper, magnesium, aluminium alloys and electrical contacts	GMA, GTA	Lung
Cadmium and cadmium compounds	Sufficient	Sufficient	1	100C (2012)	Platings on base metals, SS containing cadmium	All	Lung, kidney, prostate
Chromium VI compounds	Sufficient	Sufficient	1	100C (2012)	Alloy in SS, also in welding rods	All SS	Lung, nasal sinuses, nose
Electric fields, extremely low frequency	Inadequate	No relevant data	3	80 (2002)	Electrical currents from welding processes	All (more with processes using higher currents, such as resistance welding)	
Formaldehyde	Sufficient	Sufficient	1	100F (2012)	Metal coatings, degreasing solvents	All	Nasopharynx, nasal sinuses, leukaemia,
Inorganic lead compounds	Limited	Sufficient	2A	87 (2006)	In solder, brass, and bronze alloys; welding on lead-containing or -coated materials	GMA, GTA	Stomach
Magnetic fields, extremely low frequency	Limited	Inadequate	2B	80 (2002)	Electrical currents from welding processes	All (more with processes using higher currents, such as resistance welding)	Childhood leukaemia
Nickel compounds	Sufficient	Sufficient	1	100C (2012)	Alloy in SS, also in welding rods	All SS	Lung, paranasal sinuses, nasal cavity
Silica dust or crystalline, in the form of quartz or cristobalite	Sufficient	Sufficient	1	100C (2012)	Some welding fluxes contain silica	GMA, FCA, GTA	Lung
Titanium dioxide	Inadequate	Sufficient	2B	93 (2010)	Found in SMA (MMA) electrodes	SMA (MMA)	

Table 1.1 (continued)

Agent	Evidence for carcinogenicity		Overall evaluation	Most recent volume (year)	Occurrence	Welding types	Organ sites (sufficient or limited evidence in humans)
	Humans	Animals					
Ultraviolet radiation	Sufficient	Sufficient	1	100D (2012)	Arcs from welding guns	All	Ocular melanoma
Iron oxides (evaluation specific to iron and steel founding)	Sufficient	Inadequate	1	100F (2012)	Main component of steel	All	Lung
Vanadium pentoxide	Inadequate	Sufficient	2B	86 (2006)	Alloy in SS	All SS	
Outdoor air pollution ($PM_{2.5}$)	Sufficient	Sufficient	1	109 (2016)	$PM_{2.5}$ generated from all welding processes	All	Lung
Welding fume	Limited	Inadequate	2B	49 (1990)	Generated from welding processes	All	Lung

FCA, flux cored arc; GMA, gas metal arc; GTA, gas tungsten arc; MMA, manual metal arc; PM, particulate matter; SMA, shielded metal arc; SS, stainless steel

Table 1.2 Welding processes, materials, and uses

Welding type	Primary exposures encountered	Common industrial uses	Most common base metals welded	References
Oxyfuel	NO_2	Repair/maintenance	MS[a], AS	Weman (2003), Moniz & Miller (2010)
MMA	Metals, silicates, fluoride, asbestos[b], UV radiation, ELF-EMF	Steel fabrication, construction	MS[a], SS, AS	Burgess (1995), Weman (2003)
GMA	Metals, O_3, NO_2, CO, chlorinated HC, UV radiation, ELF-EMF	Various metal fabrication	MS[a], SS, AS, Al	Burgess (1995), Weman & Lindén (2006)
FCA	Metals, CO_2, UV radiation, ELF-EMF	Equipment repair, shipbuilding	MS[a], SS, AS	Spiegel-Ciobanu (2010)
GTA	O_3, NO, NO_2, metals, chlorinated HC, UV radiation, ELF-EMF	Aerospace, bicycle manufacturing, various metal fabrication	MS, SS[a], AS, Al	Burgess (1995), Weman (2003)
SA	Fluorides, UV radiation, ELF-EMF	Steel fabrication, shipbuilding	MS[a], SS, AS	Burgess (1995), Weman (2003)
ER	Metals, UV radiation, ELF-EMF	Aerospace, automobile, shipbuilding	MS, SS, AS, Al	Weman (2003), Moniz & Miller (2010)
Brazing/soldering	Metals, UV radiation	Metal arts, plumbing, electric components	All metals/steels	Moniz & Miller (2010)
Cutting/gouging	Metals, O_3, NO_2, UV radiation	Fabrication, construction, shipbuilding	All metals/steels	Weman (2003), Moniz & Miller (2010)

[a] Most common type welded

[b] Used historically as an insulating material in ships, to insulate covered rod electrodes, in cylinders holding acetylene gas, and in heat-protective equipment of welders and the weld

Metals include but are not limited to: Fe, Mn, Al, Ni, Cr, K, Ba, Ca, F, Ti, Co, Zn, Mo, Pb, Mg, and As. These will vary by composition of base metal

Al, aluminium alloys; AS, alloyed steel; CO, carbon monoxide; CO_2, carbon dioxide; ELF-EMF, extremely low-frequency electromagnetic fields; ER, electric resistance; FCA, flux cored arc; GMA, gas metal arc; GTA, gas tungsten arc; HC, hydrocarbon; MMA, manual metal arc; MS, mild steel; NO, nitric oxide; NO_2, nitrogen dioxide; O_3, ozone; SA, submerged arc; SS, stainless steel; UV, ultraviolet

Compiled by the Working Group

Table 1.3 Type of welding and material welded by both welders and non-welders reporting welding activities, as included in the ECRHS II study

Type of welding or metal	Proportion associated with various processes/metal welded	
	Welders ($n = 27$ job periods held during 1969–2001, 23 subjects) (%)	Non-welders ($n = 388$ job periods held during 1962–2001, 340 subjects) (%)
Type of welding		
MMA	70.4	66.2
GMA	81.5	48.7
GTA	40.7	20.0
SA	11.1	5.2
FCA	25.9	16.0
Other (includes oxyfuel)	10.1	19.6
Type of metal		
Stainless steel	55.6	33.5
Mild steel	85.2	63.9
Galvanized steel	74.1	60.0
Aluminium	48.1	17.5
Painted metal	40.7	47.2
Other	3.7	21.6

FCA, flux-cored arc; GMA, gas metal arc; GTA, gas tungsten arc; MMA, manual metal arc; SA, submerged arc
Compiled by the Working Group from the ECRHS study (described in Lillienberg et al., 2008)

cutting were developed soon after with resistance welding as the common joining process. MMA welding technology was introduced in the late 1800s and achieved commercial status in the early 1900s. Various types of electrodes were developed and used during the 1920s and 1930s, but covered electrodes dominated after the 1930s as better welds could be achieved. Research into the use of shielding gas began in the 1920s, which led to the development of GTA welding. GTA welding began to be used commercially in the early 1940s, with GMA welding processes being developed and used commercially in the late 1940s. The use of consumable electrodes with carbon dioxide as a shielding gas was introduced in the late 1950s, which led to the development of FCA welding. Dual-shield FCA welding was introduced in the late 1950s, and a few years later inner-shield FCA welding was introduced (Cary, 1998; Weman, 2003). New or modified methods of welding continue to be developed to meet the needs of industry. Notably, laser welding and cutting are becoming popular and prevalent, although this type of welding is frequently carried out by robots (Klein et al., 1998).

1.1.2 Description of welding processes

See Table 1.2

(a) Gas welding

(i) Oxyfuel gas welding (ISO Nos 3, 31, 311, 312, and 313)

Oxyfuel gas welding includes oxyacetylene welding, oxypropane welding, and oxyhydrogen welding. The process uses heat from the combustion of oxygen mixed with a fuel gas, such as acetylene, methylacetylene-propadiene (MAPP), propane, hydrogen, or propylene. Oxyacetylene is the most commonly used oxyfuel welding process, and can also be used for cutting metals (flame cutting, ISO No. 81). Oxyfuel gas welding can be performed with or without a filler metal and is very portable and flexible; it is therefore encountered in all metalworking industries. It is most commonly used for maintenance and repair work on light sheet metal, for tack welding pieces that are to be arc welded, or in locations where no electricity is available (Weman, 2003; Moniz & Miller, 2010).

(b) Arc welding

(i) Manual metal arc welding (ISO No. 111)

MMA welding is also referred to as shielded metal arc welding, stick welding, electrode welding, or flux shielded arc welding. The process draws an electric arc between a consumable electrode (welding rod) covered with a flux, and the base metal, melting the metals together and leaving a joint of molten metal. As the weld is laid the flux disintegrates from the electrode, the vapours of which serve as a shielding gas. When the weld has cooled, a slag cover is left behind which is a mixture of the flux and impurities; this is typically removed using a chipper or grinder. The MMA welder will go through many electrodes while laying a weld, with an electrode replacement required every few minutes. MMA welding is most commonly used to weld steels of varying thicknesses (mild, alloyed, and stainless steels), making it popular in construction and fabrication of steel structures. Typically, the welding rod or electrode is of a similar metal alloy to the base metal, with a variety of different flux coatings including rutile (25–35% TiO_2), calcium fluoride, cellulose, and iron powder (Burgess, 1995; Weman, 2003).

(ii) Gas metal arc welding (ISO No. 13)

GMA welding is also called metal inert gas welding, metal active gas welding, and gas-shielded metal arc welding. It is the most common industrial welding process due to its versatility, speed, relatively low cost, and adaptability to robotic welding. GMA welding forms an electric arc between a consumable wire electrode fed through the welding gun, and the base metal, creating enough heat to melt and join the metals together. A shielding gas is also fed through the welding gun, protecting the weld from contaminant and eliminating slag. While the addition of the shielding gas makes GMA welding a difficult welding process to perform outdoors or in areas with heavy ventilation, no additional grinding or chipping of slag is required to reveal the completed weld. The shielding gas is typically helium, argon, carbon dioxide, nitrogen, or a blend of these gases, and is chosen according to the base metal being welded and the specifics of the process. GMA welding can be used to weld aluminium, copper, magnesium, nickel alloys, titanium, and steel alloys, making it a very versatile welding process that is popular for metal fabrication in a variety of (mostly indoor) settings (Burgess, 1995; Weman & Lindén, 2006).

(iii) Flux-cored arc welding (ISO Nos 132, 136, and 114)

FCA welding, also known as self-shielded tubular cored arc welding, uses the same equipment as for GMA welding. It is rapidly becoming a popular and prevalent welding process worldwide due to the fact it can be used in all welding positions, is a quick process, requires less pre- and post-cleaning of the base metal and weld, and requires less skill to achieve good-quality welds. FCA welding uses a continuously fed automatic or semi-automatic consumable electrode containing a flux and a voltage to lay a weld. Dual-shield FCA welding uses an externally supplied shielding gas to protect the weld, in addition to a powder flux in the centre of the electrode. The common external shielding gases are carbon dioxide and argon, or a mixture of the two. Inner-shield or self-shielding FCA welding (ISO No. 114) does not require a separate shielding gas, as the flux core in the consumable electrode can generate a shielding gas. This makes dual-shield FCA welding ideal for outdoor or windy conditions. FCA welding is generally used to weld thicker materials with a single pass, such as in equipment repair or the shipbuilding industry, and can be performed on carbon steels, cast iron, nickel-based alloys, and some types of SS (Burgess, 1995; Moniz & Miller, 2010).

(iv) Gas tungsten arc welding (ISO No. 14)

GTA welding, also known as tungsten inert gas welding, uses a tungsten electrode to produce the weld. Due to the high melting point of tungsten, the electrode does not melt during the welding process. Further, a shielding gas (Ar or He) is used to protect the weld and a consumable filler metal is added to make the joint. GTA welding is commonly used for welding on thin pieces of SS, aluminium, magnesium, and copper alloys, but it can be used on nearly all metals except zinc. The process can utilize a variety of filler metals since the weld metal is not transferred across the electric arc; this allows the filler and base metal to be matched, leading to reduced corrosion and cracking. GTA welding is therefore considered a high-quality weld, requiring a higher level of skill to master. It is commonly employed in the aerospace and bicycle industries, in machinery production for the food industry, in maintenance and repair work, and for spot welding (Burgess, 1995; Weman, 2003).

(v) Submerged arc welding (ISO No. 12)

SA welding uses a bare wire electrode as the filler metal, and a granular flux to protect the weld which is fed onto the base metal before the arc path. Typically, SA welding is a fully automated process; the operator does not handle the weld, but is only involved in setting up and monitoring. The flux typically contains oxides of manganese, silicon, titanium, aluminium, or calcium fluoride. SA welding can be used for welding straight, thick sections on carbon steels, low alloy steels and, less commonly, on SS and nickel-based alloys. It is commonly used in shipyards or for other large steel fabrication projects. SA welding allows for quick and deep welds, and can be performed in both indoor and outdoor environments (Burgess, 1995; Weman, 2003).

(c) Other processes

(i) Electric resistance welding (ISO Nos 21 and 22)

ER welding, also called resistance spot welding, spot welding, resistance seam welding, and seam welding, is a group of seam or spot welding processes that produce a weld at a faying surface. The heat for the weld is generated from the electrical resistance of the material; small pools of molten metal are created by passing an electrical current through the metal workpiece. ER welding methods are typically used with thin materials, and it is a popular welding process in aerospace or automobile manufacturing. As for SA welding, ER welding is generally a fully automated process with the operator only responsible for setting up and monitoring the welding (Weman, 2003; Moniz & Miller, 2010).

(ii) Other hot work processes (brazing/soldering, cutting, gouging) (ISO Nos 8 and 9)

Welders routinely perform other hot work processes, such as brazing, soldering, cutting, and gauging. Brazing and soldering are similar, although brazing is conducted at a higher temperature and can therefore use stronger filler metals. Unlike welding, where the two metals being joined typically need to be similar and are melted to join them together, soldering and brazing involve using a filler metal with a melting temperature below the metals being joined; they can therefore be used to join dissimilar metals. Welded joints are stronger than brazed joints, which are in turn stronger than soldered joints. Brazing and soldering are both common in metal arts, jewellery making, plumbing, or for electric components. While soldering historically used lead as a filler metal, this is now less common in more developed countries and gold, silver, copper, brass, tin alloys, and iron are generally used (Weman, 2003; Moniz & Miller, 2010).

There are many types of cutting that welders may routinely perform. Plasma arc cutting removes molten metal with a jet of ionized gas (plasma). The superheated plasma can conduct an electric arc, which melts the base metal. Plasma arc cutting is typically used to cut aluminium, SS, brass, and copper and uses a tungsten electrode similar to that for GTA welding. While plasma arc cutting can be carried out manually, computer-assisted cutters are commonly used which can make complex shapes and cuts. Air carbon arc cutting heats and cuts metal using a carbon arc, while the molten metal is removed with a blast of air. This method can be used to cut SS, aluminium, copper, magnesium, and carbon steels. It can also be used to gouge metals, which is the removal of metal from a surface to prepare it for welding (Weman, 2003; Moniz & Miller, 2010). Table 1.2 lists the exposures common to the welding and hot work processes described here, and their typical uses in industry.

1.1.3 Welding materials

See Table 1.2

The majority of welding in occupational settings is performed on MS and SS. All steel is an alloy of iron and other elements, primarily carbon, with MS containing small amounts of manganese (typically $< 1.6\%$) in addition to carbon (typically $< 0.3\%$) and iron (Jones & Ashby, 2005). SS contains at least 12% chromium, making it more resistant to corrosion than MS (Verhoeven, 2007). Depending on the grade of SS, it may contain up to 25% chromium, 7% nickel, and 4% molybdenum, with the levels of these metals varying to achieve particular characteristics (Bringas, 2004; Outokumpu, 2013). MS that is galvanized (coated with zinc) or painted (typically with primers) is also welded.

Alloy steels contain specific amounts of alloying elements other than carbon, such as additional manganese, chrome, nickel, molybdenum, silicon, titanium, copper, vanadium, or aluminium. The specific elements and their proportions determine the weldability, resistance to corrosion, strength, ductility, or magnetic properties of the steel (Verhoeven, 2007).

Welding is also performed on cast iron (alloys of iron, carbon, silicon) and nonferrous metals (such as alloys of nickel, copper, aluminium, magnesium, and titanium), which may contain other metals over a range of concentrations to achieve particular characteristics (Moniz & Miller, 2010; Table 1.1).

1.1.4 People exposed to welding fumes or welding worldwide

See Table 1.4

It is challenging to quantify the number of welders worldwide. Such estimates typically come from a population census or survey; however, variability in sampling and coding methods, inclusion and exclusion criteria, year of data collection, and language of results combine to make it difficult to meaningfully compare and combine data from various countries for a worldwide estimate. Acknowledging these limitations, the Working Group used the Integrated Public Use Microdata Series, International (IPUMS-International) data system to gather census microdata from 60 countries that had an occupational census between 1973 and 2015 (Minnesota Population Center, 2015). These data, representing the percentage of the economically active population which the job designations represent in 60 countries over a 40-year period, are listed in Table 1.4. Assuming that historical estimates are reflective of current estimates, it can be estimated that over 6 million people worldwide may have the occupational title of welder either full-time or part-time (Minnesota Population Center, 2015).

