ECHA Scoping Study report

for evaluation of limit values for welding fumes and fumes from other processes that generate fume in a similar way at the workplace

Prepared by the European Chemicals Agency

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List of abbreviations

Abbreviation	Definition
AC	Alternating current
ACGIH	American Conference of Governmental Industrial Hygienists, U.S.
AGS	Ausschuss für GefahrStoffe (German Committee on Hazardous Substances)
AM	Additive manufacturing
ANSES	Agence Nationale de Securité Sanitaire de l'alimentation, de l'environnement et du travail (French Agency for Food, Environmental and Occupational Health & Safety)
BAL	Biological Action Levels (for occupational exposure)
BAR	Background level of a substance which is present concurrently at a particular time in a reference population of persons of working age who are not occupationally exposed to this substance.
BAT	Biologische Arbeitsplatztoleranzwert (German biological tolerance value for occupational exposure)
BAuA	Bundesanstalt für Arbeitsschutz und Arbeitsmedizin ("German Federal Institute for Occupational Safety and Health")
BLV	Biological Limit Value
BOEL(s)	Binding Occupational Exposure Limit(s)
CAD	Chemical Agents Directive 98/24/EC
CI	Confidence Interval
CLP	Regulation (EC) No 1272/2008 on Classification, Labelling and Packaging of substances and mixtures (CLP Regulation)
CMD / CMRD	Carcinogens and Mutagens Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work The amendment of the CMD, the Directive 2022/431/EU also brought reprotoxic substances within the scope of the directive, changing the original title on the protection of workers from the risks related to exposure to carcinogens or mutagens at work to the protection of workers from the risks related to exposure to carcinogens, mutagens or reprotoxic substances at work (CMRD).
CMR	Carcinogens, mutagens or substances toxic to reproduction
CNC	Computer numerical control
COPD	Chronic obstructive pulmonary disease
DC	Direct current
DFG	Deutsche ForschungsGemeinschaft (German Research Foundation)
DIN	Deutsches Institut für Normalisierung (German Institute for Standardisation)
EB	Electron beam
EC	European Commission
ECHA	European Chemicals Agency
EKA	Expositionsäquivalente für Krebserzeugende Arbeitsstoffe (Exposure equivalence for carcinogenic substances)
EN	European standard
ERR	Exposure-risk relationship
ESW	Electro-Slag Welding
EU	European Union
FCAW	Flux Cored Arc Welding
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding

Abbreviation	Definition
HI	Hazard Index
HRR	Hazard Rate Ratio
HSE	Health and Safety Executive
HVAC	Heating, ventilation and air conditioning
HVAF	High Velocity Air Fuel spraying
HV-Arc	High Velocity Arc Spraying
HVOF	High Velocity Oxy-gas Fuel spraying
IARC	International Agency for Research on Cancer, World Health Organization
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrometry
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
INRS	Institut National de Recherche et de Sécurité (Reference body for occupational risk prevention in France)
IOELV(s)	Indicative Occupational Exposure Limit Value(s)
ISO	International Organization for Standardization
JEM	Job Exposure Matrix
LOD	Limit of detection
LOQ	Limit of quantification
MAG	Metal Active Gas
MDHS	Methods for the Determination of Hazardous Substances, Health and Safety Laboratory
MIG	Metal Inert Gas
MMA/MMAW	Manual Metal Arc Welding
mRR	Meta Relative Risk
MS	Member State
NIOSH	National Institute for Occupational Safety and Health (USA)
OEL(s)	Occupational exposure limit(s)
OR	Odds ratio
OSHA	Occupational Safety and Health Administration (USA)
PAW	Plasma Arc Welding
PCBs	Printed circuit boards
PPE	Personal protective equipment
PSD	Particle size distribution
PSLT	Poorly Soluble Low Toxicity (particles)
PTA	Powder plasma transferred arc
RAC	Committee for Risk Assessment
RADS	Reactive airways dysfunction syndrome
REACH	Regulation (EC) No 1907/2006 of the European Union concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals
SAW	Submerged Arc Welding
SLA	Service Level Agreement
SLIC	Senior Labour Inspectors' Committee established by DG Employment, Social Affairs and Inclusion
SMAW	Shielded Metal Arc Welding
SW	Arc Stud Welding
TIG	Tungsten Inert Gas Welding
TLV	Threshold Limit Value
TRGS	Technische Regeln für GefahrStoffe (German Technical regulations for hazardous substances)

Abbreviation	Definition
TWA	Time-Weighted-Average
UBM	Under bump metallization
U.S./USA	United States of America
UV	Ultraviolet
VBR	Valeur biologique de référence (Biological reference value)
VIS	Visible absorption spectrophotometry
VLB	Valeur Limite Biologique (Biological limit value)
WG	Working group
WPC	Working Party on Chemicals of the Advisory Committee on Health and Safety at Work
WSP	Water stabilized plasma spraying

Executive summary

Welding and other processes that generate fume in a similar way

Welding is a broad term for the process of joining metals through coalescence. This coalescence is achieved by applying heat (energy) to melt the base metal pieces and fusing them together to form a secure joint. A filler material (also containing metals) is typically added to the joint during welding to form a pool of molten material, that cools to form a joint that is usually stronger than the base material. Welding techniques can then be broadly classified in terms of how the heat/energy is applied: gas welding (using fuel gases), arc welding (using electricity) or beam welding (using laser/electron beams).

Other processes that generate fume in a similar way include soldering (uses lower temperatures, where only the filler melts), thermal cutting or gouging (melting to cut a shape), thermal spraying (melting to deposit a coating), flame straightening (heating not necessarily melting, to remove distortions). Additionally additive manufacturing has been considered in this report due to the metal melting-joining on cooling aspect. However this occurs in an inert atmosphere inside a machine where no exposure to workers can occur.

Composition of fumes and exposure

When heat is applied, the metals (in the base and filler materials) are vapourised and their vapours rapidly condense into very fine particles. This particulate matter is the fume and consists of the metals and their oxides, including spinels (complex structures of metals with different valences with oxygen, silicon and/or fluorine which are present in the fillers). The metals in the fume are diverse, depending on the base and filler materials.

In terms of measuring welding fume exposure different strategies can be followed: the total amount of fumes can be measured as well as the individual components of the fumes (metal or metal compounds). The limits of detection that can be achieved are much lower for the measurement of the individual metals (and metals compounds) than for the determination of the total amount of fumes. The gases generated during the welding can also be measured independently.

Some misconceptions exist about the content/composition of welding fumes. They are often described simply as metals and their oxides, but in reality the fume particulates are complex structures (spinels) with other substances present in the fillers. The interaction between these spinels can also be complex and difficult to predict as they can inhibit each other’s effect or have synergistic effects.

The different welding processes (and other processes that generate fume in a similar way), the substances generated, an indication of whether or not CMRs are present, and the potential for worker exposure are summarised in the table below.

Summary of welding processes+, generated substances, indication of CMRs and worker exposure – see Table 3

		Hazardous substances generated	CMRs (1A/1B) or not	Presence of the hazardous substances is known/proven, possible or exceptional	Workers are likely to be exposed or not
1	**Fusion welding**				
	Gas welding	Metal oxides from the base and filler materials, nitrogen oxides	Yes, depending on the base and filler materials	Base and filler materials: mild steel (Fe, Mn), copper alloys (Cu, Ni, Zn), aluminium (fluorides from the flux)	Yes, usually manual process, but low particle emissions.
	Arc welding - consumable electrode (filler) (MIG, MAG, SMAW, FCAW, SAW, ESW, SW)	Metal oxides mostly from the filler material, nitrogen oxides, carbon monoxide (MAG), ozone (aluminium alloys)	Yes, depending on the filler material, carbon monoxide (MAG)	Base and filler materials: mild steel (Fe, Mn, fluorides), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V, fluorides), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu)	Yes, mainly in the craft sector. Automated processes are often used in industrial applications.
	Arc welding - non-consumable electrode (TIG; PAW)	Metal oxides mostly from the filler material, ozone	Yes, depending on the filler material	Base and filler materials: mild steel (Fe, Mn), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu), titanium alloys (Ti, Al, V), zirconium alloys (Zr)	Yes, mainly in the craft sector. Automated processes are often used in industrial applications.
	Beam welding	Metal oxides from the base material	Yes, depending on the base material	Base materials: mild steel (Fe, Mn), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu), titanium alloys (Ti, Al, V), zirconium alloys (Zr)	Not directly as almost completely automated. However, fume extraction system required to protect workers in the vicinity.

		Hazardous substances generated	CMRs (1A/1B) or not	Presence of the hazardous substances is known/proven, possible or exceptional	Workers are likely to be exposed or not
2	**Soldering**				
	Soft soldering (90°C- 450°C)	Mainly tin and tin oxides (from filler material), aldehydes (from rosin) and hydrogen chloride, evaporating solvents (isopropanol) from fluxes.	No, as long as lead-free due to restriction	Filler materials: mainly tin-based solders (e.g. Sn99Cu1 or Sn95Ag4Cu1) Fluxes: natural resins (e.g. rosin), organic acids (e.g. adipic acid) and chlorides (e.g. zinc chloride or ammonium chloride)	Yes, in the craft sector. Automated processes are often used in industrial applications.
	Hard (silver) soldering (> 450°C, flame brazing)	Copper oxide, zinc oxide, silver oxide, chlorides and fluorides (hydrogen chloride and hydrogen fluoride)	No	Filler materials: brazing solders made of copper-zinc alloys with additives of silver	Yes, in the craft sector. Automated processes are often used in industrial applications.
	Brazing (> 450°C, Laser beam brazing, Brazing with an electric arc (MIG, TIG, plasma)	Copper oxide Exceptionally cadmium oxide	No, with specific exceptions	Filler materials: copper-based alloys (e.g. CuSi3, CuAl8 or CuSn6) Exceptionally in defence and aerospace applications and when used for safety reasons (brazing fillers with cadmium)	Yes, in the craft sector. Automated processes are often used in industrial applications.
3	**Thermal cutting or gouging**	Metal oxides from the base material, nitrogen oxides, ozone	Yes, depending on base materials (e.g. Cr(VI) and Ni)	Base materials: mild steel (Fe, Mn), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu), titanium alloys (Ti, Al, V), zirconium alloys (Zr)	Yes, in the craft sector. Automated processes are often used in industrial applications.
4	**Thermal spraying**	Metal oxides from the spray additive, nitrogen oxides	Yes, depending on the spray additives (e.g. Cr(VI), Ni, Co)	Spray additives: boron, cobalt, molybdenum, nickel, chromium, silicon, plastics,	Yes, in the craft sector. For large components open

		Hazardous substances generated	CMRs (1A/1B) or not	Presence of the hazardous substances is known/proven, possible or exceptional	Workers are likely to be exposed or not
		(depending on energy source)		copper, carbides (WC-12Co, WC-27NiCr, WC-14CoCr, WC/Ti-C-17-Ni, Cr_3C_2-25NiCr etc.), steel, aluminium, zinc, bronze (Cu, Sn), tin, Monel (Ni, Cu, Fe), oxide ceramics (Al_2O_3, Cr_2O_3, TiO_2, Y_2O_3, ZrO_2), tantalum	spraying, for small components in spray booths. Automated processes are often used in industrial applications.
5	**Flame straightening**	Nitrogen oxides	No	Nitrogen oxides occur	Yes, usually manual process.
6	**Additive production processes**	Metal powders	No, the substrates do not contain carcinogenic substances. Carcinogenic substances can be formed in the closed installation space (e.g. nickel oxide).	Metal powders, especially iron, titanium, nickel, chromium and aluminium alloys	No, construction occurs inside closed machines.

Health effects

Due to the complex nature of the welding fumes and the sites of deposition of the inhaled particles in the respiratory tract, as well as the clearance mechanisms in the lungs, the potential health effects are diverse, but can be summarised in the following way:

- acute (short-term) health effects: due to irritation caused by the gases or exposure to the fume containing certain metals (zinc or copper), leading to conditions like asthma or pneumonia
- chronic (long-term) health effects: lung cancer is the main issue, caused by chromium VI compounds or nickel oxides (present in certain steels), but also COPD, occupational asthma and welder's lung
- other health effects: mainly neurological caused by the presence of manganese (in certain steels)

Classification of fumes and components

As welding fumes are process-generated, complex and have variable compositions, welding fumes as such do not have a harmonised classification and labelling for carcinogenic or other hazards under the CLP Regulation. Some of the metals involved (such as chromium or nickel in steels) may be classified as carcinogenic under the CLP regulation, and their exposure needs to be controlled under the carcinogens, mutagens and reprotoxic substances directive (CMRD). Other metals (such as aluminium and copper) do not have such hazard classifications, but exposure still needs to be controlled under the Chemical Agents Directive (CAD). Employers are required to minimise exposures following the STOP (or hierarchy of control principles), but since it remains a prominent concern that welders are at high risk from various diseases, including cancers, more needs to be done to ensure that the needed measures to minimise exposure are in place.

The carcinogenicity of welding fumes has recently been evaluated by IARC (2018), who considered *welding fumes* as carcinogenic to humans (Group 1). It is noted that IARC concluded on *welding fumes* overall without specifying for which type of welding or for which base metal welded the conclusions apply.

In the context of this scoping study, the study descriptions by IARC for the studies assessed in that evaluation were scrutinised in order to assess what types of welding or welding fumes were covered. The human cancer studies evaluated by IARC cover welders predominantly or exclusively exposed in steel welding and the animal studies cover exclusively (stainless) steel welding fumes. Solderers as a specific occupation were explicitly excluded from the human studies evaluated by IARC and additive processes as 3D printing are not mentioned by the IARC assessment.

The lung cancer risk estimates vary quite widely in the epidemiological studies assessed by IARC. However, IARC did not perform a meta-analysis to combine these risk estimates to a meta-relative risk estimate (mRR) that would overcome the statistical variation in the individual studies. Nor did IARC assess potential variation of risk between types of welding. However, parallel to the IARC evaluation such a meta-analysis was performed and published separately (Honaryar et al. 2019). The metaRR estimate for lung cancer for 'ever' compared with 'never' being a welder or exposed to welding fumes was 1.43 (95% CI 1.31 – 1.55). The mRR estimate was reduced to 1.17 (95% CI 1.04 – 1.38) for studies that adjusted for smoking and asbestos exposure simultaneously. Mild steel welders had approximately the same magnitude of lung cancer risk as stainless-steel welders.
In another meta-analysis (Ambroise et al. 2006), the risk increased by number of years in welding from 1.14 for 1-3 years to 1.77 for > 25 years. Similar to IARC (2018) assessment, these meta-analyses did not cover soldering, brazing or additive processes

like 3D printing. Nor did they report estimates for welding according to any other base metal than mild steel or stainless steel.

Proposed approaches for setting an OEL and other limit values

The European Commission (COM) requested ECHA to evaluate, in accordance with the CMD (later CMRD), "welding fumes+": to assess and define the scope of these process-generated substances of mixed and varying composition to allow for a description of the relevant processes, or sub-processes, to be included in Annex I of CMRD to ensure legal certainty of inclusion within the scope of the directive.

A proposal for entry into Annex I of CMRD brings some prominence to this issue, that welding is an activity/ process that merits specific attention by employers, and brings clarity with regard to their duties. The entry itself must be in simple and clear language, and any additional information should be provided in another way, than in the entry itself. A number of proposals for wording are suggested in Section 10.

A further consideration is that currently there are no metals that are harmonised classified as mutagenic or reprotoxic category 1A or 1B that are not also carcinogenic 1A/B. Some of the metals involved are suspected reprotoxic (e.g. solders (fillers) containing antimony, silver, or brass (zinc oxide)), but without a harmonised classification. If in the future these metals have an harmonised classification as reprotoxic category 1A/B, then it would have to be considered how they could be covered by this entry as Annex I of CMRD is for carcinogenic substances.

In addition a number of different approaches for controlling exposure have been explored:

1. Set a generic occupational exposure limit (OEL) for inhalable and respirable dust;
2. Existing specific OELs could be complemented with a generic dust metric (an inhalable limit and a respirable limit) as described in point 1;
3. Monitoring only those welding-related specific substances that are established carcinogens, i.e. to apply a BOEL for each of them under CMRD (narrow approach);
4. Consider mandatory protective/control measures (e.g. enclosures, source extraction) on those welding techniques that lead to greater emissions of welding fumes , or to promote substitution to low-emission processes;
5. Implement Health Surveillance Programmes for welders under certain conditions. This could be done in addition to any other option.

The pros and cons of each approach have been described in Section 10 of the report. For the first three approaches setting any kind of threshold value is complicated as the processes involved are many and varied, and the substances generated are diverse and complex.

For the majority of metals involved, there is already a limit value in Annex III of the CMRD which could be used. These values are significantly lower than any threshold value that could be set for inhalable and respirable dust. Any remaining metals (not in Annex III of the CMRD) that welders could be exposed to and that are classified as CMR, should be prioritised for an entry into Annex III.

The fourth and fifth options could be considered as complementary to any threshold approach, firstly to minimise exposure (according to the STOP principle). The health surveillance seems to be a clear need as welding is associated with increased lung cancer risk (although not as high as some other risk occupations, e.g. workers with past exposure to asbestos) and an increased risk of several non-cancer health effects.

1. Introduction

1.1 COM request

The Commission (COM), in view of the preparation of the proposals for amendment of Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work (CMD) and in line with the 2017 Commission Communication '*Safer and Healthier Work for All' - Modernisation of the EU Occupational Safety and Health Legislation and Policy*[1], asked the advice of ECHA to make a scoping study of Welding fumes and fumes generated from other processes such as plasma cutting and air carbon arc gouging in a way that is similar to welding (hereafter referred to as "welding fumes+").

Therefore, in accordance with the Service Level Agreement (SLA) (Ares(2019)18725), the Commission requested ECHA on 11 December 2020, to evaluate, in accordance with the CMD, welding fumes+, to assess and define the scope of these process-generated substances of mixed and varying composition to allow for a description of the relevant processes, or sub-processes, to be included in Annex I of CMD to ensure legal certainty of inclusion within the scope of the directive.

If appropriate, this should be complemented by information identifying substance(s), which could be used as potential marker(s) for monitoring exposure to welding fumes+.

In answer to the Commission's request, ECHA has prepared a scoping study report. This scoping study identifies the extent, range and nature of the key processes, and the substances involved, that lead to the exposure of workers from welding fumes+, to determine the value of setting an occupational exposure limit. Therefore it does not go into the level of detail on the hazard and toxicological parts that is standard when undertaking a full study and deriving an OEL.

Note, in March 2022 the CMD was amended to include reprotoxic substances within its scope. Therefore, any future amendments will be to the CMRD[2,3].

1.2 Literature search & data collection

In the preparatory phase of making this report, a call for evidence started on 5 July 2021 and invited interested parties to submit comments and evidence by 3 September 2021.

This report is also supported by a literature search of published papers from the last ten years.

1.3 Steps in preparing the scoping study report

The scoping study report will be presented and discussed with Advisory Committee on Safety and Health, via its Working Party on Chemicals (WPC) during its preparation. Following final agreement of the report with the WPC, it will be published on the ECHA website.

2. Identification of substance(s)

A major challenge for this study is the fact that not all welding fumes are the same.
The diversity is an outcome of the wide variety of base metals and filler material (metal alloys) being welded and the application of different welding processes, some of which use fluxing agents and some of which do not. Gases are also used (e.g. shielding gas) during

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[1] http://ec.europa.eu/social/main.jsp?langId=en&catId=148&newsId=2709&furtherNews=yes
[2] EUR-Lex - 32022L0431 - EN - EUR-Lex (europa.eu) amending directive
[3] EUR-Lex - 32022L0431 - EN - EUR-Lex (europa.eu) codified (consolidated) directive

some welding processes and/or generated (e.g. nitrogen oxides) during other welding processes. The difference between welding fumes and welding gases should be very clear.

Welding fumes contain solid particles that are temporarily suspended in the air due to vaporisation of the metals and oxides with rapid condensation to form particles, whereas welding gases are molecules in a gaseous state in the ambient air that are used as part of the process or generated by the process.