In the countries included in Table 1.4, the Working Group calculated that the average

Table 1.4 Estimates of number of welders worldwide based on publicly available population data[a]

Country	Census year	Occupational designation	Number	Welding proportion of population[b] (%)
China	1990	Welders	1 798 300	0.27
USA	2010	Welding, soldering, and brazing workers	727 122	0.40
India	2004	Welders and flame cutters	499 219	0.14
Viet Nam	2009	Metal moulders, welders, sheet metal workers, structural metal preparers, and related workers	339 106	0.71
Brazil	2010	Welders and flame cutters	292 365	0.34
Spain	2001	Welders, laminators, metal structure assemblers, blacksmiths, toolmakers, and similar	262 620	1.61
UK	2001	Metal forming, welding and related trades	227 044	0.55
Mexico	2010	Welders and flame cutters	191 819	0.45
Nigeria	2010	Welders and flame cutters	190 637	0.27
Philippines	2000	Metal moulders, welders, and sheet metal workers	185 060	0.32
Iran (Islamic Republic of)	2006	Welders and flame cutters	150 439	0.87
Indonesia	2005	Welders and flame cutters	142 572	0.16
South Africa	2007	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	121 635	0.99
Germany (West)	1987	Welder	110 040	0.39
Canada	2006	Welder	103 000	0.61
Egypt	2006	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	99 070	0.49
Thailand	2000	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	97 626	0.20
Australia[c]	2011	Structural steel and welding trades workers	86 400	0.77
Morocco	2004	Moulders, welders, and sheet metal workers	85 320	0.91
Romania	2002	Welders and flame cutters	80 460	0.95
Portugal	2011	Sheet and structural metal workers, moulders and welders, and related workers	76 580	1.55
Netherlands[d]	1996	Welders	75 000	1.21
Venezuela (Bolivarian Republic of)	2001	Mould-press workers, welders, laminators, boilermakers, assemblers of metal structures, and similar	70 170	0.31
Malaysia	2000	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	43 400	0.53
Cuba	2002	Moulders, welders, panel beaters, and assemblers	39 710	0.92
Ecuador	2010	Sheet and structural metal workers, moulders, welders, and related workers	37 640	0.64

Table 1.4 (continued)

Country	Census year	Occupational designation	Number	Welding proportion of population[b] (%)
Peru	2007	Plumbers and pipe fitters, welders and flame cutters, sheet metal workers, and structural metal preparers and erectors	37 350	0.36
France	2011	Skilled metal welders	36 164	0.14
Senegal	2002	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	25 550	0.80
Bolivia (Plurinational State of)	2001	Moulders, welders, laminators, boilermakers, assemblers of metal structures, and similar	22 090	0.27
Panama	2010	Moulders, welders, boilermakers, fitters of metallic structures, and related workers	21 550	1.53
Cameroon	2005	Sheet and structural metal workers, moulders, welders, and related workers	19 940	0.40
El Salvador	2007	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	17 930	0.91
Guinea	1996	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	17 070	0.50
Kenya	1989	Welder	15 680	0.21
Mozambique	2007	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	14 490	0.18
Malawi	2008	Plumbers, welders, sheet metal and structural metal preparers and erectors	14 240	0.34
Costa Rica	2000	Moulders, welders, locksmiths, boilermakers, metal structure builders, and similar	13 810	1.06
Mali	2009	Welder	12 860	0.23
Zambia	2010	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	12 620	0.32
Pakistan	1973	Welders and flame cutters	12 353	0.07
Nicaragua	2005	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	12 040	0.69
Greece	2001	Welders and flame cutters	11 330	0.27
Jamaica	2001	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	11 263	1.17
Ireland	2006	Welders and steel erectors	10 090	0.41
Ethiopia	1994	Welders, metal moulders, and related trades workers	9 297	0.04
Haiti	2003	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	7 990	0.38
Uruguay	2006	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	7 553	0.58
Uganda	2002	Welders, sheet metal workers, and metal moulders	7 380	0.10

Table 1.4 (continued)

Country	Census year	Occupational designation	Number	Welding proportion of population[b] (%)
Kyrgyzstan	1999	Welders and flame cutters	7 220	0.42
Cambodia	2008	Sheet and structural metal workers, moulders, welders, and related workers	6 650	0.10
Puerto Rico	2010	Welding, soldering, and brazing workers	5 220	0.33
Armenia	2011	Sheet and structural metal workers, moulders, welders, and related workers	4 930	0.45
Iraq	1997	Welders and flame cutters	4 320	0.11
Fiji	2007	Metal workers	3 240	1.34
Switzerland	2000	Welders and flame cutters	2 670	0.07
Rwanda	2002	Workers for metal smelting, foundry, welding, metal sheet work, boiler making, metal frames for houses and buildings, and assimilated	2 390	0.07
Mongolia	2000	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	1 810	0.23
Paraguay	1982	Oxyfuel cutters, welders, soldering by hand or machine, electric welders, and blowtorch welding	1 460	0.15
Jordan	2004	Metal moulders, welders, sheet metal workers, structural metal preparers, and related trades workers	1 050	0.10

[a] Unless otherwise specified, data compiled from Minnesota Population Center (2015)

[b] Percent of the economically active population for each country that the number of persons employed in the occupational designation represents

[c] Data from Australia compiled from Australian Bureau of Statistics (2012)

[d] Data from the Netherlands compiled from Simmelink (1996)

Compiled by the Working Group

percentage of job designations including welder represented in the economically active population was 0.31%. Applying these percentages to the International Labour Organization's 2010 estimate of the worldwide economically active population (3.5 billion), the Working Group estimated there may be 11 million welders worldwide (ILO, 2010). However, it must be acknowledged that the variability in how the job of welding was coded between censuses could lead to uncertainty in any estimates generated from these data. Some occupational designations (e.g. Spain) include jobs where not every worker welds, which would overestimate the number of welders for a country. At the same time, however, a census would not capture workers performing welding without the official job title of welder; for example, construction or agricultural workers might weld intermittently but would not be classified as welders (see additional discussion in Section 1.1.5).

Separate from this analysis, the German Welding Society estimated that over 1.1 million people have full-time positions in the field of welding in 19 European countries. This figure only includes welders, welding supervisors, welding inspectors, welding researchers, welding trainers, and robot operators (Von Hofe, 2009).

1.1.5 *Non-welder occupations performing welding*

In addition to workers with the job title of welder, other occupations routinely or intermittently weld. Table 1.5 lists occupational categories where workers weld, as reported in the European Community Respiratory Health Follow-up Survey (ECRHS) (ECRHS II, 2017) and the Canadian general population job-exposure matrix (CANJEM) (CANJEM, 2017).

The ECRHS II (Janson et al., 2001) prospectively assessed the relationship between welding at work and respiratory symptoms. Subjects participating in ECRHS II held 10 016 job periods (e.g. time periods defined in the study where a subject was employed in a particular job) during 1962–2001, 415 of which involved some welding activities. Table 1.5 lists the percentage of job periods for which workers reported performing welding, stratified by broad occupational category. For the 415 job periods associated with welding activities, Table 1.3 lists the processes which were used and the metals which were welded separately for the welder and non-welder occupations. The ECRHS II survey found that only 7% of workers performing welding actually had the job title of welder or flame cutter, showing that many more workers weld and are potentially exposed to welding fumes than those with the job title of welder (Lillienberg et al., 2008). The ECRHS II also found that almost 30% of the individuals who responded positively to the question "Have you carried out welding, at work or at home?" only welded at home. Of the professional welders, 3% also indicated welding at home (ECRHS II, 2017).

CANJEM (2017) covers 258 agents developed from expert assessments and informed by structured occupational interviews (Lavoue et al., 2014; Zeng et al., 2017). The matrix comprises information for 31 780 jobs held during 1921–2005 by 6222 Canadian men and 2563 Canadian women. Table 1.5 lists the proportion of job periods during which workers were exposed to any type of welding fumes (gas, arc, soldering) by occupational category (same definition as in Lillienberg et al., 2008), as calculated by CANJEM. From this analysis of CANJEM, only 12% of job periods during which workers were exposed to welding fumes corresponded to the occupation of welder (as per ISCO 1988). In addition, among the exposed jobs the median duration of exposure was 40 hours per week for welders, with 70% exposed full-time. For non-welders, the median duration of exposure was 5 hours per week, with 24% exposed full-time [calculation performed by the Working Group].

Table 1.5 Number and proportion of job periods during which workers were exposed to welding fumes for each occupational category, by study

Occupational categories	ECRHS II		CANJEM	
	Number	Proportion (%)	Number	Proportion (%)
Miscellaneous (artist, firefighters)	5	80	950	9
Sheet metal and metalworkers	30	70	305	69
Welders and flame cutters	42	64	310	98
Blacksmiths and toolmakers	26	62	314	27
Motor vehicle, agricultural, and industrial mechanics and fitters	124	50	965	44
Building workers (frame and finisher)	216	37	1316	28
Electrical and electronic equipment mechanics and fitters	50	36	329	52
Agricultural workers	34	35	604	1
Plant and machine operators	142	32	3172	9
Painters and building structure cleaners	18	33	227	5
Production and general managers	58	29	2194	3
Engineers and engineering science technicians	127	23	3184	5
Drivers and truck operators	93	22	2183	2
Service labourer workers	117	8	1394	2
Armed forces	17	6	–	–
Teaching professionals	191	5	521	3
Secretaries	135	4	2229	2
Others (not working, unknown, student)	232	3	–	–
Occupations with no welding activities reported	8359	0	–	–

[a] Proportion of job periods associated with welding activities in the ECRHS study (assessed using self-reports of welding)

[b] Proportion of job periods in the CANJEM population that were deemed exposed to either gas, arc, or soldering welding fumes (assessed using expert judgment of job exposures)

Compiled by the Working Group from data from the ECRHS study (described in Lillienberg et al., 2008), and the CANJEM job exposure matrix (CANJEM, 2017; Lavoue et al., 2014)

For some occupational titles there are differences between CANJEM and ECRHS II data, some of which can be explained by classification; ECRHS II tends to have a higher proportion of workers exposed to welding fumes than CANJEM for most occupational categories. CANJEM relied on an expert assessment of job exposures, while workers self-reported welding activities in ECRHS II. [The Working Group noted that ECRHS II was likely able to identify more job titles that include infrequent welding, which might not have been picked up by expert assessment. Additionally, CANJEM and ECRHS II used different occupational coding systems when originally assigning job titles (Lillienberg et al., 2008; Lavoue et al., 2014; CANJEM, 2017). The Working Group therefore estimated that the number of people exposed to welding fumes might be 10 times higher than the number of people with the occupational title of welder. This would indicate that the number of people exposed to welding fumes worldwide could approach 110 million workers (3% of the worldwide economically active population).]

Table 1.6 Methods for the analysis of welding-related exposures

Sample matrix	Agent	Assay procedure	Limit of detection	Standard/method/reference
Air	Total dust	Gravimetric	0.03 mg/sample	ISO 10882-1:2011, NIOSH 0500
	Respirable dust	Gravimetric	0.03 mg/sample	NIOSH 0600
	Metals in dust	ICP-AES	1 µg/sample	NIOSH 7300
	CO	Electrochemical sensor	1 ppm	EN ISO 10882-2:2000, NIOSH 6604
	NO_2	UV-VIS	1 µg/sample	EN ISO 10882-2:2000, NIOSH 6014
	NO	UV-VIS	1 µg/sample	EN ISO 10882-2:2000, NIOSH 6014
	O_3	IC/UV-VIS	3 µg/filter	EN ISO 10882-2:2000, OSHA ID-214
Urine	Metals	ICP-AES	0.1 µg/sample	NIOSH 8310
Whole blood	Metals	ICP-AES	1 µg/100 g blood	NIOSH 8005
NA	UV	Direct measurement		Tenkate (2008); Vecchia et al. (2007)
NA	EMF	Direct measurement		IEC 61786-1:2013

CO, carbon monoxide; EMF, electromagnetic fields; IC, ion chromatography; ICP-AES, inductively coupled plasma atomic emission spectrometry; IEC, International Electrochemical Commission; ISO, International Organization for Standardization; NA, not applicable; NIOSH, National Institute for Occupational Safety and Health; NO, nitric oxide; NO_2, nitrogren dioxide; O_3, ozone; OSHA, Occupational Safety and Health Administration; UV, ultraviolet; UV-VIS, ultraviolet visible spectrophotometry
Compiled by the Working Group

1.2 Measurement and analysis

This section reviews the methodologies of sampling and analysis for exposures related to welding in ambient air, as well as biomonitoring of exposure.

1.2.1 Detection and quantification of welding-related exposures

Exposure to welding fumes predominantly occurs via inhalation. Welding fumes in the air are generally measured by sampling of the respirable fraction (Table 1.6), which is highly correlated with sampling of the inhalable fraction (Lehnert et al., 2012). Metals in welding fumes, such as iron, chromium, copper, nickel, manganese, aluminium, titanium, molybdenum and zinc, are often analysed individually. In addition to welding fumes, gases (such as O_3, CO, and NO_x) arising from welding activities are monitored. A range of analytical methods is available, as listed in Table 1.6.

Internal exposure to specific elements in welding fumes can be determined in urine and blood samples (Table 1.6). Biomonitoring has been primarily focused on chromium and nickel, but other metals, including aluminium, cadmium and manganese, have also been frequently monitored.

Assessment of exposure to ultraviolet (UV) radiation is generally performed using radiometric, spectroradiometric or personal dosimetry techniques (Vecchia et al., 2007; Tenkate, 2008).

The International Electrochemical Commission (IEC) standard for measuring extremely low frequency electromagnetic fields (ELF-EMF) is described in IEC 61 786-1:2013 (IEC, 2013).

1.2.2 Measurement strategies

(a) Welding fumes and gases

High variability in exposure, both between and within workers, is inherent in welding due to the different base metals, different types of welding, and varying circumstances. Determinants of exposure should therefore be recorded along with personal air monitoring, including details related to the welding techniques used, base metal, duration of welding tasks and related activities (preparation, clean-up, breaks, etc.), the position of the welder, presence of local exhaust ventilation or general ventilation, or whether a helmet with clean air supply was used. In addition to the welding procedure and material used, the welders' level of experience may also influence the particles generated from welding fumes (Chang et al., 2013). It has been suggested that the quality of the welding performance influences exposure to welding fumes, implying increased exposure for apprentice welders or welders with minimal training (Graczyk et al., 2016). Repeated measurements among the same workers may provide information about the variability between and within (temporal) workers.

Personal exposure measurements are typically performed in the breathing zone to best represent the exposure of the individual worker. With welding processes it is critical to take into account the position of the monitoring device relative to the face shield, as it may physically deflect the welding fumes away from the breathing zone (ISO 10 882-2:2000). The concentration of particles inside the plume is 10–100 times higher than outside the plume (Lidén & Surakka, 2009). Personal sampling should therefore be performed behind the welder's face shield and as close to the mouth as possible (within 10 cm) (ISO 10 882-1:2011).

Welders should wear equipment that enables the sampler to stay in position throughout the sampling period (ISO 10 882-1:2011), for example, the headset-mounted mini-sampler described by Lidén & Surakka (2009) or the in-visor sampler from the Health and Safety Laboratory (2009). The position of such a sampler is not affected by the position of the face shield or helmet. This means that if the face shield or helmet is raised or completely removed during the sampling period, the sampler will stay in place.

For gases, samplers should also be positioned in the breathing zone at a maximum distance of 5 cm from the mouth. Badges for personal sampling of exposure to gases might be unsuitable for sampling behind a welder's face shield, due to limited air movement (ISO 10 882-2:2000).

(b) Biomonitoring of metals

Similar data regarding the nature of the welding activities should be collected for biomonitoring of metal exposure, both on the day of sample collection and before (depending on accumulation of the biomarker in the body). While assessment of exposure to welding fumes is primarily focused on the occupational setting, Scheepers et al. (2008) reported that one quarter of the welders in their study were also engaged in welding activities during off-work hours (Scheepers et al., 2008). Although these activities may be more difficult to identify and potentially less monitored, biomonitoring results may also measure these exposures.

(c) Radiation

Arc welding processes can lead to UV radiation exposure of the eyes and skin. Since arc welding procedures emit radiation with fluctuation and instability, and due to interference by electromagnetic radiation, it can be complicated to obtain accurate radiometric and spectroradiometric results (Tenkate, 2008). The geometrical aspects of exposure to UV radiation must be considered, including the diameter of aperture of the detector if the irradiance profile is heterogeneous, and the field of view of the detector (Vecchia et al., 2007). The "arc time" (i.e. the time for which the arc is actually struck) will affect the overall exposure during a working day (Tenkate, 2008), as well as eye and skin protection used. As well as the actual workers performing the welding tasks, their coworkers (bystanders) may also be exposed to UV radiation (Vecchia et al., 2007).

Exposure to UV radiation is usually expressed in terms of irradiance (power per unit area, W/m2) or radiant exposure (J/m^2), the amount of energy received per unit area accumulated over a time interval. As different wavelengths are associated with different biological impact, an "efficient" exposure rate is calculated as a weighted average across the whole UV spectrum (Vecchia et al., 2007; ACGIH, 2013). Both the American Conference of Governmental Industrial Hygienists (ACGIH) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) propose an occupational exposure limit of 3 mJ/cm^2 (effective radiant energy). In practice, effective irradiance is measured in the field and the time required to reach the permissible radiant energy is calculated (ICNIRP, 2004; ACGIH, 2013).