Both IARC (2018) and TRGS 528 (BAuA, 2021) refer to particulate matter when referring to the fumes. Alternatively ANSES (2022) and other literature describe welding fumes as "aerosols" describing not only the particulate matter, but collectively the particles suspended in air or gases present during the process. This is elaborated by {INRS, 2018 #1518} which describes gases and solid metal particles (or "dust") in variable proportions. The approach in France also gives due consideration to the individual metal components in the particulate matter, but indicates that a distinction cannot be made between exposure to particles or gases in terms of hazard assessment. It is clear that the gases used or generated do play a role in terms of exposure, even though the focus is on the metal particles, and therefore this further complicates the complex issue of how to consider what is in the "welding fume".

The variability and complexity of welding fumes has significant consequences when assessing the potential adverse health effects resulting from exposure.

2.1 Metals

Metals are involved in the welding process as base material or as filler material. Also metal oxides and other metal compounds are usually generated during the welding process. Welding fumes therefore contain both metals and metal compounds.

Below we list the possible metals and metal compounds which can be contained in the welding fumes, depending on the base and filler materials used and on the respective welding process:

Aluminium and oxides
Barium and barium compounds (e.g.$BaCO_3$)
Beryllium oxide
Cadmium oxide
Cobalt and oxides (e.g. CoO, Co_2O_3)
Chromium and Chromium(III) compounds
Hexavalent Chromium (Cr(VI)) compounds (e.g.Na_2CrO_4)
Copper and oxide
Iron and oxides (e.g. Fe_3O_4)
Magnesium and oxide
Manganese and oxides (e.g. MnO, Mn_3O_4)
Molybdenum (VI) oxide
Nickel and oxides (e.g. NiO)
Titanium dioxide
Vanadium and oxides (Vanadium pentoxide)
Zinc and oxide

Many of the metals (and metal oxides) have existing Occupational Exposure Limits (OELs), which are listed in Section 8 of this report.

For "welding fumes+" other metals can also be involved in some processes. For example soldering fumes can contain the following metals and their oxides depending on the filler used: tin, silver, copper, aluminium, gold, iron and brass (zinc oxide).

2.2 Other substances

Depending on the welding process and the welding parameters used, other hazardous substances may be released in addition to the metals:

Fluorine and Fluorides (e.g. NaF, KF, CaF2, BaF2)
Nitrogen monoxide
Nitrogen dioxide
Ozone
Carbon monoxide
Carbon dioxide
Argon

Many of these substances have existing Occupational Exposure Limits (OELs), which are listed as well in Section 8 of this report.

The surface of the metal to be welded should be clean and any coatings/contaminants removed, as the removal would also improve weld quality. This is a requirement in Germany (under TRGS 528) and at least common practice in other Member States. If the metal surface is not clean other substances may also be released, but these are considered outside the scope of this report.

3. Occurrence and Use

3.1 Occurrence

Welding fumes+ do not occur naturally. They are the result of widespread industrial processes that use high temperatures to join metals (or cut, clean etc.). Welding and associated activities present a number of potential hazards such as burns, eye and skin damage from optical radiation, fire/explosion hazard, noise, working in confined spaces etc. but these are outside the scope of this study, which is focussed on exposure to hazardous substances in the welding fumes+.

3.2 Welding

3.2.1 History and development of welding

Welding is the original technique for humans to fuse metals together, leading to the production of utensils, weapons, transportation, and more. The earliest types of welding involved hammering together two metal pieces under heat, however significant advances were made in the last 200 years, since the Industrial Revolution. In 1836, acetylene was discovered and was very important to welding as it enabled the fabrication of intricate tools and equipment made from metal.

Manual arc welding with a bare metal electrode was first introduced in 1891. Covered stick electrodes appeared in 1907, and manual arc welding with coated stick electrodes then became established. Tungsten Inert Gas (TIG) welding was developed in 1946, and Metal Inert Gas (MIG) / Metal Active Gas (MAG) welding was first used in the USA in 1948. As of the 20th century, the different variants of arc welding have been developed, and are still developing. Modern methods involve the use of laser light, electric arc, or open flames to provide the heat needed to perform the fusion process that join pieces of metal together to create or repair metal structures.

Welding has become more accurate, fast, and effective, also related to the need for arms and machinery during the World Wars. Modern welding techniques have evolved to offer better performance, rooted in safety and sustainably built products. Inspection techniques have improved defects or imperfections, setting a standard for safety and craftsmanship.

Today over 100 welding processes exist (nearly 140 according to INRS[4] and {ISO, 2010 #1519}), and these methods are constantly being developed with new research in the nuclear, space, transportation, and shipbuilding industries.

There are also highly sophisticated welding processes such as robotic welding. With this method metal can be welded more accurately and quickly than any human welder performing the task, while it also minimises or eliminates the risks to humans from the welding and welding fumes.

3.3 Advantages and disadvantages of welding

There are many advantages of welding for joining metals, such as:

1. Welded joints have a high strength, sometimes more than the parent metal.
2. Welded joints are permanent and leak-proof (suitable for fabricating pressure vessels).
3. Welding processes are flexible: different material can be welded, equipment can be made portable, processes can be performed in almost any location (e.g. under water or outer space), can be done in any shape and any direction.
4. Welding can be automated.
5. Addition and modification of existing structures is relatively easy.

Some of these advantages become apparent when comparing welding to other permanent joining processes, such as riveting. A riveted joint requires holes to be drilled, which can reduce the strength of the parent components, can be heavier than a welded joint due to the straps and rivets used, and can be limited to certain shapes (less flexible).

There are also many potential disadvantages of welding, which include:

1. Components may become distorted due to uneven heating and cooling during welding. This can lead to residual stress generation and result in reduced load carrying capacity of welded structures.
2. Permanent joints need to be broken to dismantle at the end-of-life of equipment or structure, . This can lead to significant difficulties, e.g. the dismantling of nuclear reactors.
3. Poor vibration sustaining capability - welded joints can fail if used for longer durations under vibration (in such cases riveted joints are preferred).
4. Inspection is more difficult and more costly – checking the presence of defects within welded joints can be difficult and need sophisticated testing methods (non-destructive testing).
5. Potentially high cost, related to specialised techniques or skilled operators which may be needed.
6. Potential hazards of welding
    a. From heat leading to burn hazards for workers.
    b. From the use of flammable fuels such as acetylene (potential fire hazard), or electricity (potential electric shock hazard).
    c. From the radiation hazard for the eyes and for the skin.
    d. From the inhalation of fumes that come from the welding processes (and associated processes). These fumes can be a mixture of gas and dust, the dimensions of which are almost all less than one micrometre. The dusts are therefore likely to reach the alveolar region of the lung.

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[4] https://www.inrs.fr/risques/fumees-soudage/ce-qu-il-faut-retenir.html

4. Welding and associated processes

Welding is a broad term for the process of joining metals through coalescence (IARC, 2018). This coalescence (joining/merging to form one mass) is achieved by applying heat (energy) to melt the base metal pieces and fusing them together to form a secure joint (a good mechanical connection). A filler material is typically added to the joint during welding to form a pool of molten material, that cools to form a joint that is usually stronger than the base material. Welding techniques can then be broadly classified in terms of how the heat/energy is applied mainly as arc welding (using electricity) or gas welding (using fuel gases), but also including newer techniques using lasers or plasma.

An alternative way of joining metals is via "soldering". Two or more items are joined together by melting and putting a filler metal (solder) into the joint, the filler metal having a lower melting point than the adjoining metal. Unlike welding, soldering does not involve melting the work pieces. Although it looks similar to welding the objective is usually to make a good electrical connection for soft soldering (especially in the electronics industry), although for brazing (which can be considered as a high-temperature version of soldering) the objective is still to create a high strength joint between the same or different metals.

Welders are skilled workers who specialise in joining metals, and they commonly use different types of welding processes during their professional career. As well as joining metals, welders also carry out other related tasks, such as cutting shapes or removing unwanted metal (gouging), flame straightening and thermal spraying. The German Technical regulations for hazardous substances (TRGS) 528 (BAuA, 2021) and the ANSES expert report (Comité d'experts spécialisés Valeurs Sanitaires de référence, 2021) categorise welding and these associated processes in different ways. The following sections follow mainly the TRGS 528 categorising, based on the objective of the activity (joining, cutting, spraying etc.), while incorporating the heat/energy source aspects as per the ANSES expert report. The German TRGS 528 also describes a 6th process (additive manufacturing such as 3D printing). It has been included here although it is not clear how similar it is to the other welding processes, especially with regards to potential fumes.

4.1 Fusion welding

Fusion welding is a generic term for welding processes that rely on melting to join materials of similar compositions and melting points. Melting is done via gas (fuel), electric arc, laser or plasma.

4.1.1 Gas welding

Gas welding is also known as oxyacetylene and oxyfuel welding[5]. The process is based on the combustion of oxygen and acetylene or other combustible gases such as hydrogen, methane or natural gas.. When mixed together in correct proportions within a hand-held torch or blowpipe, a relatively hot flame is produced with a temperature of about 3200°C. The chemical action of the oxyacetylene flame can be adjusted by changing the ratio of the volume of oxygen to acetylene. As steel melts at a temperature above 1500°C, the mixture of oxygen and acetylene is used as it is the only gas combination with enough heat to weld steel. However, other gases such as propane, hydrogen and coal gas can be used for joining lower melting point non-ferrous metals, and for brazing and silver soldering. Oxyacetylene equipment is portable and easy to use. It comprises oxygen and acetylene gases stored under pressure in steel cylinders. The cylinders are fitted with regulators and flexible hoses which lead to the blowpipe. The action of the oxyacetylene flame on the surface of the material to be welded can be adjusted to produce a soft, harsh or violent reaction by varying the gas flows. The blowpipe is therefore designed to accommodate different sizes of 'swan neck copper nozzle which allows the correct intensity

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[5] https://www.twi-global.com/technical-knowledge/job-knowledge/oxy-fuel-welding-003

of flame to be used. When carrying out fusion welding the addition of filler metal in the form of a rod can be made when required.