Electric welding techniques may result in exposure to ELF-EMF. The overall exposure will be affected by the source of exposure (e.g. vicinity and position in relation to welding devices, and distance to power cables) and the total welding time (Hansson Mild et al., 2009).

1.3 Occurrence and exposure

1.3.1 Exposure to welding fumes and gases

Welding fumes are produced when metals are heated above their melting point, vapourize, and condense into fumes with predominantly fine solid particles of diameter less than 1 µm. These fumes are a complex mix of particles from the wire or electrode, the base metal, and any coatings on the base metal (paint, metalworking fluid, platings, etc.) (Hewett, 1995a; Warner, 2014). Most commonly, they are composed of metal oxides (mainly iron oxides, depending on the base metal), silicates (from coated electrodes and fluxes), and fluorides (when fluoride-containing electrode coatings/fluxes are used). A variable proportion of the metal elements can also be found in the form of magnetite-like spinels, that is, multimetal oxides where the metal ions share oxygen atoms instead of the various metal-specific oxides. Fumes from SS welding contain chromium and nickel, whereas these two exposures are much lower in MS welding fumes. Welding gases are generated from the shielding gases used, the decomposition of fluxes, and interactions between UV radiation and/or high temperatures with gases found in the air (e.g. N in the air combining with heat to produce NO_2, or O interacting with the welding arc to produce O_3). Common gases encountered during welding include: shielding gases such as carbon dioxide, argon, or helium; fuel gases such as acetylene, butane, or propane; and gases produced from the welding processes such as carbon monoxide, ozone, nitrogen oxides, and hydrogen fluoride (Burgess, 1995; Antonini, 2003). The distinction between welding fumes and welding gases is that fumes contain solid particles that are temporarily suspended in the air due to a solid material being heated (such as metals), whereas gases are molecules in a gaseous state in the ambient air that have either been generated by or are used in the welding process.

Table 1.1 and Table 1.7 outline some of the common exposures encountered by welders in the complex mixtures of welding fumes and gases, and the type of welding in which the exposures are most likely to be encountered. Many of these exposures have previously been evaluated by the *IARC Monographs* (Table 1.1); common exposures that have not been evaluated by the *IARC Monographs* are listed separately (Table 1.7).

Table 1.8 summarizes the concentrations of welding fumes generated from various welding processes. Fumes from welding on SS ranged from less than 1 mg/m^3 to more than 25 mg/m^3. The lowest average concentrations are generated from GTA welding (two studies: means, 0.16 and 0.98 mg/m^3), whereas MMA welding produces the highest average concentrations (range of means, 3.0–5.4 mg/m^3).

As for SS welding, MS welding is associated with concentrations of fumes ranging from less than 1 mg/m^3 to more than 50 mg/m^3; the highest average concentration is found in MMA (range of means, 0.63–11.9 mg/m^3) or FCA

Table 1.7 Additional occupational exposures of welders that have not been evaluated by *IARC Monographs*

Agent	Occurrence	Welding types
Aluminium	Aluminium component of some alloys, welding on aluminium	GMA, GTA
Copper	Alloys such as brass, bronze, small amounts in SS and MS, some welding rods	All
Fluorides	Electrode coating and flux material for low- and high-alloy steels	All
Manganese	Found in varying amounts in most steels	All
Molybdenum	Found in varying amounts in most steels	All
Zinc	Galvanized and painted metal	All
Carbon monoxide	Formed in welding arc	GMA (when shielded with CO_2)
Hydrogen fluoride	Decomposition of rod coatings	SMA (MMA), SA
Nitrogen oxides	Formed by welding arc	All arc welding
Ozone	Formed by welding arc	Plasma arc cutting, GMA, GTA
Oxygen deficiency	Welding in confined spaces, air displacement form shielding gas	Shipbuilding, other confined space welding

CO_2, carbon dioxide; GMA, gas metal arc; GTA, gas tungsten arc; MMA, manual metal arc; MS, mild steel; SA, submerged arc; SMA, shielded metal arc; SS, stainless steel
Compiled by the Working Group

welding (one study: mean, 8.97 mg/m^3; range, 1.17–55.4 mg/m^3), and the lowest average concentration is reported in a study of GMA fabrication welders (mean, 0.51 mg/m^3). A study of welding apprentices reported very low exposures to welding fumes from gas (oxyfuel) welding, with an arithmetic mean of 0.0052 mg/m^3 (Baker et al., 2016). In this cohort of apprentice welders, oxyfuel exposures were comparable to exposures from GTA-MS and GTA-SS welding (arithmetic mean, 0.0055 mg/m^3), but nearly 7 times lower than MMA-MS welding (arithmetic mean, 0.035 mg/m^3) and 5.5 times lower than GMA-MS welding (arithmetic mean, 0.029 mg/m^3) (Baker et al., 2016). [The Working Group noted that exposures at this apprentice welding school are lower than those measured in general industry. However, as this was the only exposure assessment that could be found representing just oxyfuel welding, the Working Group included this value.]

As for all particles, the toxicological profile of welding fumes is not only dependent on the material and concentration, but also on the particle size distribution and surface characteristics; these differ by welding process and base metal. In a laboratory-based study of fumes generated from GMA and MMA welding of SS and MS, Hewett (1995a) found that GMA produced welding fumes with greater bulk density and specific surface area, and consisted of a greater quantity of smaller particle sizes, compared with MMA (although the majority of welding fumes for both processes and base metals contained particles of diameter less than 1 µm). These differences were mostly attributable to process (MMA vs GMA) as opposed to base metal (MS vs SS). In a further analysis of these laboratory-generated fumes, Hewett (1995b) found that GMA welding fumes had a 60% greater total lung deposition than MMA welding fumes, regardless of base metal, with the majority of fumes from both welding processes depositing in the alveoli. Given the differences in specific surface area between GMA and MMA, and the greater deposition of GMA, Hewett estimated that, for an equal exposure, GMA welding delivers three times the particle

Table 1.8 Occupational exposure to welding fumes

Reference	Location, collection date	Occupation description	Sampling matrix, approach, *N*, duration	Exposure level[a] (mg/m³)	Exposure range (mg/m³)	Comments/additional data
Knudsen et al. (1992)	Denmark, 1987	GMA-SS welder	Total particulate, personal, 10, full shift	1.01	NR	MCE filters placed inside the welders' face shields
		GTA-SS welder	Total particulate, personal, 40, full shift	0.98	NR	
Matczak & Chmielnicka (1993)	Poland, 1987–1990	MMA-SS welder, Plant A	Respirable, personal, 5, 7 h	9.0	2.8–23.4	Respirable samples taken behind the face shield of welders at four different industrial plants. Two-stage personal air sample with respirable fraction collected on membrane filter and glass fibre filter. Total respirable particulate adjusted to 8 h TWA
		MMA-SS welder, Plant B	Respirable, personal, 13, 7 h	3.2	NR	
		MMA-SS welder, Plant C	Respirable, personal, 31, 7 h	3.5	1.0–9.1	
		Welding assistants, Plant C	Respirable, personal, NR, 7 h	0.8	0.2–1.9	
		MMA-SS welder, Plant D	Respirable, personal, 22, 7 h	1.3	NR	
Karlsen et al. (1994)	Norway, NR	MMA-SS welder, shipyard (inside ship section)	Total particulate, personal, 48, full shift	5.4	0.3–29	12 welders were monitored for 4–5 consecutive workdays; MCE filters attached outside the welders' face shields
		MMA-SS welder, shipyard (inside the module)	Total particulate, personal, 30, full shift	3.0	1.0–5.8	Personal samples on unspecified number of welders taken over 2 weeks; MCE filters attached outside the welders' face shield
		MMA-SS welder, shipyard (welding shops)	Total particulate, personal, 42, full shift	2.0	0.5–6.6	
		MMA-SS welder, shipyard (grinding)	Total particulate, personal, 34, full shift	11	3.1–51	

Table 1.8 (continued)

Reference	Location, collection date	Occupation description	Sampling matrix, approach, *N*, duration	Exposure level[a] (mg/m^3)	Exposure range (mg/m^3)	Comments/additional data
Karlsen et al. (1994) (cont.)		MMA-SS welder, shipyard (grinding)	Total particulate, environmental, NR, full shift	2.0	0.4–3.0	Area samples placed near aerosol generation but not directly in plume; filter cassettes placed 1.5 m above floor, at least 5 m from nearest welding or grinding site, cassette inlets faced downwards
		MMA-SS welder, shipyard (welding shops)	Total particulate, environmental, NR, full shift	0.7	0.2–2.2	
		MMA-SS welder, shipyard (inside the module)	Total particulate, environmental, NR, full shift	0.4	0.2–0.5	
Wallace et al. (2001)	USA, NR	GMA-SS, fabrication	Total particulate, personal, 11, NR	1.61	0.49–2.67	Closed-face, 37 mm PVC filters hanging outside face shield; filters were changed periodically throughout the day to prevent overloading, and summed at the end of the day to approximate a full shift sample
		GTA-SS welder, fabrication	Total particulate, personal, 10, NR	0.16	0.06–0.27	
		FCA welder, boilerplate fabrication	Total particulate, personal, 20, NR	8.97	1.17–55.46	
Dryson & Rogers (1991)	New Zealand, NR	GMA-MS welder	Total particulate, personal, 6, 2–4 h	2.56	0.86–4.51	Samples collected inside the face shield
		MMA-MS welder	Total particulate, personal, 4, 2–4 h	2.59	0.35–5.16	
Järvisalo et al. (1992)	Finland, NR	MMA-MS welder, shipyard	Total particulate, personal, 24, NR	11.8	3.4–19.2	Samples collected inside the face shield from 5 welders, with repeat measures for 5 days (1 welder only measured 4 days)
Akbar-Khanzadeh (1993)	England, NR	Various/MS welder, shipyard	Total particulate, personal, 209, 6.5 h (average)	4.39	NR	Samples collected inside the face shield
		Administrative controls, shipyard	Total particulate, environmental, 109, 7.1 h (average)	0.67	NR	Non-welder controls from the shipyard (office workers, joiners, fitters, drivers, staging makers, electricians) had area sampling in their work environment
Woskie et al. (2002)	USA, June 1994–April 1999	Various/MS welder, construction	Inhalable, personal, 22, 6 h	9.325	Max, 21.07	IOM inhalable sampler outside the face shield

Table 1.8 (continued)

Reference	Location, collection date	Occupation description	Sampling matrix, approach, *N*, duration	Exposure level[a] (mg/m^3)	Exposure range (mg/m^3)	Comments/additional data
Balkhyour & Goknil (2010)	Saudi Arabia, NR	MMA-MS welder, Factory 1	Total particulate, environmental, 10, 2 h	6.3	2.0–15.5	Took 10 area samples from each of 6 factories within 0.5 m of welders' breathing zone; 1–4 samples were collected per shift, each over a period of ~2 h, and were adjusted to 8 h average concentrations
		MMA-MS welder, Factory 2	Total particulate, environmental, 10, 2 h	5.3	3.0–10.5	
		MMA-MS welder, Factory 3	Total particulate, environmental, 10, 2 h	11.3	3.0–24.0	
		MMA-MS welder, Factory 4	Total particulate, environmental, 10, 2 h	6.8	4.5–12.0	
		MMA-MS welder, Factory 5	Total particulate, environmental, 10, 2 h	4.7	1.0–13.0	
		MMA-MS welder, Factory 6	Total particulate, environmental, 10, 2 h	3.0	1.5–4.5	
Schoonover et al. (2011)	USA, NR	MMA-MS welder, fabrication	Total particulate, personal, 7, full shift	GM, 0.630	0.150–2.100	37 mm open-faced cassette attached outside face shield
		GMA-MS welder, fabrication	Total particulate, personal, 6, full shift	GM, 0.510	0.140–1.700	Personal exposure samples collected using 37 mm open-faced cassette; sampled over 5 consecutive Mondays, each worker sampled once; samplers attached outside face mask
		Non-welder controls, fabrication	Total particulate, personal, 22, full shift	GM, 0.060	0.0038–0.370	
Hedmer et al. (2014)	Sweden, NR	GMA-MS welder, Company 1	Respirable, personal, 43, 6.2 h (0.5–9.1 h)	1.5	0.2–6.5	11 companies in south-west Sweden included in the study; Company 1 was visited 3 times for exposure measurements and a total of 16 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 2	Respirable, personal, 30, 6.2 h (0.5–9.1 h)	2.3	0.2–7.7	Company 2 was visited 3 times for exposure measurements and a total of 12 workers participated; respirable dust sampler placed outside the face shield

Table 1.8 (continued)

Reference	Location, collection date	Occupation description	Sampling matrix, approach, *N*, duration	Exposure level[a] (mg/m^3)	Exposure range (mg/m^3)	Comments/additional data
Hedmer et al. (2014) (cont.)		GMA-MS welder, Company 3	Respirable, personal, 37, 6.2 h (0.5–9.1 h)	2.3	0.3–11.9	Company 3 was visited 3 times for exposure measurements and a total of 14 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 4	Respirable, personal, 12, 6.2 h (0.5–9.1 h)	1.2	0.5–2.3	Company 4 was visited 3 times for exposure measurements and a total of 5 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 5	Respirable, personal, 21, 6.2 h (0.5–9.1 h)	5.7	0.1–38.3	Company 5 was visited 3 times for exposure measurements and a total of 9 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 6	Respirable, personal, 13, 6.2 h (0.5–9.1 h)	3.2	0.5–11.2	Company 6 was visited 3 times for exposure measurements and a total of 5 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 7	Respirable, personal, 21, 6.2 h (0.5–9.1 h)	3.0	1.2–10.5	Company 7 was visited 3 times for exposure measurements and a total of 9 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 8	Respirable, personal, 28, 6.2 h (0.5–9.1 h)	3.1	0.7–8.3	Company 8 was visited 3 times for exposure measurements and a total of 11 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 9	Respirable, personal, 29, 6.2 h (0.5–9.1 h)	0.4	0.1–1.8	Company 9 was visited 3 times for exposure measurements and a total of 14 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 10	Respirable, personal, 12, 6.2 h (0.5–9.1 h)	1.4	0.1–6.1	Company 10 was visited 3 times for exposure measurements and a total of 6 workers participated; respirable dust sampler placed outside the face shield
		GMA-MS welder, Company 11	Respirable, personal, 18, 6.2 h (0.5–9.1 h)	1.6	0.4–3.3	Company 11 was visited 3 times for exposure measurements and a total of 7 workers participated; respirable dust sampler placed outside the face shield
Matczak & Gromiec (2002)	Poland, NR	GMA-Al welder, Plant I and II	Total particulate, personal, 34, 6–7 h	6	0.8–17.8	Samples collected with 37 mm filters for total dust and adjusted to 8 h TWA concentrations; not specified whether inside or outside of face shield; Plant 1 had AM concentration 8.8 mg/m^3 and Plant II had AM concentration of 5.0 mg/m^3
		GMA-Al welder, Plant II	Respirable, personal, 12, 6–7 h	2.6	0.7–6.0	Samples collected with cyclones for respirable dust and adjusted to 8 h TWA concentrations; not specified whether inside or outside of face shield

Table 1.8 (continued)

Reference	Location, collection date	Occupation description	Sampling matrix, approach, *N*, duration	Exposure level[a] (mg/m³)	Exposure range (mg/m³)	Comments/additional data
Matczak & Gromiec (2002) (cont.)		Turner and crane operator, Plant I	Total particulate, personal, 3, 6–7 h	1.4	1.3–1.6	For non-welders working in the same room as GMA-Al welders; 37 mm filters for total dust adjusted to 8 h TWA concentrations; not specified whether inside or outside of face shields
		GTA-Al welder, Plant III	Total particulate, personal, 13, 6–7 h	0.69	0.25–1.36	Samples collected with 37 mm filters for total dust and adjusted to 8 h TWA concentrations; not specified whether inside or outside of face shield
		GTA-Al welder, Plant III	Respirable, personal, 5, 6–7 h	0.79	0.32–1.85	Samples collected with cyclones for respirable dust and adjusted to 8 h TWA concentrations; not specified whether inside or outside of face shield

[a] Exposure level expressed as arithmetic mean unless indicated otherwise

Al, aluminium; AM, arithmetic mean; FCA, flux cored arc; GM, geometric mean; GMA, gas metal arc; GTA, gas tungsten arc; h, hour(s); IOM, Institute of Occupational Medicine; MCE, mixed cellulose ester; MMA, manual metal arc; MS, mild steel; NR, not reported; PVC, polyvinyl chloride; SS, stainless steel; TWA, time-weighted average surface area to the respiratory system compared with that of MMA.