4.1.2 Arc welding (also: gas metal arc welding, GMAW) (manual arc/ MAG/MIG/TIG/plasma/submerged arc welding)

This type of welding process uses an electric arc to create heat to melt and join metals[6]. A power supply creates an electric arc between a consumable or non-consumable electrode and the base material using either direct (DC) or alternating (AC) currents. Depending on the voltage, arc length, and atmosphere, the arc temperature can range from around 3000°C to above 20000°C (for a plasma arc), which creates an intense heat to melt the metal at the join between two work pieces. As the metals react chemically with oxygen and nitrogen in the air when heated to high temperatures by the arc, a protective shielding gas or slag is used to minimise the contact of the molten metal with the air. Once cooled, the molten metals solidify to form a metallurgical bond.

There are a number of different processes within this category that can be categorised into two different types: consumable and non-consumable electrode methods.

4.1.2.1 Consumable Electrode Methods

4.1.2.1.1 Metal Inert Gas Welding (MIG) and Metal Active Gas Welding (MAG)

Metal Inert Gas (MIG) welding and Metal Active Gas (MAG) welding are both variations of the Gas Metal Arc Welding (GMAW) process. These use heat created from an electric arc between a consumable metal electrode and a workpiece, creating a weld pool and fusing them together, forming a joint[7]. The arc and weld pool is protected from the environment and contaminants by a shielding gas. The metal electrode is a small diameter wire fed continuously through the contact tip of the welding torch from a wire spool, while a shielding gas is fed through the welding torch. The only difference between MIG and MAG is the type of shielding gas used. MIG uses inert gases which don’t react with the filler material or weld pool (such as argon and helium or Ar/He mixes) for welding of non-ferrous metals such as aluminium. MAG uses active shielding gases (such as carbon dioxide or mixtures of argon, carbon dioxide and oxygen) which can react with filler metal transferring across the arc and the weld pool, affecting its chemistry and/or resulting mechanical properties. MAG welding is one of the most widely-used welding processes according to The Welding Institute.

4.1.2.1.2 Shielded Metal Arc Welding (SMAW)

Also known as manual metal arc welding (MMA or MMAW), flux shielded arc welding or stick welding is a process where the arc is struck between the metal rod (electrode flux coated) and the work piece, both the rod and work piece surface melt to form a weld pool[8]. Simultaneous melting of the flux coating on the rod will form gas, and slag, which protects the weld pool from the surrounding atmosphere. This is a versatile process ideal for joining ferrous and non-ferrous materials with a range of material thicknesses in all positions.

4.1.2.1.3 Flux Cored Arc Welding (FCAW)

Created as an alternative to SMAW, FCAW uses a continuously fed consumable flux cored electrode and a constant voltage power supply, which provides a constant arc length. This process either uses a shielding gas or just the gas created by the flux to provide protection from contamination.

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[6] https://www.twi-global.com/technical-knowledge/faqs/what-is-arc-welding

[7] https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-mig-mag-welding

[8] https://www.twi-global.com/technical-knowledge/job-knowledge/the-manual-metal-arc-process-mma-welding-002

4.1.2.1.4 Submerged Arc Welding (SAW)

A frequently-used process with a continuously-fed consumable electrode and a blanket of fusible flux which becomes conductive when molten, providing a current path between the part and the electrode. The flux also helps prevent spatter and sparks while suppressing fumes and ultraviolet radiation.

4.1.2.1.5 Electro-Slag Welding (ESW)

A vertical process used to weld thick plates (above 25mm) in a single pass. ESW relies on an electric arc to start before a flux addition extinguishes the arc. The flux melts as the wire consumable is fed into the molten pool, which creates a molten slag on top of the pool. Heat for melting the wire and plate edges is generated through the molten slag's resistance to the passage of the electric current. Two water-cooled copper shoes follow the process progression and prevent any molten slag from running off.

4.1.2.1.6 Arc Stud Welding (SW)

Similar to flash welding, SW joins a nut or fastener, usually with a flange with nubs that melt to create the join, to another metal piece.

4.1.2.2 Non-consumable Electrode Methods

4.1.2.2.1 Tungsten Inert Gas Welding (TIG)

Also known as Gas Tungsten Arc Welding (GTAW)**,** uses a non-consumable tungsten electrode to create the arc and an inert shielding gas to protect the weld and molten pool against atmospheric contamination.

4.1.2.2.2 Plasma Arc Welding (PAW)

Similar to TIG, PAW uses an electric arc between a non-consumable electrode and an anode, which are placed within the body of the torch. The electric arc is used to ionise the gas in the torch and create the plasma, which is then pushed through a fine bore hole in the anode to reach the base plate. In this way, the plasma is separated from the shielding gas.

4.1.3 Beam welding (laser beam/electron beam)

Laser welding is a process used to join together metals using a laser beam to form a weld. Being such a concentrated heat source, in thin materials laser welding can be carried out at high welding speeds of metres per minute, and in thicker materials can produce narrow, deep welds between square-edged parts[9]. The process is frequently used in high volume applications using automation, as in the automotive industry. Laser welding operates in two fundamentally different modes: conduction limited welding and keyhole welding. In conduction welding the material gets heated above the metal’s thawing point, but not to an extent that it evaporates. This procedure uses a low-power laser that ranges from 500 watts to produce welds that don’t require high weld strength. One benefit of thermal conduction welding is that the last weld comes out aesthetically and highly smooth. In keyhole welding, the laser beam heats the metal in a way that its contact surface evaporates and penetrates deep into the metal. It forms a keyhole in which a plasma-like condition is created with temperatures increasing to more than 10,000K. This procedure needs high-powered lasers with a power output of above 105W/cm^2.

Electron beam (EB) welding is a fusion welding process whereby electrons are generated by an electron gun and accelerated to high speeds using electrical fields. This high speed stream of electrons is tightly focused using magnetic fields and applied to the materials to be joined. The beam of electrons creates kinetic heat as it impacts with the workpieces, causing them to melt and bond together. Electron beam welding is performed in a vacuum

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[9] https://www.twi-global.com/technical-knowledge/faqs/faq-how-does-laser-welding-work

environment as the presence of gas can cause the beam to scatter. Due it being a vacuum process and because of the high voltages used, this welding method is heavily automated and computer controlled. As a result, specialised fixtures and computer numerical control (CNC) tables are used to move the workpieces inside the welding vacuum chamber. Recent developments in electron beam welding machine technology have realised a local method of electron beam welding, whereby the electron beam gun is enclosed in a vacuum box on the side of the material to be joined, rather than placing the entire workpiece inside a vacuum chamber[10].

4.2 Soldering

Soldering is a process in which two or more items are joined together by melting and putting a filler metal (solder) into the joint, the filler metal having a lower melting point than the adjoining metal. Unlike welding, soldering does not involve melting the work pieces.

4.2.1 Categories of solder

There are numerous varieties of solder available on the market based on the relative ratios of lead, tin and flux. However there are three main categories of solder[11]:

- Lead-based solder supported the electronics revolution. The most common mixture is a 60/40 (tin/lead) blend with a melting point around 180-190°C. Known colloquially as soft solder, tin is selected for its lower melting point while lead is used to inhibit the growth of tin whiskers. The higher the tin concentration, the better the tensile and shear strengths.
- Lead-free solder started when the EU started restricting the inclusion of lead in consumer electronics[12]. In the US, manufacturers could receive tax benefits for using lead-free solders. Tin whiskers can be mitigated by using newer annealing techniques, incorporating SnAgCu alloy as a solder , and using conformal coatings. Lead-free solders generally have a higher melting point than conventional solder.
- Flux core solder is sold as a spool of “wire” with a reducing agent at the core. The flux is released during soldering and reduces (reverses oxidation of) metal at the point of contact to give you a cleaner electrical connection. It also improves the wetting properties of the solder. In electronics, flux is usually rosin. Acid cores are for metal mending and plumbing, and should not be used on electronics.

Owing to building knowledge about the hazards of lead, and regulations, lead-based solders are increasingly replaced with lead-free solders for soft solders, which may consist of antimony, bismuth, brass, copper, indium, tin or silver. These may be added to give the solder certain properties or enhance its conductivity, or they may occur only in traces. Some examples of the additives and what they do are[13]:

- Antimony increases mechanical strength without reducing wettability while preventing tin pest.
- Bismuth significantly lowers the melting point and improves wettability. Inhibits growth of tin whiskers.
- Copper lowers the melting point and improves wetting properties in the molten state.
- Indium lower the melting point, improves ductility, and is used for soldering to gold or for cryogenic applications due to its high resistance to temperature swings. Indium alloys are expensive and prone to corrosion.

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[10] https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-electron-beam-welding
[11] https://resources.pcb.cadence.com/blog/what-are-the-different-types-of-solder-2
[12] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0065&from=EN
[13] https://resources.pcb.cadence.com/blog/what-are-the-different-types-of-solder-2

- Nickel in solder alloy can protect UBM (under bump metallization) layer from dissolution.
- Silver provides mechanical strength, but with lower ductility than lead. It can improve resistance to fatigue from thermal cycles in lead-free solders.

4.2.2 Soldering processes

There are also three types of soldering process which use increasingly higher temperatures, which in turn produce progressively stronger joints[14].

4.2.2.1 Soft soldering (90°C - 450°C)

This process has the lowest liquidus temperatures among the soldering processes. Typical liquidus temperatures for soft soldering with lead-free solder in the electronics industry are 210 to 230°C. Because of the low temperatures used in soft soldering, it thermally stresses components the least but does not make strong joints and is therefore unsuitable for mechanical load-bearing applications. It is also not suited for high-temperature use as this type of solder loses strength and melts.

4.2.2.2 Hard (silver) soldering (>450°C)

For flame brazing (working temperature > 450 °C), brass solders made of copper-zinc alloys are mainly used, which also contain silver additives ("silver brazing alloys").

4.2.2.3 Brazing (>450°C)

This type of soldering uses a metal with a much higher melting point than those used in hard and soft soldering. In arc brazing (MIG, TIG, plasma brazing) and laser beam brazing, the working temperature is 900-1100 °C, and mainly wire-shaped copper-based alloys are used as filler material, e.g. the alloys "CuSi3", "CuAl8" or "CuSn6". However, similarly to hard soldering, the metal being bonded is heated as opposed to being melted. Once both the materials are heated sufficiently, you can then place the soldering metal between them which melts and acts as a bonding agent.

The two processes "hard soldering" and "brazing" overlap in the temperature ranges and thus a separation does not completely make sense, although described in this way in some published literature. In other literature (such as ISO 857-2:2005) "soldering" includes all processes up to 450 °C, and "brazing" includes all processes above 450°C.

It should also be noted that Restriction Entry 23[15] on cadmium and its compounds, restricts the use of cadmium in brazing fillers. However it contains a derogation that the restriction *"…shall not apply to brazing fillers used in defence and aerospace applications and to brazing fillers used for safety reasons"*. A study by ECHA in 2012 identified two specific applications that might fit within the "safety reasons" derogation: (i) the manufacturing of turbine wheels used in power plant technology (approximately 2kg/year of cadmium was used for 100 turbine wheels) and (ii) the production of high pressure acetylene systems (which mainly occurred in the UK, but the systems could be exported into the EU)[16]. Information on the extent of the use of brazing fillers containing cadmium in defence and aerospace applications could not be found. However searching for this information identified a number of suppliers of cadmium-free brazing fillers for aerospace applications. Overall while there remains this derogation on the restricted use of cadmium in brazing fillers, there are a limited number of specific applications where they can still be used for safety reasons, and even within the defence and aerospace sector there are alternatives available.

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[14] https://www.twi-global.com/technical-knowledge/faqs/what-is-soldering
[15] https://echa.europa.eu/substances-restricted-under-reach/-/dislist/details/0b0236e1807e2518
[16] Cadmium in brazing fillers for safety reasons_final_08112012 (europa.eu)

Some metals are easier to solder than others, such as copper, silver, and gold. Next are iron, mild steel and nickel, and because of their thin, strong oxide films, stainless steel and some aluminium alloys are more difficult to solder.

4.2.3 Soldering uses and tools

Soldering is used in plumbing, electronics, and metalwork from flashing to jewellery and musical instruments. It provides reasonably permanent but reversible connections between copper pipes in plumbing systems as well as joints in sheet metal objects such as food cans, roof flashing, rain gutters and automobile radiators.

Electronic soldering connects electrical wiring to devices, and electronic components to printed circuit boards. Electronic connections may be hand-soldered with a soldering iron. Automated methods such as wave soldering or use of ovens can make many joints on a complex circuit board in one operation, vastly reducing production cost of electronic devices.

Musical instruments, especially brass and woodwind instruments, use a combination of soldering and brazing in their assembly. Brass bodies are often soldered together, while keywork and braces are most often brazed.

Different types of soldering tools are made for specific applications. The required heat can be generated from burning fuel or from an (electrically operated) heating element.

- An electric **soldering iron** is widely used for hand-soldering. It can be fitted with a variety of tips, ranging from blunt, to very fine, to chisel heads for hot-cutting plastics rather than soldering. The simplest irons do not have temperature regulation. Small irons rapidly cool when used to solder to, say, a metal chassis, while large irons have tips too cumbersome for working on printed circuit boards (PCBs) and similar fine work. A 25-watt iron will not provide enough heat for large electrical connectors, joining copper roof flashing, or large stained-glass lead came. On the other hand, a 100-watt iron may provide too much heat for PCBs. Temperature-controlled irons have a reserve of power and can maintain temperature over a wide range of work.
- A **soldering gun** heats faster but has a larger and heavier body. Gas-powered irons using a catalytic tip to heat a bit, without flame, are used for portable applications. Hot-air guns and pencils allow rework of component packages which cannot easily be performed with electric irons and guns.
- A **soldering torch** uses a flame rather than a soldering tip to heat solder. Soldering torches are often powered by butane and are available in sizes ranging from very small butane/oxygen units suitable for very fine but high-temperature jewellery work, to full-size oxy-fuel torches suitable for much larger work such as copper piping.
- A **soldering copper** is a tool with a large copper head and a long handle which is heated in a blacksmith's forge fire and used to apply heat to sheet metal for soldering. The head provides a large thermal mass to store enough heat for soldering large areas before needing re-heating in the fire; the larger the head, the longer the working time. Historically, soldering coppers were standard tools used in auto bodywork, although body solder has been mostly superseded by spot welding for mechanical connection, and non-metallic fillers for contouring.
- Another method for soldering is to place solder at the locations of joints in the object to be soldered, then heat the entire object in an **oven** to melt the solder.

4.2.4 Soldering and related health hazards

Soldering can produce dust and fumes that are hazardous. However soft soldering is not expected to emit similar fumes to welding as it does not melt the base material due to the lower temperatures used. In addition, using flux containing rosin produces solder fumes that, if inhaled, can result in occupational asthma or worsen existing asthmatic conditions; as well as cause eye and upper respiratory tract irritation.

The health hazards for common solder components are detailed below[17]:

- Tin – Considered relatively harmless but may generate benign pneumoconiosis, or eye, skin, and respiratory system irritation.
- Silver – May create throat irritation, blue gray eyes, nasal septum irritation, and gastrointestinal disturbance.
- Copper – Can produce eye and upper respiratory irritation, and metal fume fever. Metal fume fever symptoms include fever, chills, aches, pains, nausea, and dizziness.
- Aluminium – May provoke irritation to eyes, skin, respiratory system.
- Gold – Regarded as generally harmless but exercise caution with certain alloys.
- Iron – May lead to siderosis a form of pneumoconiosis.
- Brass (Zinc Oxide) – Can cause metal fume fever.

In addition solder fluxes containing fluoride should be monitored due to the toxic nature of hydrogen fluoride and boron trifluoride. Both substances can cause eye, skin, nose, and throat irritation. Hydrogen fluoride exposure may cause pneumonitis, while boron trifluoride can lead to bronchitis and pulmonary edema due to the excess of fluid in the lungs. Rosin core solders and rosin based solder fluxes contain rosin which comes from the resins of pine trees. When heated, rosin creates a flux fume called colophony containing a complex mix of particulate and gases. The colophony particles can be deposited in the lungs and subsequently lead to lung damage and occupational asthma. The colophony gases include acetone, methyl alcohol, methane, ethane, CO, and CO_2 and aliphatic aldehydes with exposure causing upper respiratory irritations and possible formation of cancer.

4.3 Thermal cutting or gouging

Thermal cutting or gouging is a generic term for welding processes that rely on melting to cut a shape or the removal of unwanted metal.

Common cutting processes[18] can also be classified according to the source of energy used, and include:

- flame cutting, also known as torch or oxygen-gas cutting, is a chemical reaction between pure oxygen and steel to form iron oxide. It is rapid, controlled rusting. Only low-carbon steel and some low alloys can be cut effectively with this process
- arc-air gouging, an electric arc-cutting process where the metals to be cut are melted by the heat of a carbon arc. The most common metals cut with the process include cast irons, copper alloys and stainless steel.
- plasma cutting, which uses the principle of a welding arc to cut metal with a clean profile. Most plasma cutting has pre-programmed computer numerical control with the operator at a distance from the fume source
- laser cutting, which uses a focused laser beam, usually with an annular gas jet to create a fine cut, with minimal loss of material and a quality profile. Most laser cutting has pre-programmed computer numerical control with the operator at a distance from the fume source

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[17] https://www.sentryair.com/blog/industry-applications/electronics-technology/the-hazards-of-solder-fumes/

[18] https://www.hse.gov.uk/welding/similar-to-welding-fume.htm

Thermal gouging is used for rapid removal of unwanted metal. The material is locally heated and molten metal ejected - usually by blowing it away. Oxyfuel gas or arc (carbon or plasma) processes can be used to produce rapid melting and metal removal. Gouging relies on molten metal being forcibly ejected, often over quite large distances, therefore the welder must take appropriate precautions to protect himself, other workers and his equipment. These precautions include protective clothing for the welder, shielding inside a specially-enclosed booth or screens, adequate fume extraction, and removal of all combustible material from the immediate area[19].

Originally developed as a process for removing defective welds in stainless steel armour plate on U.S. warships, where common methods of gouging (mechanical techniques such as grinding, hand milling, routing, and chipping) were difficult to use, thermal gouging now has a wide range of applications in engineering industries such as for the repair and maintenance of structures, the removal of cracks and imperfections, and removal of surplus metal (including for demolition). In maintenance and repair, operators can use gouging to remove welds or metal to replace a worn or defective part, or reweld it.

The act of violently moving/blowing away metal gives an additional dimension to any possible fume generation. In carbon arc gouging the constituents of the molten metal react strongly with air, and the force of the air blast tends to vaporise much of the molten metal into fine droplets, creating a high level of fume consisting of metal vapour, carbon dust, and metallic by-products[20]. Typically, the fume level of an air carbon-arc gouging operation is higher than the allowed exposure level to welding fumes in a workplace. Depending on the material being gouged, exposure to particular toxins that are constituents of the base metal can also cause problems.

Plasma gouging is a variation of plasma cutting, in which the arc is "defocused" slightly by increasing the hole size in the constricting orifice. In plasma gouging, the torch is inclined at an angle to the workpiece, and the arc ploughs out a groove on the metal surface and blows the molten metal off to the side. A more intense cutting arc causes a groove too deep and narrow for most applications, so the defocused arc is used for gouging. To produce a groove of specific dimensions, particularly regarding depth and width, the welder must exercise careful control of the gouging operation.

Plasma also uses an electric arc to melt the metal being gouged, but the plasma gas itself pushes the molten metal out of the groove. Because this is done less violently than in air carbon-arc gouging, less molten metal vaporizes, reducing the metallic vapor and reaction with the surrounding atmosphere. When air is used as the plasma gas, some reaction occurs, but the volume of air is lower than that found in air carbon-arc gouging.

If inert gas is used, the molten metal in the gouge is protected from the surrounding atmosphere and has little chance to react with the air. However, aluminium applications are an exception to this. This metal's lightness and strong affinity for oxygen do create fumes. Also, the strong ultraviolet content of the radiation from the plasma arc increases the carbon monoxide, ozone, and nitrogen oxides generated. These amounts generally are below threshold limits.