The concentration of welding fumes which a welder is exposed to depends on several factors, including welding process, welded metal, presence of coatings, arc time, and workplace and personal characteristics. Kromhout et al. (2004) created a database of welding fumes consisting of over 1200 measurements from 10 individual studies conducted during 1983–2003 in the Netherlands. The authors had information on welding process (GMA, GTA, MMA, other), ventilation (general or local), and whether the welder wore an improved helmet to provide cleaner air. Fitting a mixed model with these fixed effects, including random effects for worker and factory, the authors found that these determinants explained 18% of the variability between factories and 16% of the variability between workers within the same factory. The type of metal welded did not have an apparent effect in the model when considering total welding fumes. When including background concentration of welding fumes on a subset of workers for which this was known, 36% of the total variance was explained.

Liu et al. (2011) compiled over 2000 individual total particulate measurements from welders to assess sources of variability, with the major factors related to exposure being country (higher exposure levels in Finland and the USA, and lower exposure levels in Canada, the United Kingdom, and New Zealand), industry (highest levels in manufacturing and lowest levels in automobile industries), trades (highest exposures for boilermakers, and lowest exposures for pipe and welder fitters), type of ventilation (lowest exposures with mechanical and local exhaust ventilation), and type of welding process (highest exposures in MMA, followed by GMA, GTA, and ER welding). Exposures to welding fumes had not changed over the 40-year period. Creely et al. (2007) found similar results when analysing the database of welding fumes previously described by Kromhout et al. (2004); it was noted that, while exposure to welding fumes had decreased by 4% per year during 1983–2003, this was a lower rate of reduction than for other chemicals in the same geographic region.

Hobson et al. (2011) summarized 28 articles describing particulate exposure to welding fumes in field studies, and found that welding process and degree of enclosure explained 76% of the variability in mean particulate exposures. Lehnert et al. (2012) investigated determinants of exposure to particle size specific welding fumes and, as for Hobson et al. (2011), Liu et al. (2011), and Kromhout et al. (2004), found welding process, use of ventilation, and degree of enclosure to be the major determinants of exposure. Lehnert et al. (2012) found that FCA generated the highest concentration of welding fumes, followed by GMA and MMA. While GTA generated the lowest concentration of welding fumes, this welding process did have the highest number of small particles including ultrafine particles (UFP), which are less than 0.1 μm in diameter. In GTA welders, Graczyk et al. (2016) found 92% of the particle counts were of UFP type.

Suarthana et al. (2014) used the exposure models developed by Kromhout et al. (2004), Liu et al. (2011), and Lehnert et al. (2012) to estimate exposure to UFP in Canadian apprentice welders. Comparing estimates from the three models (which were developed using measurements of inhalable, total particulate, and respirable welding fumes) to measured concentrations of UFP, Suarthana et al. found low R^2 correlations ranging from 0.11 to 0.22. However, R^2 correlations between the Kromhout, Liu, and Lehnert models were higher, ranging from 0.41 to 0.74, showing that they correlated better with each other than any of the three models correlated with the measured concentrations of UFP. [The Working Group noted that this perhaps shows that particle size and nature of work (apprentice welder vs skilled welder) are other relevant

Table 1.9 Occupational exposures to chromium and nickel within the stainless steel and mild steel welding industries by process and industry

Reference (country)	Welding process	Industry	Total Cr (µg/m^3)[a]	Cr(VI) (µg/m^3)[a]	Ni (µg/m^3)[a]
Stainless steel welding processes					
Åkesson & Skerfving (1985) (Sweden)	MMA (high Ni alloy, 75% Ni)	Fabrication	101 (26–220)	–	440 (70–970)
Angerer & Lehnert (1990); Angerer et al. (1987) (Germany)	MMA	Shipbuilding	4[b] (< 1–50)	–	72 (< 50–260)
Angerer et al. (1987); Angerer & Lehnert (1990) (Germany)	GMA	Shipbuilding	10[b] (< 1–80)	–	100 (< 50–320)
Bonde (1990) (Denmark)	GTA	Fabrication	14.8; SD, 11.4	3.6; SD, 2.8	-
Knudsen et al. (1992) (Denmark)	GMA	NR	14.7; SD, 6.2	–	11.6; SD, 9.2
Knudsen et al. (1992) (Denmark)	GTA	NR	27.7; SD, 60.4	–	15.2; SD, 17.3
Matczak & Chmielnicka (1993) (Poland)	MMA	NR	(5–991)	50 (5–842)	20 (10–150)
Karlsen et al. (1994) (Norway)	MMA, shipyard	Shipyard	230 (8.3–1000)	140 (3.6–640)	50 (2.8–150)
Karlsen et al. (1994) (Norway)	MMA, offshore module	Fabrication	30 (4.7–87)	6.2 (< LOD–18)	11 (1.6–41)
Karlsen et al. (1994) (Norway)	MMA, welding shops	Fabrication	50 (< LOD–270)	12 (< LOD–84)	14 (5.5–39)
Karlsen et al. (1994) (Norway)	Grinding, small shop	Fabrication	1100 (270–4300)	< LOD (< LOD–0.9)	250 (79–650)
Edmé et al. (1997) (France)	MMA	Fabrication	201 (16–1328)	86 (1–649)	-
Edmé et al. (1997) (France)	GMA	Fabrication	185 (13–1200)	3.7 (1–65)	-
Edmé et al. (1997) (France)	GTA	Fabrication	52 (1–308)	2.4 (1–16	-
Wallace et al. (2001) (USA)	GMA	Fabrication	GM, 89.67 (SD, 64.62)	–	GM, 44.84 (SD, 31.32)
Wallace et al. (2001) (USA)	GTA	Fabrication	GM, 2.74 (SD, 0.86)	–	GM, 1.57 (SD, 0.54)
Stridsklev et al. (2004) (Norway)	FCA	NR	200 (2.4–2.744)	11.3 (< 0.2–151.3)	50.4 (< 2.0–416.7)
Ellingsen et al. (2006) (the Russian Federation)	MMA	Fabrication and shipyard	57 (5–976)	–	34 (3–240)
Ellingsen et al. (2006) (the Russian Federation)	GMA	Fabrication and shipyard	73 (7–387)	–	28 (2–270)
Ellingsen et al. (2006) (the Russian Federation)	FCA	Fabrication and shipyard	9 (3–18)	–	7 (2–25)
Mild steel welding processes					
Dryson & Rogers (1991) (New Zealand)	GMA	NR	< LOD	–	(< LOD–0.002)
Dryson & Rogers (1991) (New Zealand)	MMA	NR	< LOD	–	< LOD
Bonde (1990) (Denmark)	MMA, GMA	Fabrication	3.0 (SD, 1.8)	2 (SD, 1.2)	–

Table 1.9 (continued)

Reference (country)	Welding process	Industry	Total Cr (μg/m³)[a]	Cr(VI) (μg/m³)[a]	Ni (μg/m³)[a]
Wallace et al. (2001) (USA)	FCA, boilerplate[c]	Fabrication	GM, 12.61 (SD, 15.86)	–	GM, 11.76 (SD,13.78)
Schoonover et al. (2011) (USA)	MMA	Fabrication	1.8 (0.051–1.90)		0.36 (0.14–2.5)
Schoonover et al. (2011) (USA)	GMA	Fabrication	0.46 (0.14–1.6)		0.29 (0.11–1.2)

[a] Arithmetic mean unless otherwise specified, range in parentheses

[b] Median

[c] Defined as carbon steel with no further information, but defined separately from stainless steel in the article

Cr, chromium; Cr(VI), hexavalent chronium; FCA, flux-cored arc; GM, geometric mean; GMA, gas metal arc; GTA, gas tungsten arc; LOD, limit of detection; MMA, manual metal arc; Ni, nickel; NR, not reported; SD, standard deviation considerations when characterizing exposures to welding fumes.]

1.3.2 Exposure to chromium and nickel

Airborne exposures to chromium and nickel compounds are summarized in Table 1.9 for both SS and MS welding processes. For total chromium exposures, the ranges of mean concentration for MMA-SS and GMA-SS welding were 4–230 µg/m³ (Angerer & Lehnert, 1990; Karlsen et al., 1994; Edmé et al., 1997) and 10–185 µg/m³ (Angerer & Lehnert, 1990; Knudsen et al., 1992; Edmé et al., 1997), respectively. The mean concentrations from two FCA-SS welding studies were 200 µg/m³ and 9 µg/m³ (Stridsklev et al., 2004; Ellingsen et al., 2006). GTA-SS welding was observed to result in lower mean total chromium exposures, ranging from 14.8 to 52 µg/m³ (Bonde, 1990; Knudsen et al., 1992; Edmé et al., 1997).

Chromium VI exposures tended to be highest for MMA-SS welders (range of means, 50–140 µg/m³) (Matczak & Chmielnicka, 1993; Karlsen et al., 1994; Edmé et al., 1997). Considering only SS welders again, nickel exposures were lowest in two studies of GTA welding (means, 15.2 and 1.57 µg/m³) (Knudsen et al., 1992; Wallace et al., 2001), and concentrations varied in studies of MMA (range of means, 11–440 µg/m³) (Åkesson & Skerfving, 1985; Karlsen et al., 1994; Ellingsen et al., 2006), FCA (means, 7 and 50.4 µg/m³) (Stridsklev et al., 2004; Ellingsen et al., 2006), and GMA welding (range of means, 11.6–100 µg/m³) (Angerer & Lehnert, 1990; Knudsen et al., 1992; Wallace et al., 2001; Ellingsen et al., 2006).

Airborne exposures to chromium and nickel compounds could be 10 times lower for MS processes (Dryson & Rogers, 1991; Schoonover et al., 2011).

In the WELDOX study, Weiss et al. (2013) characterized determinants of exposure to both airborne and urinary chromium and nickel. They found that metal content in electrodes or base material and the welding process explained most of the variability in air measurements; SS welding demonstrated much higher concentrations of both chromium and nickel in air than MS welding. In urine, chromium and nickel concentrations were higher when welding was performed in a confined space or with poor ventilation. The use of respiratory protection was associated with a decrease in urinary chromium and nickel concentrations.

Persoons et al. (2014) investigated determinants of exposure to chromium and nickel as measured in the urine of GMA-SS welders. They found that welding by the more experienced, in a confined space, or for a longer time during the previous working week resulted in higher concentrations of chromium in urine, whereas welding of MS (as opposed to SS) and using mechanical ventilation resulted in lower concentrations of urinary chromium. Urinary nickel concentrations were found to be highest for welders with greater experience and who had performed grinding, and lowest for welders of MS. The metal content of the consumable electrode did not influence urinary chromium or nickel in this model. As in the models of welding fumes described by Kromhout et al. (2004), Hobson et al. (2011), Liu et al. (2011), and Lehnert et al. (2014), when assessing determinants of exposure to urinary chromium and nickel, the use of ventilation resulted in reduced exposures, confined space welding resulted in higher exposures, and there were differences in measured exposure due to type of welding or base metal used.

1.3.3 Exposures from aluminium welding

GMA and GTA processes can be used for welding aluminium and aluminium alloys (which often include beryllium, Be), which can present additional exposures to fumes and gases. Higher levels of ozone and UV exposure can also be generated from aluminium welding due to the high currents and pure argon shielding gas used (Faggetter et al., 1983). Typically, exposures to aluminium experienced by welders are measured in urine or plasma. However, airborne aluminium was measured in a study of 52 GMA and 18 GTA aluminium welders; mean aluminium concentrations of 2.1 mg/m^3 (range, 0.1–7.7 mg/m^3) and 0.17 mg/m^3 (range, 0.07–0.50 mg/m^3) were measured in GMA and GTA welding fumes, respectively (Matczak & Gromiec, 2002).

1.3.4 Exposure to welding gases

Table 1.10 provides a summary of exposures to welding gases. Only one study was found that quantified exposures to gases related to SS welding. Among GTA-SS welders, measured nitrogen dioxide and nitric oxide exposures ranged from less than 0.3 to 21.2 ppm, and from less than 0.04 to 13.8 ppm, respectively (Dryson & Rogers, 1991).

Gases such as carbon monoxide, nitrogen oxides, or ozone are also generated during MS welding processes. Carbon monoxide exposures as high as 1.5 ppm for GMA and MMA welders have been reported (Dryson & Rogers, 1991; Golbabaei et al., 2012). Oxides of nitrogen (NO_2 and NO) were highest for GMA (mean NO_2, 3.29 ppm; mean NO, 0.54 ppm) and GTA (mean NO_2, 3.54 ppm; mean NO, 0.41 ppm) welding operations in the Islamic Republic of Iran (Azari et al., 2011).

1.3.5 Exposure to radiation

(a) UV

In addition to exposures to welding fumes and gases, welders of all types in all industries are exposed to UV radiation from the welding arc. Arc welding produces UV radiation over the full spectrum (UVA, UVB, and UVC), with demonstrated harmful effects on exposed skin and the eyes (Vecchia et al., 2007; ACGIH, 2013).

The exposure of welders to UV radiation has been well characterized in the literature, and is summarized in Table 1.11. Compared with outdoor UV radiation exposure, arc welding UV radiation exposures are very intense within a few metres of the arc; exposure guidelines can be exceeded in a matter of seconds to minutes. This is compatible with the frequent occurrence of skin erythema (sunburn) and photokeratoconjunctivitis ("welder's flash") as reported in the literature (Kimlin & Tenkate, 2007). Despite welders typically wearing UV protective face shields or goggles when arcing, relevant exposure can still occur. Unprotected bystanders can also be exposed to UV radiation (Tenkate & Collins, 1997).

Exposure to UV radiation is higher when: the welder works close to the arc; arc energy, duration, or electrical current are increased; aluminium is being welded (because of the higher energy required); or argon is being used as the shielding gas. UV radiation emission is greatest in GMA, followed by MMA and then GTA welding, although this order can vary depending on current and other parameters (IARC, 1990; American Welding Society, 2014). UV radiation emissions from oxyfuel (gas) welding are generally much lower, but could be associated with less-frequent use of eye protection (Burgess, 1995). Peng et al. (2007) monitored UV radiation exposure during experimental MMA welding scenarios to compare with ACGIH UV exposure guidelines. The effective irradiance at 50 cm from the arc was in the range 0.03–0.3 mW/cm^2 (median, 0.155 mW/cm^2), and reported permissible exposure times ranging from 9.6 to 90.6 seconds (average, 19.4 seconds). In comparison, measurements taken behind a protective mask corresponded to approximately 6 minutes of permissible exposure time (Peng et al., 2007). A similar analysis for GTA welding of aluminium alloys found an effective irradiance at 50 cm from the arc in the range 0.1–0.9 mW/cm^2, reporting a permissible exposure

Table 1.10 Occupational exposures to gases within the stainless steel and mild steel welding industries by process and industry

Reference (country)	Welding process	Industry	CO (ppm)[a]	NO_2 (ppm)[a]	NO (ppm)[a]	F (mg/m^3)[a]	O_3 (ppm)[a]
Stainless steel welding processes							
Dryson & Rogers (1991) (New Zealand)	GTA	NR	–	(< 0.3–21.2)	(< 0.04–13.8)	–	–
Mild steel welding processes							
Dryson & Rogers (1991) (New Zealand)	GMA	NR	1.5 (1.2–1.8)	(< 0.01–0.7)	(< 0.01–0.17)	–	–
Dryson & Rogers (1991) (New Zealand)	MMA	NR	–	(< 0.1–4.4)	(< 0.07–1.6)	–	–
Akbar-Khanzadeh (1993) (UK)	Various	Shipyard	1.1 (SD, 0.5)	0.06 (SD, 0.03)	0.25 (SD, 0.27)	–	–
Wallace et al. (2001) (USA)	FCA, boilerplate	Fabrication	10 (single grab sample)	ND	–	–	ND
Woskie et al. (2002) (USA)	MS	Construction	–	–	–	0.73 (SD, 1.13)	–
Schoonover et al. (2011) (USA)	MMA	Fabrication		0.064 (0.052–0.22)			0.0047 (< LOD–0.020)
Schoonover et al. (2011) (USA)	GMA	Fabrication		0.038 (0.037–0.061)			0.012 (< LOD–0.037)
Hedmer et al. (2014) (Sweden)	GMA	Fabrication	–	–	–	–	GM, 0.03 (< 0.01–0.66)
Azari et al. (2011) (Islamic Republic of Iran)	GTA	Fabrication	–	3.54 (SD, 0.65)	0.41 (SD, 2.7)	–	0.21 (SD, 0.12)
Azari et al. (2011) (Islamic Republic of Iran)	GMA	Fabrication	–	3.29 (SD, 0.60)	0.54 (SD, 3.2)	–	0.37 (SD, 0.22)
Golbabaei et al. (2012) (Islamic Republic of Iran)	MMA	Fabrication	1.8 (SD, 1.40)	0.397 (SD, 0.35)	–	–	0.018 (SD, 0.02)

[a] Arithmetic mean unless otherwise specified, range in parentheses

CO, carbon monoxide; F, fluoride; FCA, flux-cored arc; GM, geometric mean; GMA, gas metal arc; GTA, gas tungsten arc; LOD, limit of detection; MMA, manual metal arc; MS, mild steel; ND, not determined; NO, nitric oxide; NO_2, nitrogen dioxide; NR, not reported; O_3, ozone; ppm, parts per million; SD, standard deviation

Compiled by the Working Group

Table 1.11 Occupational exposures to non-ionizing radiation within the welding industry by process and industry

Reference (country)	Welding process	Distance (cm)	Industry	ELF-EMF (μT)[a]	UV (μW/cm²)[a]
Peng et al. (2007) (China)	MMA	50	Experimental		Median, 154.9 (33.1–311)
	MMA	100	Experimental		Median, 39.3 (14.2–76.2)
	MMA	200	Experimental		Median, 5.0 (0.2–16.6)
	MMA	300	Experimental		Median, 2.0 (0.0–12.1)
Nakashima et al. (2016) (Japan)	GTA, aluminium	50	Experimental		(91–910)
Okuno et al. (2001) (Japan)	GMA with CO_2 shielding gas	100	Experimental		(28–785)
Wolska (2013) (Poland)	GTA, MMA	60–34			Mean range, 779–3760
Skotte & Hjøllund (1997) (Denmark)	MMA direct current		Shipyard	Workday, 21.2 (range of means, 5.3–43)	
	GMA alternating current		Shipyard	Workday, 2.3 (range of means, 0.59–4.9)	
Dasdag et al. (2002) (Turkey)	MMA		Fabrication	(100–250)	

[a] Range in parentheses

CO_2, carbon dioxide; ELF-EMF, extremely low frequency electromagnetic fields; GMA, gas metal arc; GTA, gas tungsten arc; MMA, manual metal arc; UV, ultraviolet

Compiled by the Working Group

time of 3.3–33 seconds. UV emissions caused by GTA aluminium welding were about one tenth of the emissions by GMA aluminium welding, based on previous results (Nakashima et al., 2016). Wolska (2013) reported on UV radiation exposure measurements at 13 workstations involving GTA and MMA welding with varying process parameters. Mean effective irradiance varied from 0.7 to 3.7 mW/cm², corresponding to a permissible exposure time in the range 1.7–75 seconds. It was not possible to distinguish patterns of higher exposure for GTA or MMA welding due to variations in other parameters such as current.

UV radiation associated with arc welding is generally much higher than for other artificial UV radiation generating processes (e.g. germicidal lamps, photocuring, tanning lamps); exposure concentrations are typically orders of magnitude higher than natural sunlight (Tenkate & Collins, 1997).

(b) ELF-EMF

Welders are also exposed to ELF-EMF, and measured exposures are summarized in Table 1.11. While the number of publications assessing the exposure of welders to EMF is limited, Stern (1987) reported that welders operate devices using a direct, alternating, or pulsing current in the range 100–100 000 A. These currents create magnetic flux densities of 100–10 000 μT at distances of 0.2–1 m from the weld device (Stern, 1987). The arc time of welders typically occupies 30–50% of the working day and welders can work in close proximity to other welders; Stern (1987) calculated that the cumulative EMF exposure for welders can exceed that of the general population by a factor of 2–200.

Skotte & Hjøllund (1997) measured the exposure to ELF-EMF of 50 metalworkers and 15 shipyard welders, who reported welding activity for 5.8 and 56% of the workday, respectively. The personal exposure metres worn by the workers recorded a measurement every 10 seconds for the metalworkers, and every 4 seconds for the shipyard welders. For the metalworkers, the mean ELF-EMF exposure for the workday (calculated using all measurements from all metalworkers) was 0.50 µT, and the maximum of the workday mean exposures (the maximum mean calculated for all of the 50 metalworkers) was 9.73 µT. For the shipyard welders, the mean ELF-EMF exposure for the workday was 7.22 µT and the maximum of the workday mean exposures was 27.5 µT. Higher ELF-EMF exposures were found for MMA direct current welders (workday arithmetic mean, 21.2 µT) than for GMA alternating current welders (workday arithmetic mean, 2.3 µT). During welding-only time, mean exposure was 65 µT for MMA direct current welders and 7 µT for the GMA alternating current welders (Skotte & Hjøllund, 1997). Resistance welders may experience the highest exposures to ELF-EMF compared with other welding processes, as the former involves electric currents up to 100 000 A, resulting in peak ELF-EMF exposures in the millitesla range (Håkansson et al., 2002).

The United States National Institute for Occupational Safety and Health (NIOSH) reports average ELF-EMF daily median and exposure ranges for a variety of workers. Of the workers listed, welders have the highest average daily median exposure of 8.2 milligauss [0.82 µT] and largest range of exposures of 1.7–96 milligauss [0.17–9.6 µT]. As a comparison, electric line workers have an average daily median exposure of 2.5 milligauss [0.25 µT] over the range 0.5–34.8 milligauss [0.05–3.48 µT], and clerical workers experience a median exposure of 1.2 milligauss [0.12 µT] over the range 0.5–4.5 milligauss [0.05–45 µT] (NIOSH, 1996).

(c) Thorium-232

Tungsten electrodes used for GTA welding usually contain 1–4% thorium oxide, added to facilitate arc starting, increase arc stability, reduce weld metal contamination, and improve the current-carrying capacity. Thorium-232 (^{232}Th) is a major radioactive isotope of thorium and an emitter of α particles with a very long decay half-life (1.4 × 10^{10} years) (Saito et al., 2003). Exposure to ionizing radiation may occur during grinding of the electrode before and after welding, and during welding. In three studies monitoring air sampled in the breathing zone of workers performing welding and grinding, radioactivity was measured within the range 0.1–100 mBq/m^3; this corresponds to estimated yearly effective doses which are mostly below the current general population limit set by the International Commission on Radiological Protection (Ludwig et al., 1999; Gäfvert et al., 2003; Saito et al., 2003). Exposure tended to be higher when alternating current was used, since it is associated with a higher electrode consumption rate (Ludwig et al., 1999).

1.3.6 Coexposures (asbestos, solvents)

A historical exposure related to welding is asbestos, as it was commonly used as an insulating material in ships, in the material covering rod electrodes, in the cylinders holding acetylene gas, and in the heat-protective equipment of welders and blankets to slow cooling of the weld. As asbestos fibres are not stable at the high temperatures used for welding, during such processes they are more likely to aerosolize (Kendzia et al., 2013). Exposure to asbestos in shipyards is most commonly assessed via questionnaire or expert (industrial hygienist) opinion based on historic job duties and tasks. In one cohort study performed by NIOSH at a US shipyard, cumulative exposure to asbestos was determined through a combination of historic asbestos air samples (*n* = 915) collected from

Table 1.12 Limit values for welding fumes (8 hours)

Country	Limit value (mg/m^3)
Australia	5[a]
Austria	5 (respirable aerosol)
Belgium	5
Canada – Québec	5
France	5
Ireland	5
Latvia	4
New Zealand	5[a, b]
People's Republic of China	4[c]
Singapore	5
Republic of Korea	5
Spain	5
Netherlands	1[d]

[a] Not otherwise classified

[b] A range of airborne contaminants are associated with gas and arc welding. The type of metal being welded, the electrode employed and the welding process will all influence the composition and amount of fumes. Gaseous products such as nitrogen oxides, carbon monoxide, and ozone may also be produced. In the absence of toxic elements such as chromium, and where conditions do not support the generation of toxic gases, the concentration of fumes inside the welder's helmet should not exceed 5 mg/m^3

[c] Inhalable fraction

[d] Until 1 April 2010, the legal limit value was 3.5 mg/m^3

Adapted from GESTIS International Limit Values, Update: March 2017 (GESTIS, 2016)

the 1940s to the 1990s and informed by an industrial hygiene panel. The majority (852) of asbestos samples fell below the limit of detection (< 0.004 fibres/mL) with the remaining 63 samples ranging from 0.004 to 25.0 fibres/mL; that is, 6% of welders were considered to have experienced high exposures to asbestos (Seel et al., 2007).

The use of chlorinated solvents, such as trichloroethylene (TCE) or tetrachloroethylene, for cleaning coated metal in tandem with welding may result in exposures to hydrogen chloride and possibly phosgene (Burgess, 1995). The Working Group could not find reported exposure levels to these solvents for welders. Among job periods exposed to any welding fumes in CANJEM, 15% were also deemed exposed to chlorinated solvents. Among welder occupations (sheet metal workers, mechanics, welders), 10–20% of the job periods were deemed exposed to both chlorinated solvents and welding fumes. Higher proportions of coexposure (30%) were found in occupations related to electric/electronic maintenance.

Benzene has historically been used in solvents for metal cleaning. Among CANJEM job periods exposed to any welding fumes, 11% were also deemed exposed to benzene (4% after 1980) (CANJEM, 2017).

1.4 Regulations and guidelines

Limit values for occupational exposure to welding fumes are generally set at 5 mg/m^3; exceptions are in the People's Republic of China (limit value of 4 mg/m^3) and the Netherlands where, on 1 April 2010, a limit value of 1 mg/m^3 over 8 hours came into force. In most countries the size fraction of welding fumes has not been defined but, given the process during which the fumes are generated, it is assumed that the welding fumes fall into the respirable aerosol size range (Table 1.12). No short-term limit values exist.

A range of airborne contaminants are associated with gas and arc welding. The type of metal being welded, the electrode employed, and the welding process all influence the composition and amount of fumes. Gaseous products such as nitrogen oxides, carbon monoxide, and ozone may also be produced. Some countries no longer have an exposure limit for welding fumes, but instead use limits for specific metals in welding fumes or respirable dust (e.g. Germany, the United Kingdom, and the USA) (BG-Regel, 2006; OSHA, 2013; HSE, 2017). In the United Kingdom a generic exposure limit to welding fumes of 5 mg/m^3 as total inhalable particulate (TIP) was withdrawn in 2005 (Garrod & Ball, 2005), as the limit was not considered to be protective of health.

The World Health Organization has recommended the use of personal protective equipment for welders and helpers and the use of engineering controls (e.g. "light-tight" cabinets and enclosures, UV-absorbing glass, plastic shielding, baffles) to protect non-involved staff in the welding workplace (ICNIRP, 2007).

1.5 Exposure assessment of epidemiological studies

Table 1.13, Table 1.14, and Table 1.15 provide an overview of the exposure assessment methods used in the key epidemiological studies that were evaluated by the Working Group. The strengths and the weaknesses of each study were assessed, as well as the potential effects of these on the interpretation of the risk estimates.

Some studies used the job title "welder" as a measure of exposure (Tucker et al., 1985; Schoenberg et al., 1987; Holly et al., 1996; Kogevinas et al., 2003; Reulen et al., 2008; Pukkala et al., 2009; Kendzia et al., 2013; 't Mannetje et al., 2016; MacLeod et al., 2017). Job title alone does not provide information on different tasks and circumstances; since these influence the level and frequency of exposure to welding fumes, job title does not specifically characterize exposure to welding fumes. Additionally, workers with job titles other than welder may also perform welding tasks (see Table 1.3). Some of the studies using job titles separately classified welders and "occasional welders" (Kendzia et al., 2013; Matrat et al., 2016; MacLeod et al., 2017). Definitions of occasional welder vary between studies and have been based on job titles judged by study authors to involve welding tasks, for example plumbers and sheet metal workers. The exact definition will affect the level of exposure misclassification, so both classifications (regular welders and occasional welders) should always be assessed separately. The reference group should not include either welders or occasional welders when calculating risk estimates in epidemiological studies.

Exposure assessment in several studies on ocular melanoma relied on self-reported UV radiation exposure (Seddon et al., 1990; Ajani et al., 1992; Vajdic et al., 2004); although this is more informative than job title alone, it may be prone to recall bias.

Several studies used general job-exposure matrices (JEMs) (Pesch et al., 2000; Guénel et al., 2001; Lutz et al., 2005), with some based on monitoring data (Simonato et al., 1991; Sørensen et al., 2007; Yiin et al., 2007; Siew et al., 2008). However, Yiin et al. (2007) acknowledged that scarcity of data on welding fumes was a complicating factor in the quantitative assessment. Since JEMs are a standardized method of assessing exposures, any misclassification is likely to be non-differential and the assessment process is transparent. On the other hand, standardization negatively affects the possibility of accounting for between-worker variations, since workers with the same job title will all be assigned the same exposure.

Exposure to welding fumes can also be determined from welding-specific questionnaires, either through case-by-case expert assessment (e.g. industrial hygienists) or directly reporting on specific tasks performed by the respondent (Siemiatycki, 1991; van Loon et al., 1997; Gustavsson et al., 1998; Jöckel et al., 1998a, b; Gustavsson et al., 2000; 't Mannetje et al., 2012; Vallières et al., 2012). The assessment can therefore incorporate all available information (job title, type and name of the company, what was being produced in the department, time period, welding type and material, control measures) and account for between-worker variations within the same job. These assessment methods also have their limitations, because they rely on the reported work histories and welding characteristics. Self-reported occupational information is susceptible to recall bias, but this bias is minimized when exposure assessment is based on reported tasks rather than specific exposures.

Occupational information collected from proxy respondents is not very useful for assessing exposure to welding fumes, as spouses or other relatives will not be able to provide details on specific welding tasks and materials.

Several studies have reported good inter-rater agreement analyses in the exposure assessment of welding fumes. Seel et al. (2007) found good concordance (78%) for estimating intensity of exposure to welding fumes and excellent concordance (98%) for frequency estimates, defined as the number of 8-hour working days per year at the estimated intensity (Seel et al., 2007). Benke et al. (1997) also reported good agreement between raters for welding fumes ($\kappa = 0.57$). 't Mannetje et al. (2012) reported a κ of 0.9 for agreement between experts in assessing exposures to welding fumes in a multicentre study on lung cancer. [The Working Group noted that high agreement between experts does not necessarily relate to correct assessments of exposure.]

[The main strengths of most of the case–control studies listed in Table 1.14 are that full job histories were assessed. The cohorts listed in Table 1.13 do not have full job histories of the subjects, which might have led to underestimation of exposure to welding fumes.]

1.5.1 Summary exposure assessment quality of epidemiological studies

In summary, the cohort studies with the strongest exposure assessment are those that applied a "welding exposure matrix" (Simonato et al., 1991; Sørensen et al., 2007), followed by studies that applied either case-by-case expert assessment (van Loon et al., 1997) or general JEMs (Yiin et al., 2005; Meguellati-Hakkas et al., 2006; Yiin et al., 2007; Siew et al., 2008). Studies that only looked at job titles (Gerin et al. 1984; Kjuus et al. 1986; Pukkala et al., 2009; MacLeod et al., 2017) are considered less informative.

Taking into account all available information, exposure assessments based on welding-specific questionnaires in the case–control studies of cancer of the lung are considered the most informative on exposure to welding fumes (Siemiatycki, 1991; Jöckel et al., 1998a, b; 't Mannetje et al., 2012; Vallières et al., 2012; Matrat et al., 2016). Caution is warranted when interpreting studies based on information (partly) collected from proxy respondents, since they will often be unfamiliar with the detailed technical and workplace characteristics needed for welding-specific questionnaires. Exposure assessment based on job titles alone (Kendzia et al., 2013) provides no information on the level of exposure to welding fumes. Studies that only reported ever versus never welder (Schoenberg et al., 1987), or were based predominantly on data collected from proxy respondents (Hull et al., 1989; Gustavsson et al., 2000), are considered to be least informative regarding the characterization of exposure to welding fumes.

The case–control studies of ocular melanoma applying a JEM (Guénel et al., 2001; Lutz et al., 2005) are the most informative regarding exposure to UV radiation, followed by self-reported eye burns (Guénel et al., 2001; Vajdic et al., 2004) and self-reported exposure from specific welding types (Vajdic et al., 2004), although caution is advised with regards to recall bias. The studies assessing exposure to welding fumes (Siemiatycki, 1991) and ever exposure to welding arcs (Seddon et al., 1990; Ajani et al., 1992) as a proxy for UV radiation exposure are less informative. Studies reporting on ever versus never welders alone provide the least information on UV radiation exposure (Tucker et al., 1985; Holly et al., 1996).

For the case–control studies on other cancer types, assessment of exposure to welding fumes based on expert judgement (Siemiatycki, 1991) or on a JEM (Pesch et al., 2000) is preferred over assessments based on job title alone (Kogevinas et al., 2003; Reulen et al., 2008; 't Mannetje et al., 2016).