4.4 Thermal spraying

Thermal spraying is a technology which improves or restores the surface of a solid material. The process can be used to apply coatings to a wide range of materials and components, to provide resistance to wear, erosion, cavitation, corrosion, abrasion or heat. Thermal spraying is also used to provide electrical conductivity or insulation,

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[19] https://www.twi-global.com/technical-knowledge/job-knowledge/thermal-gouging-008

[20] https://www.thefabricator.com/thewelder/article/powertools/choosing-a-gouging-method

lubricity, high or low friction, sacrificial wear, chemical resistance and many other desirable surface properties[21].

Thermal spraying is distinguished by its ability to deposit coatings of metals, cermets, ceramics and polymers in layers of substantial thickness, typically 0.1 to 10mm, for engineering applications[22]. Almost any material can be deposited so long as it melts or becomes plastic during the spraying operation. At the substrate surface, the particles form 'splats' or 'platelets' that interlock and build up to give the coating. The deposit does not fuse with the substrate or have to form a solid solution to achieve a bond. The bond between a thermally sprayed coating and the substrate is primarily mechanical, and not metallurgical or fused.

Thermal spray coatings are extensively used in the manufacturing of gas turbines, diesel engines, bearings, journals, pumps, compressors and oil field equipment, as well as coating medical implants. It can extend the life of new components or repair and re-engineer worn or damaged components. Thermal spraying is principally an alternative to arc welded coatings, although it is also used as an alternative to other surfacing processes, such as electroplating, physical and chemical vapour deposition and ion implantation for engineering applications.

There are several type of thermal spraying usually classified according to the type of energy source used to melt the feedstock material (Vuoristo, 2014), see Figure 2 below. The most typical energy sources in thermal spraying are:

- thermal (and/or kinetic) energy obtained from combustion of gases, typically hydrocarbon or hydrogen, or liquids;
- thermal energy obtained from electric discharges such as electric arcs or ionized plasma gases;
- energy from molten liquids or high-power laser beams.
- purely kinetic energy sources.

Depending on the type of energy source, thermal spray processes can be further classified according to the spray gun principle or design, type of feedstock material used in the process, type of fuel (gas or liquid), type of deposition atmosphere (atmospheric, low/high pressure, inert gas, under water, etc.), type of oxidizer in combustion, etc.

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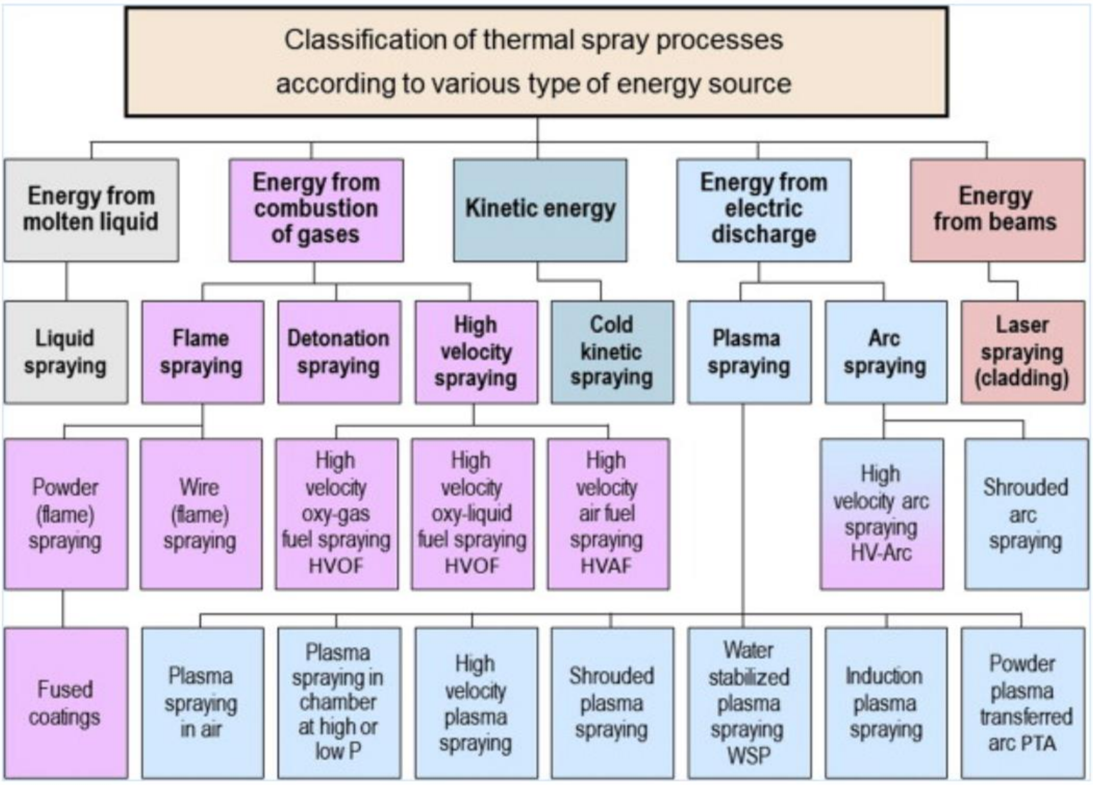
[21] https://www.metallisation.com/applications/thermal-spray-engineering-applications/#:~:text=Thermal%20spraying%20is%20a%20technology,%2C%20corrosion%2C%20abrasion%20or%20heat.

[22] https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-thermal-spraying

Figure 1: Classification of thermal spray processes



In addition, the design of the spray gun, type of feedstock material used in the process, type of fuel (gas or liquid), type of deposition atmosphere (atmospheric, low/high pressure, inert gas, under water, etc.), type of oxidizer in combustion, etc. are all important considerations in choosing the most suitable process. Also important is the temperature of the heat source, as refractory materials (i.e., high-melting-point ceramics and refractory metals) can only be melted by plasma spray-based processes. Easily oxidizing metals may require spray atmospheres in which oxygen has been eliminated, e.g. using an inert gas shroud. Cold spraying may be considered a clear exception, because in this process the powder material does not melt at all, and therefore can be processed to coatings even in air atmosphere.

A typical thermal spray system consists of the following:

- Spray torch (or spray gun) – the core device performing the melting and acceleration of the particles to be deposited
- Feeder – for supplying the powder, wire or liquid to the torch through tubes.
- Media supply – gases or liquids for the generation of the flame or plasma jet, gases for carrying the powder, etc.
- Robot/Labour – for manipulating the torch or the substrates to be coated
- Power supply – often standalone for the torch
- Control console(s) – either integrated or individual for all of the above

Ideally, equipment should be operated automatically in enclosures specially designed to extract fumes, reduce noise levels, and prevent direct viewing of the spraying head. Such techniques will also produce coatings that are more consistent. There are occasions when the type of components being treated, or their low production levels, require manual equipment operation. Under these conditions, thermal spraying presents a number of hazards, including noise (metal being sprayed with compressed gas) and UV light (from electric arc and plasma), and in particular the atomization of molten materials produces a large amount of dust and fumes made up of very fine particles (ca. 80–95% of the particles by number <100 nm) (Bémer et al., 2010). Proper extraction facilities are vital not only for personal safety, but to minimize entrapment of re-frozen particles in the sprayed coatings. The use of respirators fitted with suitable filters is strongly recommended where equipment cannot be isolated. Certain materials offer specific known hazards (J Blunt, 2002):

- Finely divided metal particles are potentially pyrophoric and harmful when accumulated in the body.
- Certain materials e.g. aluminium, zinc and other base metals may react with water to evolve hydrogen. This is potentially explosive and special precautions are necessary in fume extraction equipment.
- Fumes of certain materials, notably zinc and copper alloys, have a disagreeable odour and may cause a fever-type reaction in certain individuals (known as metal fume fever). This may occur some time after spraying and usually subsides rapidly. If it does not, medical advice must be sought.
- Fumes of reactive compounds can dissociate and create harmful gasses. Respirators should be worn in these areas and gas meters should be used to monitor the air before respirators are removed.

4.5 Flame straightening

Welding and other manufacturing processes where significant heat is applied can leave stresses within the workpiece and during the subsequent cooling phase distortions may develop. Flame straightening is an efficient, well-established method of correcting the weld distortion without impairing the material.

Flame straightening is based on the physical principle that metals expand when heated and contract when cooled. If expansion is restricted, compressive stresses build up and result in plastic deformations if the temperatures are high enough. Upon cooling, the plastic deformations remain[23].

In practice, an oxy-acetylene flame is used to rapidly, precisely and locally heat a well-defined section of the workpiece, to the material-specific flame straightening temperature at which plastic deformation occurs. Upon cooling, the metal contracts more than it could expand when heated and any resulting distortions can therefore be straightened out. Although various fuel gases can be used, the highest flame temperatures and intensities for rapid heating are achieved with acetylene and oxygen.

In comparison to acetylene, other fuel gases such as propane or natural gas require more time for local heating due to their combustion properties, and they develop a larger flame due to the higher fuel gas/oxygen ratio. Areas adjacent to the flame straightening point are thus heated as well. This causes the heated zone to buckle and the straightening result is unsatisfactory.

All materials suited to welding can be flame-straightened without difficulty, if the material's specific properties are taken into consideration, as is common practice for welding. Suitable materials include steel, nickel, copper, brass and aluminium. Different materials require correspondingly differing flame straightening temperatures (e.g. for mild steel and copper this is 600-800°C, and for pure aluminium it is 150-450°C). Other important factors

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[23] https://www.boconline.co.uk/en/images/Fundamentals-of-Flame-Straightening_tcm410-113398.pdf

are the design of the torch and the flame setting which depend on the workpiece thickness and on the material itself.

During flame straightening potentially hazardous fumes can be generated, depending on the material being straightened, the fuel gas being used and the surface condition of the workpiece (e.g. if there is oil or paint present). Flame straightening produces nitrogen oxides in particular due to the process. The workpieces should be prepared in such a way that no exposure can occur through surface coatings (a requirement in Germany, but not necessarily the real occupational situation across the EU).