Table 1.13 Exposure assessment in key epidemiological studies of welders: cohort studies

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metrics reported
Welding exposure matrix	Cohort study of male metal workers employed for at least 1 yr at 1 or more Danish SS or MS industrial companies Ever welders, who started work in 1960 or later, were included for analyses Information on lifetime occupational exposures was collected during a questionnaire in 1986; for deceased workers, proxy respondents were interviewed	Exposure to welding fumes assessed specifically Quantitative exposure assessment, based on measurement data Standardized assessment by JEM; any exposure misclassification therefore likely to be non-differential Details on individual welding tasks taken into account	Retrospective recall of details of the welding process has questionable accuracy No full job histories	Sørensen et al. (2007)	Exposure to welding fumes up to baseline, expressed as mg/m^3-yr
Welding exposure matrix	Multicentre cohort study of male welders from 135 companies in 9 European countries Exposure histories were constructed for each cohort member, including employment dates, base metal welded, welding process used, work environment, and changes in exposure over time	Exposure to welding fumes assessed specifically Quantitative exposure assessment based on expert judgment and measurement data Standardized assessment by JEM; any exposure misclassification therefore likely to be non-differential Detailed job information, accounting for welding material and process	No full job histories In some cases company information was used to complete individual exposure histories	Simonato et al. (1991); Gérin et al. (1993)	Years since first exposure to welding fumes (0–9, 10–19, 20–29, ≥ 30) and duration of employment in years (< 9, ≥ 10) were assigned Welders were classified by type of welding: shipyards, MS only, ever SS, predominantly SS Level of exposure was expressed in units of mg/m^3; cumulative exposure to welding fumes was then derived by multiplying level by duration and expressed as mg/m^3-yr

Table 1.13 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metrics reported
Expert assessment	Prospective cohort study, men and women aged 55–69 yr in September 1986 Job history was obtained via self-administered questionnaire, collecting data on job title, company, department, and period	Exposure to welding fumes assessed specifically Blinded exposure assessment; any exposure misclassification therefore likely to be non-differential All available information used (job title, type, name of the company, what was being produced in the department, time period) Final re-evaluation round performed to minimize miscategorization of exposures	No quantitative data on welding fumes Job histories only up to start of follow-up, so may have missed up to 10 yr of the end of career	van Loon et al. (1997)	Probability of exposure to welding fumes (particularly SS), classified into four categories (no exposure; possible exposure, < 30%; probable exposure, 30–90%; nearly certain exposure, > 90%), given the weights 0, 0.15, 0.6, and 0.95, respectively Cumulative probability of exposure was assigned based on the combination of probability weight and duration in years
JEM	Cohort study of men and women employed at the Portsmouth Naval Shipyard for at least 1 day between 1 January 1952 and 31 December 1992, who were monitored for radiation Detailed computerized work histories collected from personnel records	Exposure to welding fumes assessed specifically Expert assessment by panel of industrial hygienists who were familiar with shipyard operations Standardized assessment by JEM; any exposure misclassification therefore likely to be non-differential	No full job histories No quantitative data on welding fumes	Yiin et al. (2005)	Exposure to welding fumes (0, none; 1, possible; 2, probable) was assigned to each job title/shop combination by an expert panel Cumulative exposure score was calculated as the sum of the duration of exposed jobs (in years) multiplied by the exposure probability score Cumulative exposure to welding fumes was then classified into three categories: 0, > 0–5, and > 5

Table 1.13 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metrics reported
JEM	Cohort study of workers in technical branch of the telephone company on 1 January 1978 and newly hired up to 31 December 1994 Individual job histories since start of employment in the company were obtained from company records Occupations were classified into six groups, as well as into seven sectors; start and end date of each occupation was recorded	Exposure to welding fumes assessed specifically Standardized assessment by JEM; any exposure misclassification therefore likely to be non-differential	No full job histories No quantitative data on welding fumes	Meguellati-Hakkas et al. (2006)	Exposure to arc welding fumes was expressed by duration in years
JEM	Cohort study of men and women employed at the Portsmouth Naval Shipyard for at least 1 day between 1 January 1952 and 31 December 1992, who were monitored for radiation Detailed computerized work histories collected from personnel records, including job titles, shop assignment, and employment dates	Exposure to welding fumes assessed specifically Quantitative exposure assessment based on expert judgement Standardized assessment by JEM; any exposure misclassification therefore likely to be non-differential	No full job histories Scarcity of monitoring data on welding fumes hindered quantitative assessment based on data	Yiin et al. (2007)	Intensity and frequency of exposure to welding fumes (as Fe_2O_3 fumes) were assessed Cumulative exposure (mg-days/m^3) was assigned to each subject
JEM	Cohort study of all economically active Finnish men born during 1906–1945 Occupations were obtained from the 1970 population census; jobs were coded according to ISCO-1958 and FIN-JEM was applied	Exposure to welding fumes assessed specifically Quantitative exposure assessment, based on measurement data Standardized assessment by JEM; any exposure misclassification therefore likely to be non-differential	No full job history	Siew et al. (2008)	Level of exposure to welding fumes in mg/m^3; any occupation with more than 5% of workers exposed was considered potentially exposed

Table 1.13 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metrics reported
Job title	Census-based cohort study of male workers aged 24–74 in 1991 in Canada Occupation in week before census or the longest-held job in the previous year was asked for	Both welders and occasional welders identified	No full job histories, only occupation at one point in time Exposure to welding fumes was not assessed specifically Number of occasional welders overestimated since many occupations were classified as such	MacLeod et al. (2017)	Employment as welder or occasional welder vs non-welders
Job title	Census-based cohort study, men and women aged 30–64 yr in the 1960, 1970, 1980/81, and/or 1990 censuses in the Nordic countries Occupation and industry were recorded in the census	Standardized classification of jobs across countries (ISCO-1958)	Only ever vs never employment as welder Exposure to welding fumes was not assessed specifically Workers may be performing welding tasks and/or be exposed to welding fumes without having the job title “welder” No full job histories	Pukkala et al. (2009)	Ever vs never employment as welder

Fe_2O_3, iron oxide; FIN-JEM, Finnish job-exposure matrix; ISCO, International Standard Classification of Occupations; JEM, job-exposure matrix; MS, mild steel; SS, stainless steel; vs, versus; yr, year(s)

Table 1.14 Exposure assessment in key epidemiological studies of welders: cancer of the lung case–control studies

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metric reported/notes
Expert assessment	Two lung cancer case–control studies Detailed job histories were obtained by interview; case-by-case expert assessment was used to assess exposures	Exposure to welding fumes assessed specifically Full job histories All available information used (job title, tasks, materials used, company, department, protective equipment) Separated by arc welding and gas welding fumes Welding-specific questionnaire, also administered to other job titles if indicating welding tasks Blinded exposure assessment; any exposure misclassification therefore likely to be non-differential	No quantitative data on welding fumes Information for ~23% of the subjects was collected via proxy respondents, who may not be aware of the specific tasks and working conditions of the case or control under study	Vallières et al. (2012)	Confidence of exposure occurrence (possible, probably, definite) Intensity of exposure (non-exposed, low, medium, high) Frequency of exposure (low, 1–5% of time; medium, 5–30%; high, > 30%) Ever exposed to gas welding fumes, arc welding fumes vs never exposed to welding fumes
Expert assessment	Case–control study on lung cancer (1998–2001) in 6 central and eastern European countries and in the UK Questionnaire assessing occupations held for more than 1 yr, including questions on welding or gas cutting and if any welding or gas cutting was done near the subject; a specialized questionnaire on welding was administered when the general questionnaire indicated employment as a welder; case-by-case expert assessment was used to assess exposures	Exposure to welding fumes assessed specifically Full job histories All available information used (job title, tasks, materials used, company, department, protective equipment) Separated by arc welding and gas welding fumes Welding-specific questionnaire, also administered to other job titles if indicating welding tasks Blinded exposure assessment; any exposure misclassification therefore likely to be non-differential Standardization through yearly training of experts and use of manual for assessment; high agreement ($\kappa = 0.9$) between experts for welding fumes	No quantitative data on welding fumes Expert's ability to assess the level of exposure to welding fumes was limited	't Mannetje et al. (2012)	Confidence of exposure occurrence (possible, probably, definite) Intensity of exposure (non-exposed, low, medium, high) Frequency of exposure (low, 1–5% of time; medium, 5–30%; high, > 30%) Ever exposed to gas welding fumes, arc welding fumes vs never exposed to welding fumes

Table 1.14 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metric reported/notes
Expert assessment	Case–control study for several cancer sites Detailed job histories were obtained by interview; case-by-case expert assessment was used to assess exposures	Exposure to welding fumes assessed specifically Full job histories All available information used (job title, tasks, materials used, company, department, protective equipment) Separated by arc welding, gas welding, and soldering fumes Welding-specific questionnaire, also administered to other job titles if indicating welding tasks Blinded exposure assessment; any exposure misclassification therefore likely to be non-differential	No quantitative data on welding fumes Information for 29% of the subjects was collected via proxy respondent, who may not be aware of the specific tasks and working conditions of the case or control under study	Siemiatycki (1991)	Intensity of exposure (non-exposed, low, medium, high) Frequency of exposure (low, 1–5% of time; medium, 5–30%; high, > 30%)
Welding-specific questionnaire	Case–control study on cancers of the respiratory tract in France (2001–2007) Face-to-face interviews using standardized questionnaires Lifetime occupational history, including the start and end dates, industry and tasks, and a job-specific questionnaire for welding, brazing, or metal cutting	Full job histories Job-specific questionnaire on welding for anyone who indicated being exposed to welding, including information on the welding process, type of metals welded, type of coating covering the metal, treatments applied before welding and the use of protective clothing Both regular welders and occasional welders defined	Exposure to welding fumes was not assessed specifically Self-reported occupational information susceptible to recall bias; however, reporting tasks probably less prone to recall bias	Matrat et al. (2016)	Ever regular welder, ever occasional welder vs never welder Ever gas, arc, spot, or other welding vs never welding Frequency of welding (≤ 5%, > 5%) Total duration of exposure to welding activity (≤ 10, > 10 yr) Time since last exposure (≤ 35, > 35 yr) Time since last exposure (0, 0–10, 10–20, 20–30, 30–40, > 40 yr)

Table 1.14 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metric reported/notes
Welding-specific questionnaire	Case–control study on lung cancer in Germany (1988–1993) A structured questionnaire was used to obtain information on job history (for jobs held for at least 6 mo) and occupational exposures; supplemental questionnaires were used for exposure to welding fumes	Full job histories Job-specific questionnaire on welding, including type of welding, metals welded, coating on metals, working conditions, and time dimensions For each individual possibly using welding devices (based on job history), the welding-specific supplementary questionnaire was administered	No quantitative data on welding fumes Self-reported occupational information susceptible to recall bias. However, reporting tasks probably less prone to recall bias	Jöckel et al. (1998a, b)	Ever vs never exposed Lifetime hours of welding oxyacetylene or MMA welding, or both (non-exposed, ≤ 1000, > 1000 to ≤ 6000, > 6000 h)
Job title	Pooled analysis of lung cancer case–control studies Full job histories were collected, including all jobs held for at least 1 yr; start and end year was recorded for each job	Standardized classification of jobs (ISCO-1968) and industries (ISIC revision 2) across studies Full job histories Taking into account workers without the job title welder who may be performing welding tasks and/or exposed to welding fumes	Exposure to welding fumes was not assessed specifically No information on welding process available	Kendzia et al. (2013)	Ever vs never employment as welder Ever vs never employment as occasional welder Longest-held occupation as welder or occasional welder vs never
Welding-specific questionnaire	Lung cancer case–control study among white male welders in Los Angeles County (1972–1987) Interviews collecting information on occupational exposures to specific welding processes, metals welded, asbestos, and confined-space welding	Full job histories Information on type of welding and welding material	Information was largely collected via proxy respondents, who may not be aware of the specific tasks and working conditions of the case or control under study	Hull et al. (1989)	Ever vs never exposed Ever MMA, SS, MS, high-alloy steel welding, confined-space welding, shipyard welding Ever exposed for > 5 yr

Table 1.14 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metric reported/notes
Job title	Pooled analysis of lung cancer case–control studies Full job histories were collected, including all jobs held for at least 1 yr; start and end year was recorded for each job	Standardized classification of jobs (ISCO-1968) and industries (ISIC revision 2) across studies Full job histories Taking into account workers without the job title welder who may be performing welding tasks and/or exposed to welding fumes	Exposure to welding fumes was not assessed specifically No information on welding process available	Kendzia et al. (2013)	Ever vs never employment as welder Ever vs never employment as occasional welder Longest-held occupation as welder or occasional welder vs never
Job title	Case–control study on lung cancer in New Jersey (1980–1981) Personal interviews of the subjects or their next of kin; information was also obtained on each full-time or part-time job held for 3 mo or more since 12 yr of age Information recorded: name and address of employer; type of business; job title; duties performed; materials handled; exposure to solvents, fumes, or dust; and time period of employment For shipbuilding workers, supplemental questions on employment in specific shipyard trades were also asked	Full job histories	Exposure to welding fumes was not assessed specifically No information on welding process available Workers without the job title welder may be performing welding tasks and/or be exposed to welding fumes	Gerin et al. (1984); Kjuus et al. (1986); Schoenberg et al. (1987)	Ever welder or burner

Table 1.14 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metric reported/notes
Expert assessment	Case–control study on lung cancer in Sweden (1985–1990) Postal questionnaire recording start and end date, job title, job tasks, and company for each job held for more than 1 yr Case-by-case expert assessment was used to assess exposures; probability and intensity of exposure to a range of occupational exposures, including welding fumes, was assigned	Exposure to welding fumes assessed specifically Full job histories Blinded exposure assessment; any exposure misclassification therefore likely to be non-differential All available information used (work tasks were taken into account in addition to job titles) Only one expert conducted the assessments, enhancing uniform assignments	Information was mostly collected via proxy respondents, who may not be aware of the specific tasks and working conditions of the case or control under study Proxy respondents more often used for cases, possibly resulting in differential misclassification Only one expert conducted the assessments, hindering evaluation of the quality of assessments No quantitative data on welding fumes	Gustavsson et al. (2000)	Exposure to welding fumes was assessed as low, medium, or high, with category averages assigned as 1, 5, and 15 units, respectively, where 15 units corresponded to full-time employment as a MMA welder Probability of exposure (0%, 20%, 50%, or 85%) Cumulative exposure for each factor was calculated as the product of the intensity, the probability, and the duration of the exposure, summed over all work periods in the person's occupational history

h, hour(s); ISCO, International Standard Classification of Occupations; ISIC, International Standard Industrial Classification; mo, month(s); MMA, manual metal arc; MS, mild steel; SS, stainless steel; vs, versus; yr, year(s)

Table 1.15 Exposure assessment in key epidemiological studies of welders: ocular melanoma (ultraviolet radiation)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metrics reported/notes
JEM	Case–control study on ocular melanoma in France Interviews collecting detailed description of each job held for at least 6 mo, using open-ended questions; for selected work tasks (including welding), details on work procedures (e.g. type of welding process) and materials were obtained from a specific questionnaire Jobs were coded with ISCO-1968 and a study-specific JEM was applied	Full job histories Artificial and solar UV radiation assessed separately Ever eye burn from welding recorded Interviewer not aware of research questions and coders blinded Standardized assessment by JEM; any exposure misclassification therefore likely to be non-differential	No quantitative data on artificial UV radiation JEMs do not take into account variability in exposure between people with the same job	Guénel et al. (2001)	Exposure to artificial UV radiation Exposure probability, i.e. estimated proportion of workers exposed within job (< 20% exposed workers, 20–50%, > 50%) Exposure frequency (occasional, several days per month, several days per week, daily) Exposure intensity (high, medium, low) Summary score was the product of probability, frequency, and intensity
JEM	Pooled analysis of case–control studies on ocular melanoma Interviews collecting occupational histories, including each job held for at least 6 mo Jobs were coded with ISCO-1968 and a study-specific JEM was applied	Full job histories Artificial and solar UV radiation separately assessed Standardized assessment by using JEM; any exposure misclassification therefore likely to be non-differential	Short intense exposures may have been missed; information on eye burns due to welding not included No quantitative data on artificial UV radiation JEMs do not take into account variability in exposure between people with the same job	Lutz et al. (2005)	Exposure to artificial UV radiation Exposure probability, i.e. estimated proportion of workers exposed within job (< 20% exposed workers, 20–50%, > 50%) Exposure frequency (occasional, several days per month, several days per week, daily) Exposure intensity (high, medium, low) Summary score was the product of probability, frequency, and intensity

Table 1.15 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metrics reported/notes
Self-report	Case–control study on ocular melanoma in Australia Telephone interview with structured questions about use of welding equipment Ever welder or exposure to others arc welding < 5 m away, and further detailed questions about exposure	Artificial UV radiation exposure assessed specifically, including bystander exposure Welding either at work or at home Information on type of welding, wearing of goggles/mask, and number of eye burns due to welding	No quantitative data on artificial UV radiation Self-reported exposure susceptible to recall bias	Vajdic et al. (2004)	Lifetime hours of exposure (based on years, usual frequency, and duration of exposure) Exposed to own welding (ever, never) Type of welding (none, arc and oxy, arc only, oxy only, electric/spot only, other) Welding at work (ever, never) Exposed to others welding (ever, never)
Expert assessment	Case–control study for several cancer sites, including ocular melanoma, in Canada Case-by-case expert assessment was used to assess exposures	Full job histories All available information used (job title, tasks, materials used, company, department, protective equipment) Welding-specific questionnaire, administered to other job titles also if indicating welding tasks Blinded exposure assessment; any exposure misclassification therefore likely to be non-differential	Exposure assessment focused on (arc) welding fumes, not UV radiation from welding No quantitative data Assessment of many (293) substances overall, creating a large burden on the assessors Information for about 12% of the subjects was collected via proxy respondent, who may not be aware of the specific tasks and working conditions of the case or control under study	Siemiatycki (1991)	Exposure to welding fumes Intensity of exposure (low, medium, high) Frequency of exposure (low, 1–5% of time; medium, 5–30%; high, > 30%)

Table 1.15 (continued)

Exposure assessment method	Description	Strengths	Limitations	Reference	Exposure metrics reported/notes
Self-report	Case–control study on uveal melanoma in the USA Telephone interview recording exposure to potential risk factors, including natural and artificial sources of UV, occurring at present or 15 yr before the interview	Sources of artificial and natural UV radiation assessed separately	No full job histories Exposure to welding arcs occurring 15 yr before interview Self-reported exposure susceptible to recall bias Exposure to UV radiation was not assessed specifically No information on duration or intensity of exposure or on eye protection worn	Seddon et al. (1990); Ajani et al. (1992)	Ever vs never exposure to welding arcs
Job title	Case–control study on intraocular melanoma in the USA Interviews were held (controls via telephone), collecting information on occupational history (six longest-held jobs), exposure to chemicals, and sun exposure ”Welders” included men who were exposed to welding for at least 3 h/wk for 6 mo or men who worked as welder or cutter, or those in proximity of welding	Including bystander exposure	Exposure to UV radiation was not assessed specifically Short intense exposures may have been missed due to criteria for “welder” Type of welder not taken into account No information on eye protection worn Unclear how workers “exposed to welding by proximity of working conditions” were identified	Holly et al. (1996)	Ever vs never welder Duration of employment (0, ≤ 1, 2–10, ≥ 11 yr)
Job title	Case–control study on intraocular melanoma. Telephone interview recording employment history.	Full job histories	Type of welder not taken into account. Exposure to UV radiation was not assessed specifically. No information on duration or intensity of exposure or eye protection worn.	Tucker et al. (1985)	Ever vs never welder

h, hour(s); ISCO, International Standard Classification of Occupations; JEM, job-exposure matrix; mo, month(s); UV, ultraviolet; vs, versus; wk, week(s); yr, year(s)

References

ACGIH (2013). Documentation on TLV: Ultraviolet radiation. Cincinnati (OH), USA: American Conference of Governmental Industrial Hygienists.

Ajani UA, Seddon JM, Hsieh CC, Egan KM, Albert DM, Gragoudas ES (1992). Occupation and risk of uveal melanoma. An exploratory study. *Cancer*, 70(12):2891–900. doi:10.1002/1097-0142(19921215)70:12<2891::AID-CNCR2820701228>3.0.CO;2-1 PMID:1451071

Akbar-Khanzadeh F (1993). Short-term respiratory function changes in relation to workshift welding fume exposures. *Int Arch Occup Environ Health*, 64(6):393–7. doi:10.1007/BF00517944 PMID:8458654

Åkesson B, Skerfving S (1985). Exposure in welding of high nickel alloy. *Int Arch Occup Environ Health*, 56(2):111–7. doi:10.1007/BF00379382 PMID:4055066

American Welding Society (2010). Standard welding terms and definitions including terms for adhesive bonding, brazing, soldering, thermal cutting, and thermal spraying. ANSI/AWS A3.0M/A3.0:2010. Miami (FL), USA: American Welding Society.

American Welding Society (2014). Safety and health fact sheet No. 26: Arc viewing distance. Available from: http://www.aws.org.

Angerer J, Amin W, Heinrich-Ramm R, Szadkowski D, Lehnert G (1987). Occupational chronic exposure to metals. I. Chromium exposure of stainless steel welders–biological monitoring. *Int Arch Occup Environ Health*, 59(5):503–12. doi:10.1007/BF00377845 PMID:3653996

Angerer J, Lehnert G (1990). Occupational chronic exposure to metals. II. Nickel exposure of stainless steel welders–biological monitoring. *Int Arch Occup Environ Health*, 62(1):7–10. doi:10.1007/BF00397842 PMID:2295525

Antonini JM (2003). Health effects of welding. *Crit Rev Toxicol*, 33(1):61–103. doi:10.1080/713611032 PMID:12585507

Australian Bureau of Statistics (2012). 3223 Structural steel and welding trades workers. Australian and New Zealand Standard Classification of Occupations, First Edition. Australian Workforce Development Agency. Canberra, Australia: Department of Industry, Innovation and Science. Available from: https://industry.gov.au/Office-of-the-Chief-Economist/SkilledOccupationList/Documents/2014SOLOccupationalSummarySheets/3223StructuralSteelandWeldingTradesWorkers.pdf, accessed May 2018.

Azari MR, Esmaeilzadeh M, Mehrabi Y, Salehpour S (2011). Monitoring of occupational exposure of mild steel welders to ozone and nitrogen oxides. *Tanaffos*, 10(4):54–9. PMID:25191389

Baker MG, Stover B, Simpson CD, Sheppard L, Seixas NS (2016). Using exposure windows to explore an elusive biomarker: blood manganese. *Int Arch Occup Environ Health*, 89(4):679–87. doi:10.1007/s00420-015-1105-3 PMID:26589320

Balkhyour MA, Goknil MK (2010). Total fume and metal concentrations during welding in selected factories in Jeddah, Saudi Arabia. *Int J Environ Res Public Health*, 7(7):2978–87. doi:10.3390/ijerph7072978 PMID:20717553

Benke G, Sim M, Forbes A, Salzberg M (1997). Retrospective assessment of occupational exposure to chemicals in community-based studies: validity and repeatability of industrial hygiene panel ratings. *Int J Epidemiol*, 26(3):635–42. doi:10.1093/ije/26.3.635 PMID:9222790

BG Regel (2006). Welding fumes. Federation of Institutions for Statutory Accident Insurance and Prevention. Available from: https://www.bghm.de/fileadmin/user_upload/Arbeitsschuetzer/Fachinformationen/Schweissen/BGR_220_englisch.pdf.

Bonde JP (1990). Semen quality and sex hormones among mild steel and stainless steel welders: a cross sectional study. *Br J Ind Med*, 47(8):508–14. PMID:2118383

Bringas JE (2004). Handbook of comparative world steel standards: Third edition. ASTM International. Available from: http://kmcenter.rid.go.th/kcresearch/MANUAL_OUT/MAEN0006.pdf.

Burgess WA (1995). Recognition of health hazards in industry: a review of materials and processes. New York (NY), USA: John Wiley and Sons.

CANJEM (2017). CANJEM Occupational Exposure Information System. Available from: www.canjem.ca.

Cary HB (1998). Modern welding technology, 4th ed. Upper Saddle River (NJ), USA: Prentice Hall.

Chang C, Demokritou P, Shafer M, Christiani D (2013). Physicochemical and toxicological characteristics of welding fume derived particles generated from real time welding processes. *Environ Sci Process Impacts*, 15(1):214–24. doi:10.1039/C2EM30505D PMID:24592438

Creely KS, Cowie H, Van Tongeren M, Kromhout H, Tickner J, Cherrie JW (2007). Trends in inhalation exposure–a review of the data in the published scientific literature. *Ann Occup Hyg*, 51(8):665–78. PMID:17932083

Dasdag S, Sert C, Akdag Z, Batun S (2002). Effects of extremely low frequency electromagnetic fields on hematologic and immunologic parameters in welders. *Arch Med Res*, 33(1):29–32. doi:10.1016/S0188-4409(01)00337-X PMID:11825628

Dryson EW, Rogers DA (1991). Exposure to fumes in typical New Zealand welding operations. *N Z Med J*, 104(918):365–7. PMID:1891137

ECRHS II (2017). European Community Respiratory Health Survey. Available from: http://www.ecrhs.org/.

Edmé JL, Shirali P, Mereau M, Sobaszek A, Boulenguez C, Diebold F, et al. (1997). Assessment of biological chromium among stainless steel and mild steel welders in relation to welding processes. *Int Arch Occup Environ Health*, 70(4):237–42. doi:10.1007/s004200050213 PMID:9342623

Ellingsen DG, Dubeikovskaya L, Dahl K, Chashchin M, Chashchin V, Zibarev E, et al. (2006). Air exposure assessment and biological monitoring of manganese and other major welding fume components in welders. *J Environ Monit*, 8(10):1078–86. doi:10.1039/b605549d PMID:17240914

Faggetter AK, Freeman VE, Hosein HR (1983). Novel engineering methods for ozone reduction in gas metal arc welding of aluminum. *Am Ind Hyg Assoc J*, 44(5):316–20. doi:10.1080/15298668391404897

Gäfvert T, Pagels J, Holm E (2003). Thorium exposure during tungsten inert gas welding with thoriated tungsten electrodes. *Radiat Prot Dosimetry*, 103(4):349–57. doi:10.1093/oxfordjournals.rpd.a006152 PMID:12797558

Garrod A, Ball E (2005). Welding fume – limit-less exposure? British Occupational Hygiene Society. *BOHS newsletter insert*, 20(2):1–2.

Gérin M, Fletcher AC, Gray C, Winkelmann R, Boffetta P, Simonato L (1993). Development and use of a welding process exposure matrix in a historical prospective study of lung cancer risk in European welders. *Int J Epidemiol*, 22(Suppl 2):S22–8. doi:10.1093/ije/22.Supplement_2.S22 PMID:8132388

Gerin M, Siemiatycki J, Richardson L, Pellerin J, Lakhani R, Dewar R (1984). Nickel and cancer associations from a multicancer occupation exposure case-referent study: preliminary findings. *IARC Sci Publ*, 53(53):105–15. PMID:6532976

GESTIS (2016). Welding fumes. GESTIS Substance Database. Sankt Augustin, Germany: IFA (Institut für Arbeitsschutz). Available from: http://www.dguv.de/ifa/gestis/gestis-stoffdatenbank/index-2.jsp, accessed 29 December 2016.

Golbabaei F, Hassani H, Ghahri A (2012). Risk assessment of exposure to gases released by welding processes in Iranian natural gas transmission pipelines industry. *IJOH*, 4(1):6–9.

Graczyk H, Lewinski N, Zhao J, Concha-Lozano N, Riediker M (2016). Characterization of tungsten inert gas (TIG) welding fume generated by apprentice welders. *Ann Occup Hyg*, 60(2):205–19. doi:10.1093/annhyg/mev074 PMID:26464505

Guénel P, Laforest L, Cyr D, Févotte J, Sabroe S, Dufour C, et al. (2001). Occupational risk factors, ultraviolet radiation, and ocular melanoma: a case-control study in France. *Cancer Causes Control*, 12(5):451–9. doi:10.1023/A:1011271420974 PMID:11545460

Gustavsson P, Jakobsson R, Johansson H, Lewin F, Norell S, Rutkvist LE (1998). Occupational exposures and squamous cell carcinoma of the oral cavity, pharynx, larynx, and oesophagus: a case-control study in Sweden. *Occup Environ Med*, 55(6):393–400. doi:10.1136/oem.55.6.393 PMID:9764099

Gustavsson P, Jakobsson R, Nyberg F, Pershagen G, Järup L, Schéele P (2000). Occupational exposure and lung cancer risk: a population-based case-referent study in Sweden. *Am J Epidemiol*, 152(1):32–40. doi:10.1093/aje/152.1.32 PMID:10901327

Håkansson N, Floderus B, Gustavsson P, Johansen C, Olsen JH (2002). Cancer incidence and magnetic field exposure in industries using resistance welding in Sweden. *Occup Environ Med*, 59(7):481–6. doi:10.1136/oem.59.7.481 PMID:12107298

Hansson Mild K, Alanko T, Decat G, Falsaperla R, Gryz K, Hietanen M, et al. (2009). Exposure of workers to electromagnetic fields. A review of open questions on exposure assessment techniques. *Int J Occup Saf Ergon*, 15(1):3–33. doi:10.1080/10803548.2009.11076785 PMID:19272237

Health and Safety Laboratory (2009). In visor testing. RR733 Research Report. Buxton, England: Health and Safety Laboratory, Health and Safety Executive.

Hedmer M, Karlsson J-E, Andersson U, Jacobsson H, Nielsen J, Tinnerberg H (2014). Exposure to respirable dust and manganese and prevalence of airways symptoms, among Swedish mild steel welders in the manufacturing industry. *Int Arch Occup Environ Health*, 87(6):623–34. doi:10.1007/s00420-013-0896-3 PMID:23979145

Hewett P (1995a). The particle size distribution, density, and specific surface area of welding fumes from SMAW and GMAW mild and stainless steel consumables. *Am Ind Hyg Assoc J*, 56(2):128–35. doi:10.1080/15428119591017150 PMID:7856513

Hewett P (1995b). Estimation of regional pulmonary deposition and exposure for fumes from SMAW and GMAW mild and stainless steel consumables. *Am Ind Hyg Assoc J*, 56(2):136–42. doi:10.1080/15428119591017169 PMID:7856514

Hobson A, Seixas N, Sterling D, Racette BA (2011). Estimation of particulate mass and manganese exposure levels among welders. *Ann Occup Hyg*, 55(1):113–25. doi:10.1093/annhyg/meq069 PMID:20870928

Holly EA, Aston DA, Ahn DK, Smith AH (1996). Intraocular melanoma linked to occupations and chemical exposures. *Epidemiology*, 7(1):55–61. doi:10.1097/00001648-199601000-00010 PMID:8664402

HSE (2017). Welding health and safety. UK: Health and Safety Executive. Available from: http://www.hse.gov.uk/welding/index.htm.

Hull CJ, Doyle E, Peters JM, Garabrant DH, Bernstein L, Preston-Martin S (1989). Case-control study of lung cancer in Los Angeles county welders. *Am J Ind Med*, 16(1):103–12. doi:10.1002/ajim.4700160111 PMID:2750746

IARC (1990). Chromium, nickel and welding. *IARC Monogr Eval Carcinog Risks Hum*, 49:1–648. Available from: http://publications.iarc.fr/67 PMID:2232124

ICNIRP (2007). Protecting workers from ultraviolet radiation. International Commission on Non-Ionizing Radiation Protection (ICNIRP) in collaboration with International Labour Organization and World Health Organization. ICNIRP 14/2007. Available from: http://www.who.int/uv/publications/Protecting_Workers_UV_pub.pdf?ua=1.

IEC (2013). IEC 61786-1:2013 Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 1: Requirements for measuring instruments. International Electrotechnical Commission. Available from: https://webstore.iec.ch/publication/5906.

ILO (2010). Evolution of the economically active population from 1950 to 1995 and forecasts for the year 2010. Geneva, Switzerland: International Labour Organization. Available from: http://www.ilo.org/global/statistics-and-databases/WCMS_087891/lang--en/index.htm.

International Commission on Non-Ionizing Radiation Protection (2004). Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation). *Health Phys*, 87(2):171–86. doi:10.1097/00004032-200408000-00006 PMID:15257218

ISO (2009). Welding and allied processes – nomenclature of processes and reference numbers. International Standard ISO 4063. Fourth edition. Geneva, Switzerland: International Organization for Standardization.

Janson C, Anto J, Burney P, Chinn S, de Marco R, Heinrich J, et al.; European Community Respiratory Health Survey II (2001). The European Community Respiratory Health Survey: what are the main results so far? European Community Respiratory Health Survey II. *Eur Respir J*, 18(3):598–611. doi:10.1183/09031936.01.00205801 PMID:11589359

Järvisalo J, Olkinuora M, Kiilunen M, Kivistö H, Ristola P, Tossavainen A, et al. (1992). Urinary and blood manganese in occupationally nonexposed populations and in manual metal arc welders of mild steel. *Int Arch Occup Environ Health*, 63(7):495–501. doi:10.1007/BF00572116 PMID:1577529

Jöckel KH, Ahrens W, Jahn I, Pohlabeln H, Bolm-Audorff U (1998a). Occupational risk factors for lung cancer: a case-control study in West Germany. *Int J Epidemiol*, 27(4):549–60. doi:10.1093/ije/27.4.549 PMID:9758106

Jöckel KH, Ahrens W, Pohlabeln H, Bolm-Audorff U, Müller KM (1998b). Lung cancer risk and welding: results from a case-control study in Germany. *Am J Ind Med*, 33(4):313–20. doi:10.1002/(SICI)1097-0274(199804)33:4<313::AID-AJIM1>3.0.CO;2-V PMID:9513638

Jones DRH, Ashby MF (2005). Engineering materials 2: an introduction to microstructures, processing and design. Oxford, England: Butterworth-Heinemann.