4.6 Additive production process with metal powders

The better-known term "3D printing" is a subset of “additive manufacturing” (AM), which references technologies that grow three-dimensional objects one superfine layer at a time. Each successive layer bonds to the preceding layer of melted or partially melted material. As its name implies, additive manufacturing adds material to create an object, which is in contrast to tradition manufacturing where it is often necessary to remove material through milling, machining, carving, shaping or other means.

Objects are digitally defined by computer-aided-design (CAD) software that is used to essentially "slice" the object into ultra-thin layers[24]. This information guides the path of a nozzle or print head as it precisely deposits material upon the preceding layer. Or, a laser or electron beam selectively melts or partially melts in a bed of powdered material. As materials cool or are cured, they fuse together to form a three-dimensional object.

Metal powders used in an additive manufacturing must have distinct physical and chemical characteristics for a reliable and reproducible printing outcome. These characteristics include, but are not limited to, particle morphology, particle size distribution (PSD), density, porosity, flowability, occurrence of satellites, agglomeration, humidity, tribocharging properties and chemical composition. These characteristics need to be tested and optimized for each AM process or technology to produce high quality and reliable parts through metal AM. A large number of metal AM research articles focus on the following three types of alloys: titanium, nickel and aluminium alloys (Moghimian et al., 2021). Nickel and aluminium alloys find applications in different industries such as aerospace and automotive, and titanium alloys in medical and dental industries.

There are currently several metal powder atomization methods tailored for additive manufacturing including water atomization, gas atomization, centrifugal atomization and plasma atomization. The majority of metal powders used in additive manufacturing (AM) are produced by gas atomization. In this process, a feedstock is melted in a crucible and then ejected through a nozzle into a high-pressure gas stream (usually argon or nitrogen), breaking the molten stream into droplets. Air or helium can also be used as the atomizing gas, the choice depending on its cost, its thermal conductivity and reactivity with the alloy. As a final step, the metal droplets cool down to form powder particles. The characteristics of the resulting atomized powder depend on several parameters such as the diameter and the velocity of the melt stream (mass flow rate) as well as the mass-flow and shear rates of the atomizing gas. There is also post-processing of raw metal powders, which includes passivation against oxidation, classification (i.e. sieving or air classification), and blending to obtain the final homogenous powder lot. There are also various technologies in order to improve the flowability of powders post atomization, although there is no agreed acceptable value for flowability.

As metal powders are costly there is interest in reusing them. Only a small amount of the metal powder melts and fuses into a part during the additive manufacturing process. The rest of the powder can be used several times until it reaches a condition when the powder becomes unusable.

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[24] https://www.ge.com/additive/additive-manufacturing

Several factors can influence the reusability of a batch of powder, including:

1) The chemical composition of the used powder.
2) Contamination of the used powder.
3) Physical characteristics such as particle size distribution, flowability, tap/apparent density or the appearance of a high portion of angular or interfused particles.
4) The mechanical properties of the parts being printed with those powders, such as tensile and fatigue properties, may be affected.

This relatively new technology is included in the report as it is referred to be within in the scope of TRGS 528. The TRGS 528 covers industrial processes where metal powders are used, which are introduced in layers into a closed room (assembly space) using a loading device and selectively melted with a laser beam (this seems to come under laser welding, selective laser melting and selective laser sintering).

However, the "construction process" takes place inside the "construction unit", a closed system, so exposure of workers is excluded (for example industrial 3D printers using metal powders must encapsulate the build process in a sealed chamber that is oxygen free). The TRGS 528 covers this activity from the point of view of the potential hazards from the handling of metal powders before and after the construction process, which can lead to exposure to metal dust (airborne or inhalable dust particle). Therefore, this activity is not particularly relevant in the context of worker exposure to welding fumes+.

5. Exposure

5.1 Exposure

5.1.1 Exposure to welding fumes+

Welding processes generate a complex and variable mixture of gases and particulates of varying sizes. A commonly used term is 'the plume', which is used to mean the visible and invisible emissions during the welding processes.

According to the SLIC Guidance on addressing health risks from welding fumes[25] the composition, rate of generation and particle size of the fume will depend on the:

- Composition of the consumable electrode and the materials being welded;
- Welding process parameters (current, shielding gas and technique);
- Surface coatings, contamination and 'flash rust';
- Local environmental conditions (e.g. outdoors, indoors, enclosed.); and
- Control measures and their effectiveness (general ventilation, extraction at source e.g. on tool extraction, local exhaust ventilation, automation etc.)

In addition, the extent of the formation of welding fumes+ depends strongly on the skills of the welder.

The German Technical regulations for hazardous substances (TRGS) 528 presents the following figure indicating the size of the particulate hazardous substances from welding processes in relation to dust particles according to DIN EN 481. Fumes can contain ultra-fine particles with an aerodynamic diameter of less than 100 nm.

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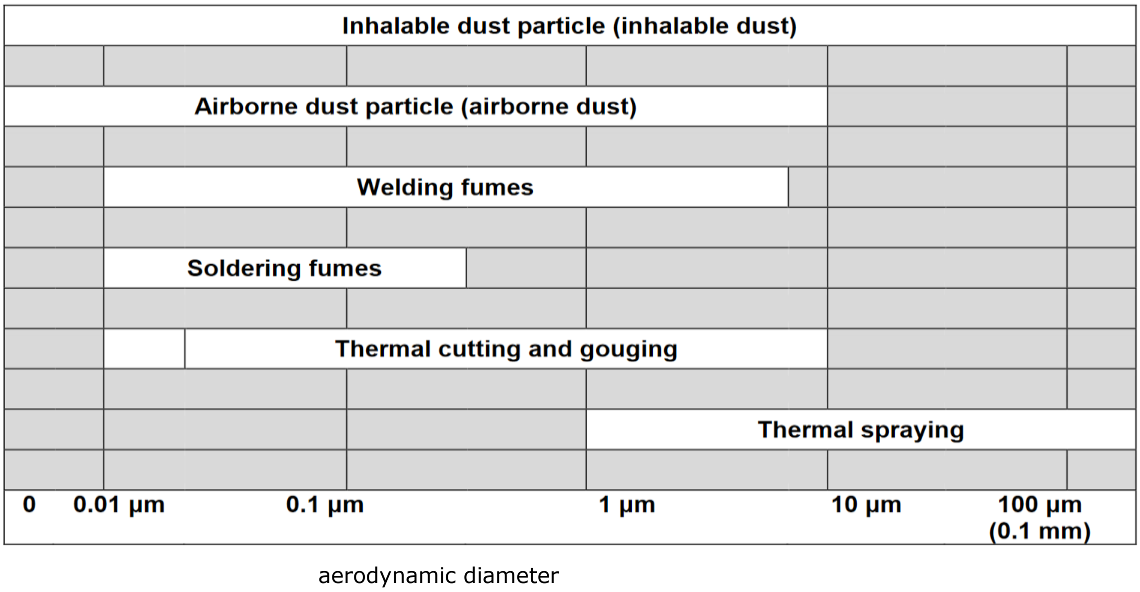
[25] https://osha.europa.eu/en/legislation/guidelines/guidance-national-labour-inspectors-addressing-health-risks-welding-fumes

Figure 2: Sizes of the particulate hazardous substances from welding processes



Another aspect to consider is the emission rate of welding fumes+, which are different depending on the process being used. The TRGS 528 proposes a measure of the release as the respective emission rate (emitted particle mass of a process per unit time in mg/s or g/h). The TRGS 528 divides the processes into the following 4 emission groups according to their emission rates of particulate matter:

1. Low (< 1mg/s),
2. Medium (1 to 2 mg/s),
3. High (2 to 25 mg/s) and
4. Very high (> 25 mg/s).

The higher the emission group, the higher the requirements for measures to reduce exposure in the workplace. The emission rates describe release of welding fumes+ by welding techniques and thus provide information about the possible exposure of workers at the workplace. See Table 1 from TRGS 528.

Table 1: Assessment of the process based on emission rates. Allocation to emission groups

Process (example list)	Emission rate $^{1)}$ (mg/s)	Emission group
Submerged arc welding	< 1	Low
Gas welding (autogenous process)	< 1	Low
WIG	< 1	Low
Laser beam welding without filler	1 to 2	Medium
MIG/MAG (low-energy inert gas welding)	1 to 4	Medium to high
Laser beam welding with additional material	2 to 5	High
MIG (solid wire, nickel, nickel-based alloys)	2 to 6	High
MIG (aluminium materials)	0.8 to 29	Low to very high
MAG (solid wire)	2 to 12	High
Manual arc welding	2 to 22	High

Process (example list)	Emission rate [1] (mg/s)	Emission group
MAG (cored wire welding with inert shielding gas)	6 to > 25	High to very high
MAG (cored wire welding with inert shielding gas)	> 25	Very high
Soft soldering	< 1	Low
Brazing / hard soldering	1 to 4	Medium to high
MIG soldering	1 to 9	Medium to high
Laser beam cutting	9 to 25	High to very high
Autogenous flame cutting	> 25	Very high
Plasma cutting	> 25	Very high
Arc spraying	> 25	Very high
Flame spraying	> 25	Very high
[1] Empirical values that can be reduced in individual cases by optimising the process parameters.		

As can be seen certain welding processes have low emission rates and are in the low emission groups, in particular those with inert shielding gases. The welding process in the highest emission group "very high" is thus arc welding with flux-cored wires without shielding gas, with shielding gas still "high" to "very high". The emission group of MAG welding with solid wires is "medium" to "high" and can be lowered to the emission group "medium" by an electronic control of the welding parameters (e.g. by a waveform control). MAG welding is also one of the most widely-used welding processes.

Soft soldering is assigned to the emission group "low", while hard soldering and high temperature soldering are assigned to the emission groups "medium" to "high". While the other processes like cutting and spraying are in the very high emission group, and have high emission rates (>25mg/s).