Karlsen JT, Torgrimsen T, Langård S (1994). Exposure to solid aerosols during regular MMA welding and grinding operations on stainless steel. *Am Ind Hyg Assoc J*, 55(12):1149–53. doi:10.1080/15428119491018222

Kendzia B, Behrens T, Jöckel K-H, Siemiatycki J, Kromhout H, Vermeulen R, et al. (2013). Welding and lung cancer in a pooled analysis of case-control studies. *Am J Epidemiol*, 178(10):1513–25. doi:10.1093/aje/kwt201 PMID:24052544

Kimlin MG, Tenkate TD (2007). Occupational exposure to ultraviolet radiation: the duality dilemma. *Rev Environ Health*, 22(1):1–37. doi:10.1515/REVEH.2007.22.1.1 PMID:17508696

Kjuus H, Skjaerven R, Langård S, Lien JT, Aamodt T (1986). A case-referent study of lung cancer, occupational exposures and smoking. I. Comparison of title-based and exposure-based occupational information. *Scand J Work Environ Health*, 12(3):193–202. doi:10.5271/sjweh.2158 PMID:3749833

Klein RM, Dahmen M, Mohlmann C, Schloms R, Zschiesche W (1998). Workplace exposure during laser machining. *J Laser Appl*, 10(3):99–105. doi:10.2351/1.521834

Knudsen LE, Boisen T, Christensen JM, Jelnes JE, Jensen GE, Jensen JC, et al. (1992). Biomonitoring of genotoxic exposure among stainless steel welders. *Mutat Res*, 279(2):129–43. doi:10.1016/0165-1218(92)90255-X PMID:1375338

Kogevinas M, 't Mannetje A, Cordier S, Ranft U, González CA, Vineis P, et al. (2003). Occupation and bladder cancer among men in Western Europe. *Cancer Causes Control*, 14(10):907–14. doi:10.1023/B:CACO.0000007962.19066.9c PMID:14750529

Kromhout H, Lillienberg L, Zock J-P, et al. (2004). Quantitative estimation of exposure to welding fumes in an international general population study on asthma *Eur Respir J*, 24(Suppl 48):Session 33.

Lavoue J, Labrèche F, Richardson L, Goldberg M, Parent M-É, Siemiatycki J (2014). 0382 CANJEM: a general population job exposure matrix based on past expert assessments of exposure to over 250 agents. *Occup Environ Med*, 71(Suppl 1):A48. doi:10.1136/oemed-2014-102362.149

Lehnert M, Pesch B, Lotz A, Pelzer J, Kendzia B, Gawrych K, et al.; Weldox Study Group (2012). Exposure to inhalable, respirable, and ultrafine particles in welding fume. *Ann Occup Hyg*, 56(5):557–67. PMID:22539559

Lehnert M, Weiss T, Pesch B, Lotz A, Zilch-Schöneweis S, Heinze E, et al.; WELDOX Study Group (2014). Reduction in welding fume and metal exposure of stainless steel welders: an example from the WELDOX study. *Int Arch Occup Environ Health*, 87(5):483–92. PMID:23719851

Lidén G, Surakka J (2009). A headset-mounted mini sampler for measuring exposure to welding aerosol in the breathing zone. *Ann Occup Hyg*, 53(2):99–116. PMID:19196747

Lillienberg L, Zock JP, Kromhout H, Plana E, Jarvis D, Torén K, et al. (2008). A population-based study on welding exposures at work and respiratory symptoms. *Ann Occup Hyg*, 52(2):107–15. doi:10.1093/annhyg/mem063 PMID:18216372

Liu S, Hammond SK, Rappaport SM (2011). Statistical modeling to determine sources of variability in exposures to welding fumes. *Ann Occup Hyg*, 55(3):305–18. PMID:21355083

Ludwig T, Schwass D, Seitz G, Siekmann H (1999). Intakes of thorium while using thoriated tungsten electrodes for TIG welding. *Health Phys*, 77(4):462–9. doi:10.1097/00004032-199910000-00015 PMID:10492354

Lutz JM, Cree I, Sabroe S, Kvist TK, Clausen LB, Afonso N, et al. (2005). Occupational risks for uveal melanoma results from a case-control study in nine European countries. *Cancer Causes Control*, 16(4):437–47. doi:10.1007/s10552-004-5029-6 PMID:15953986

MacLeod JS, Harris MA, Tjepkema M, Peters PA, Demers PA (2017). Cancer risks among welders and occasional welders in a national population-based cohort study: Canadian Census Health and Environmental Cohort. *Saf Health Work*, 8(3):258–66. doi:10.1016/j.shaw.2016.12.001 PMID:28951802

Matczak W, Chmielnicka J (1993). Relation between various chromium compounds and some other elements in fumes from manual metal arc stainless steel welding. *Br J Ind Med*, 50(3):244–51. PMID:8457491

Matczak W, Gromiec J (2002). Evaluation of occupational exposure to toxic metals released in the process of aluminum welding. *Appl Occup Environ Hyg*, 17(4):296–303. doi:10.1080/10473220252826600 PMID:11942673

Matrat M, Guida F, Mattei F, Cénée S, Cyr D, Févotte J, et al.; Icare Study Group (2016). Welding, a risk factor of lung cancer: the ICARE study. *Occup Environ Med*, 73(4):254–61. doi:10.1136/oemed-2015-102964 PMID:26865654

Meguellati-Hakkas D, Cyr D, Stücker I, Févotte J, Pilorget C, Luce D, et al. (2006). Lung cancer mortality and occupational exposure to asbestos among telephone linemen: a historical cohort study in France. *J Occup Environ Med*, 48(11):1166–72. doi:10.1097/01.jom.0000243357.70143.47 PMID:17099453

Minnesota Population Center (2015). Integrated Public Use Microdata Series, International: Version 6.4. [dataset]. Minneapolis, USA: University of Minnesota; doi:10.18128/D020.V6.4

Moniz BJ, Miller RT (2010). Welding skills. Orland Park (IL), USA: American Technical Publishers.

Nakashima H, Utsunomiya A, Fujii N, Okuno T (2016). Hazard of ultraviolet radiation emitted in gas tungsten arc welding of aluminum alloys. *Ind Health*, 54(2):149–56. doi:10.2486/indhealth.2015-0141 PMID:26632121

NIOSH (1996). EMFs in the workplace. DHHS (NIOSH) Publication Number 96-129. Atlanta (GA), USA: National Institute for Occupational Safety and Health. Available from: https://www.cdc.gov/niosh/docs/96-129/, accessed 16 January 2017.

Okuno T, Ojima J, Saito H (2001). Ultraviolet radiation emitted by CO(2) arc welding. *Ann Occup Hyg*, 45(7):597–601. doi:10.1016/S0003-4878(01)00023-0 PMID:11583661

OSHA (2013). Controlling hazardous fume and gases during welding. [cited 2016 May 5]. Washington (DC), USA: Occupational Safety and Health Administration. Available from: https://www.osha.gov/Publications/OSHA_FS-3647_Welding.pdf.

Outokumpu (2013). Handbook of stainless steel. Espoo, Finland: Outokumpu Oyi. Available from: http://www.outokumpu.com/sitecollectiondocuments/outokumpu-stainless-steel-handbook.pdf.

Peng CY, Liu HH, Chang CP, Shieh JY, Lan CH (2007). Evaluation and monitoring of UVR in shield metal arc welding processing. *Health Phys*, 93(2):101–8. doi:10.1097/01.HP.0000259903.64054.84 PMID:17622813

Persoons R, Arnoux D, Monssu T, Culié O, Roche G, Duffaud B, et al. (2014). Determinants of occupational exposure to metals by gas metal arc welding and risk management measures: a biomonitoring study. *Toxicol Lett*, 231(2):135–41. doi:10.1016/j.toxlet.2014.09.008 PMID:25223250

Pesch B, Haerting J, Ranft U, Klimpel A, Oelschlägel B, Schill W (2000). Occupational risk factors for renal cell carcinoma: agent-specific results from a case-control study in Germany. MURC Study Group. Multicenter urothelial and renal cancer study. *Int J Epidemiol*, 29(6):1014–24. doi:10.1093/ije/29.6.1014 PMID:11101542

Pukkala E, Martinsen JI, Lynge E, Gunnarsdottir HK, Sparén P, Tryggvadottir L, et al. (2009). Occupation and cancer - follow-up of 15 million people in five Nordic countries. *Acta Oncol*, 48(5):646–790. doi:10.1080/02841860902913546 PMID:19925375

Reulen RC, Kellen E, Buntinx F, Brinkman M, Zeegers MP (2008). A meta-analysis on the association between bladder cancer and occupation. *Scand J Urol Nephrol Suppl*, 42(218):64–78. doi:10.1080/03008880802325192 PMID:18815919

Saito H, Hisanaga N, Okada Y, Hirai S, Arito H (2003). Thorium-232 exposure during tungsten inert gas arc welding and electrode sharpening. *Ind Health*, 41(3):273–8. doi:10.2486/indhealth.41.273 PMID:12916759

Scheepers PT, Heussen GA, Peer PG, Verbist K, Anzion R, Willems J (2008). Characterisation of exposure to total and hexavalent chromium of welders using biological monitoring. *Toxicol Lett*, 178(3):185–90. doi:10.1016/j.toxlet.2008.03.013 PMID:18455331

Schoenberg JB, Stemhagen A, Mason TJ, Patterson J, Bill J, Altman R (1987). Occupation and lung cancer risk among New Jersey white males. *J Natl Cancer Inst*, 79(1):13–21. PMID:3474440

Schoonover T, Conroy L, Lacey S, Plavka J (2011). Personal exposure to metal fume, NO2, and O3 among production welders and non-welders. *Ind Health*, 49(1):63–72. doi:10.2486/indhealth.MS1150 PMID:20823632

Seddon JM, Gragoudas ES, Glynn RJ, Egan KM, Albert DM, Blitzer PH (1990). Host factors, UV radiation, and risk of uveal melanoma. A case-control study. *Arch Ophthalmol*, 108(9):1274–80. doi:10.1001/archopht.1990.01070110090031 PMID:2400347

Seel EA, Zaebst DD, Hein MJ, Liu J, Nowlin SJ, Chen P (2007). Inter-rater agreement for a retrospective exposure assessment of asbestos, chromium, nickel and welding fumes in a study of lung cancer and ionizing radiation. *Ann Occup Hyg*, 51(7):601–10. doi:10.1093/annhyg/mem037 PMID:17846032

Siemiatycki J (1991). Risk factors for cancer in the workplace. Boca Raton (FL): CRC Press.

Siew SS, Kauppinen T, Kyyrönen P, Heikkilä P, Pukkala E (2008). Exposure to iron and welding fumes and the risk of lung cancer. *Scand J Work Environ Health*, 34(6):444–50. doi:10.5271/sjweh.1296 PMID:19137206

Simmelink VI (1996). Welding in the Netherlands: sectors and job profiles. [Dutch]. Amsterdam, Netherlands: DIJK 12 Beleidsonderzoek.

Simonato L, Fletcher AC, Andersen A, Anderson K, Becker N, Chang-Claude J, et al. (1991). A historical prospective study of European stainless steel, mild steel, and shipyard welders. *Br J Ind Med*, 48(3):145–54. PMID:2015204

Skotte JH, Hjøllund HI (1997). Exposure of welders and other metal workers to ELF magnetic fields. *Bioelectromagnetics*, 18(7):470–7. doi:10.1002/(SICI)1521-186X(1997)18:7<470::AID-BEM2>3.0.CO;2-# PMID:9338628

Sørensen AR, Thulstrup AM, Hansen J, Ramlau-Hansen CH, Meersohn A, Skytthe A, et al. (2007). Risk of lung cancer according to mild steel and stainless steel welding. *Scand J Work Environ Health*, 33(5):379–86. doi:10.5271/sjweh.1157 PMID:17973064

Spiegel-Ciobanu VE (2010). Welding fume - risk assessment and preventive measures. Proceedings of the 4th International Conference on Innovative Technologies for Joining Advanced Materials, Timişoara, Romania, 10–11 June 2010. Available from: https://www.tib.eu/en/search/id/TIBKAT%3A736729607/Proceedings-The-4th-International-Conference-Innovative/.

Stern RM (1987). Cancer incidence among welders: possible effects of exposure to extremely low frequency electromagnetic radiation (ELF) and to welding fumes. *Environ Health Perspect*, 76:221–9. doi:10.1289/ehp.8776221 PMID:3447902

Stridsklev IC, Schaller K-H, Langård S (2004). Monitoring of chromium and nickel in biological fluids of stainless steel welders using the flux-cored-wire (FCW) welding method. *Int Arch Occup Environ Health*, 77(8):587–91. doi:10.1007/s00420-004-0560-z PMID:15538617

Suarthana E, Debia M, Burstyn I, Kromhout H (2014). Do existing empirical models for welding fumes estimate exposure to ultrafine particles among canadian welding apprentices? *J Occup Environ Med*, 56(4):e9–11. doi:10.1097/JOM.0000000000000134 PMID:24709774

’t Mannetje A, Brennan P, Zaridze D, Szeszenia-Dabrowska N, Rudnai P, Lissowska J, et al. (2012). Welding and lung cancer in Central and Eastern Europe and the United Kingdom. *Am J Epidemiol*, 175(7):706–14. doi:10.1093/aje/kwr358 PMID:22343633

’t Mannetje A, De Roos AJ, Boffetta P, Vermeulen R, Benke G, Fritschi L, et al. (2016). Occupation and risk of non-Hodgkin lymphoma and its subtypes: a pooled analysis from the InterLymph Consortium. *Environ Health Perspect*, 124(4):396–405. PMID:26340796

Tenkate T (2008). Welding arc time and UV exposure: implications for worker safety. *J Occup Health Saf Aust NZ*, 24:161–6.

Tenkate TSD, Collins MJ (1997). Angles of entry of ultraviolet radiation into welding helmets. *Am Ind Hyg Assoc J*, 58(1):54–6. doi:10.1080/15428119791013099 PMID:9018838

Tucker MA, Shields JA, Hartge P, Augsburger J, Hoover RN, Fraumeni JF Jr (1985). Sunlight exposure as risk factor for intraocular malignant melanoma. *N Engl J Med*, 313(13):789–92. doi:10.1056/NEJM198509263131305 PMID:4033707

Vajdic CM, Kricker A, Giblin M, McKenzie J, Aitken JF, Giles GG, et al. (2004). Artificial ultraviolet radiation and ocular melanoma in Australia. *Int J Cancer*, 112(5):896–900. doi:10.1002/ijc.20476 PMID:15386378

Vallières E, Pintos J, Lavoué J, Parent MÉ, Rachet B, Siemiatycki J (2012). Exposure to welding fumes increases lung cancer risk among light smokers but not among heavy smokers: evidence from two case-control studies in Montreal. *Cancer Med*, 1(1):47–58. doi:10.1002/cam4.6 PMID:23342253

van Loon AJ, Kant IJ, Swaen GM, Goldbohm RA, Kremer AM, van den Brandt PA (1997). Occupational exposure to carcinogens and risk of lung cancer: results from The Netherlands cohort study. *Occup Environ*

Med, 54(11):817–24. doi:10.1136/oem.54.11.817 PMID:9538355

Vecchia P, Hietanen M, Stuck BE, Van Deventer E, Niu S (2007). Protecting workers from ultraviolet radiation. Available from: http://www.who.int/uv/publications/Protecting_Workers_UV_pub.pdf?ua=1.

Verhoeven JD (2007). Steel metallurgy for the non-metallurgist. Ohio, USA: ASM International.

Von Hofe (2009). Determination of the number of people employed in welding technology in Europe. German Welding Society (DSV). DSV Working Group, Economics, N40, Rev. 3E.

Wallace M, Shulman S, Sheehy J (2001). Comparing exposure levels by type of welding operation and evaluating the effectiveness of fume extraction guns. *Appl Occup Environ Hyg*, 16(8):771–9. doi:10.1080/10473220117155 PMID:11504352

Warner C (2014). Lung bioaccessibility of manganese in arc welding fume. University of Washington, USA. [Master of Science thesis].

Weiss T, Pesch B, Lotz A, Gutwinski E, Van Gelder R, Punkenburg E, et al.; WELDOX Group (2013). Levels and predictors of airborne and internal exposure to chromium and nickel among welders–results of the WELDOX study. *Int J Hyg Environ Health*, 216(2):175–83. doi:10.1016/j.ijheh.2012.07.003 PMID:22926021

Weman K (2003). Welding processes handbook. Boca Raton (FL), USA: CRC Press.

Weman K, Lindén G, editors. (2006). MIG welding guide. Sawston, Cambridge: Woodhead Publishing.

Wolska A (2013). [Occupational exposure of welders to ultraviolet and “blue light” radiation emitted during TIG and MMA welding based on field measurements.] *Med Pr*, 64(1):69–82. [Polish] PMID:23650770

Woskie SR, Kalil A, Bello D, Virji MA (2002). Exposures to quartz, diesel, dust, and welding fumes during heavy and highway construction. *AIHA J (Fairfax, Va)*, 63(4):447–57. doi:10.1080/15428110208984733 PMID:12486778

Yiin JH, Schubauer-Berigan MK, Silver SR, Daniels RD, Kinnes GM, Zaebst DD, et al. (2005). Risk of lung cancer and leukemia from exposure to ionizing radiation and potential confounders among workers at the Portsmouth Naval Shipyard. *Radiat Res*, 163(6):603–13. doi:10.1667/RR3373 PMID:15913392

Yiin JH, Silver SR, Daniels RD, Zaebst DD, Seel EA, Kubale TL (2007). A nested case-control study of lung cancer risk and ionizing radiation exposure at the portsmouth naval shipyard. *Radiat Res*, 168(3):341–8. doi:10.1667/RR0843.1 PMID:17705634

Zeng F, Lerro C, Lavoué J, Huang H, Siemiatycki J, Zhao N, et al. (2017). Occupational exposure to pesticides and other biocides and risk of thyroid cancer. *Occup Environ Med*, 74(7):502–10. doi:10.1136/oemed-2016-103931 PMID:28202579