5.1.2 Composition of welding fumes+

ISO 15011-4:2018 presents information on the principal components and typical key components of commonly encountered welding fumes associated with particular “Arc welding processes” (see Table 2 below):

Table 2: Typical principal components and typical key components of commonly encountered welding fumes

Type of process	Type of consumable	Typical principal components	Other possible principal components	Typical key components
Manual metal arc welding	Unalloyed and low-alloy steel	Fe, Mn, Cr, Ni, Cu	F^-	Mn
	High-alloy steel	Cr, Cr(VI), Fe, Mn, Ni	F^-	Cr(VI) or Ni
	Cast iron	Ni, Cu, Fe, Mn	Ba, F^-	Ni or Cu
	Hardfacing	Co, Cr, Cr(VI), Fe, Ni, Mn	V	Co, Cr, Cr(VI), Ni or Mn
	Work hardening	Fe, Mn, Cr		Mn
	Nickel-based	Cr, Cr(VI), Ni	Fe	Cr, Cr(VI) or Ni
	Copper-based	Cu, Ni		Cu or Ni
Gas-shielded metal arc welding with solid wires	Unalloyed and low-alloy steel	Fe, Mn, Cr, Ni, Cu		Mn
	High-alloy steel	Cr, Cr(VI), Fe, Mn, Ni		Cr or Ni
	Aluminium alloys	Al, Mg, Mn, Zn		Al, Mn or Zn

Type of process	Type of consumable	Typical principal components	Other possible principal components	Typical key components
	Nickel-based	Cr, Cr(VI), Ni	Fe	Cr or Ni
	Copper-based	Cu, Ni		Cu or Ni
Gas-shielded metal arc welding with metal-cored and flux-cored wires	Unalloyed and low-alloy steel	Fe, Mn, Cr, Ni, Cu	F^-	Mn
	High-alloy steel	Cr, Cr(VI), Fe, Mn, Ni	F^-	Cr(VI) or Ni
	Hardfacing	Co, Cr, Cr(VI), Fe, Ni, Mn	V	Co, Cr, Cr(VI), Ni or Mn
Self-shielded metal arc welding with flux-cored wires	Unalloyed and low-alloy steel	Fe, Mn, Cr, Ni, Cu, Al	Ba, F^-	Mn
	High-alloy steel	Cr, Cr(VI), Fe, Mn, Ni, Al	Ba, F^-	Cr(VI) or Ni
	Hardfacing	Co, Cr, Cr(VI), Fe, Ni, Mn, Al	V	Co, Cr, Cr(VI), Ni or Mn

The workplace concentrations of Cr(VI) may be 1 magnitude higher in fumes from MMA/SMA and in FCW/FCAW compared to MIG/MAG/GMAW. Whereas using the former techniques about 30 % up to over 90 % of the emitted chromium may be hexavalent, in MIG/MAG/GMAW only 1 % to 5 % (in rare cases up to 10 %) of the emitted chromium may be hexavalent. These differences can be seen also in terms of the absolute emission rates of Cr(VI).

Gas welding fumes would mainly depend on the base materials being joined and oxyacetylene (no consumables, or shielding gases). In autogenous processes, nitrogen oxides and dangerous carbon compounds (such as carbon monoxide from incomplete combustion) are predominantly released. Electron beam welding fumes would also depend on the base metals being joined.

Welding fumes+ includes soldering fumes from soldering processes, where the base material is not melted. For this reason, the soldering fumes only contains evaporation products from the solders and fluxes used. In the case of soft soldering, essentially tin-based solders are used, e.g. alloys "Sn99Cu1", "Sn95Ag4Cu1”, lead-containing solders contain lead in addition to tin, e.g. alloy "Sn60Pb40”. In the case of soft soldering, tin and tin oxide are the main fume components of the solder, while tin, lead and their oxides occur when leaded solders are used. In addition, depending on the composition of lead-free solders, copper, silver and their oxides cannot be excluded. Fluxes mainly used are natural resins, e.g. rosin, organic acids, e.g. adipic acid, and chlorides, e.g. zinc chloride, ammonium chloride. In particular aldehydes (from rosin) and hydrogen chloride, e.g. from ammonium chloride, must be taken into account as gaseous hazardous substances. Furthermore, evaporating solvents from fluxes, e.g. isopropanol, occur. Soft solders (with the exception of tin solder bars) already contain approx. 2 to 3 % flux. In various applications, however, flux pins, soldering fluid and soldering grease are additionally used.

For flame brazing (hard soldering, working temperature > 450 °C), e.g. of copper-brass, copper-steel, mainly brazing alloys based on brass are used, which also contain additives of silver ("silver brazing alloys"). The fluxes used for brazing contain boron compounds, chlorides and fluorides. Depending on the alloys and fluxes used, brazing fumes consisting of copper oxide, zinc oxide, silver oxide, chlorides and fluorides can be produced. Hydrogen chloride and hydrogen fluoride must be taken into account here as gaseous hazardous substances. In flame brazing for the production of copper-copper compounds, copper-phosphorus brazing alloys, where applicable also with silver content, are used; here, no flux is required. When brazing aluminium, appropriate aluminium brazing alloys (aluminium-silicon alloys) are used at working temperatures of up to 600 °C.

In arc brazing (MIG, TIG, plasma brazing) and laser beam brazing, working temperature

900-1100 °C, predominantly wire-shaped copper-based alloys are used as addition material, e.g. alloy "CuSi3", "CuAl8" or "CuSn6", here essentially copper oxide occurs in the soldering fume. Zinc oxide can additionally occur in galvanised sheets.

Thermal cutting and gouging would have similar components in the fume as for welding, but with fewer components. The fume composition depends on the chemical composition of the base material (one metal (usually) is melted for cutting, rather than 2 or more for joining) and any coatings or impurities present. In addition, nitrogen oxides or ozone occur depending on the process used.

During flame straightening the components of the fume depend on the material being straightened (steel, nickel, copper, brass and aluminium etc.) and the fuel gas being used (usually oxy-acetylene, so nitrous gases (nitrogen oxides) in particular may occur.

For all the processes described above, in addition to the metals (base metals and fillers) it is the surface condition of the workpiece including any surface coatings that determine fume components. Some of the following may be present on the surface[26]:

- metal working fluids, oils, and rust inhibitors
- zinc on galvanized steel (vaporizes to produce zinc oxide fume)
- cadmium plating
- chromates
- paints and solvents
- lead oxide primer paints
- plastic coatings

These should be removed, before the welding, as the removal would also improve weld quality, but this may not always be possible, or at least not the complete removal.

Additive manufacturing involves metal powders such as stainless steel, titanium, aluminium, cobalt and chrome. However, exposure of employees to fumes during the construction process can be excluded due to the enclosed design of the units.

5.1.3 Structure and morphology

Welding fumes+ consist of a wide range of complex metal oxide particles which can be deposited in all regions of the respiratory tract. The aerosol is not homogeneous and is generated mostly from the filler (electrode/wire) and the base metals (except for soldering where it is only generated from the filler). The basic mechanism of welding fumes+ generation is believed to consist of vaporisation of the elements and oxides from the welding area where the filler is consumed, with rapid condensation of the vapours to form particles. This formation of particles is referred to as nucleation. Nucleation is followed by coagulation, where smaller primary particles collide to form larger, chainlike agglomerates. This agglomeration is enhanced by the turbulent conditions resulting from the extreme heat during the welding process. There are in addition coarse (larger) nonagglomerated more spherical particles.

In addition to heavy metals, other toxic substances released during the welding process include ozone, carbon monoxide, carbon dioxide, and nitrogen oxides. Hazards linked to such gases can be assessed only if these molecules are known, the elemental composition of these gases does not inform as to possible hazards. On the other hand, there is a lot of confusion concerning solid particles. The nature of welding fume solid particles is well documented but complex(Floros, 2018). However this complexity is often not

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[26] https://www.ccohs.ca/oshanswers/safety_haz/welding/fumes.html

communicated in international guidance where solid components of welding fumes are characterised by elemental contents and/or described as simple compounds, especially simple oxides.

The two common misconceptions are:

- Elemental contents are sometimes interpreted as metallic contents
- Systematic simplification of complex oxide components to mono-elemental oxides

A third misconception is made regarding welding fume risk assessment between what is used to weld (which filler metal) and what is welded (which base metal). Both organic and metallic coatings will strongly modify the nature and/or composition of welding fumes but the associated risks do not come with the welding consumable.

The actual components of welding fumes should be taken into account and in particular spinel-type compounds have to be considered. Spinels are a class of minerals of general formulation AB_2X_4 which crystallise in the cubic (isometric) crystal system, with the X anions (typically oxygen or sulphur) arranged in a cubic close-packed lattice and the cations A and B occupying some or all of the octahedral and tetrahedral sites in the lattice. Depending on the stabilisation energy of the ligand field, spinels or inverse spinels are formed. In both cases, the oxygen anion forms a cubic dense sphere packing, and the tetrahedral or octahedral gaps are filled by metal cations. In the spinels of the AB_2O_4 type, the trivalent metal cations (type "B") are in the octahedral gaps and the divalent metal cations (type "A") are in the tetrahedral gaps. In the inverse spinels, half of the trivalent metal cations (type "B") are in the octahedral gaps and the other half in the tetrahedral gaps. The divalent metal cations (type "A") are in the octahedral gaps. Magnetite (Fe_3O_4), for example, is an inverse spinel. As a rule, the spinels and inverse spinels are insoluble, also extremely poorly soluble in biological media such as the lysosomal fluid and thus difficult to bioavailable. Although the charges of A and B in the prototypical spinel structure are +2 and +3, respectively ($A^{2+}B_2^{3+}2X_4^{2-}$), other combinations incorporating divalent, trivalent, or tetravalent cations, including magnesium, zinc, iron, manganese, aluminium, chromium, titanium, and silicon, are also possible. In fumes produced by steel welding, the major component is usually iron (average content 15–50%). High iron content will drive the formation of spinel structure compounds, AB_2O_4, where A site is usually occupied by a divalent cation and B site usually by a trivalent one. Fe^{2+}, Fe^{3+}, and other elements which can adopt stable divalent and/or trivalent state (Mg^{2+}, Al^{3+}, Cr^{3+}, Ni^{2+}, Mn^{2+}, Mn^{3+}, Co^{2+}, Cu^{2+}…) are found in spinel structure leading to particles of various chemical compositions. Since several cations may occupy the same crystallographic site, it is not possible to give an accurate chemical composition of the spinel-type compounds found in welding fumes; however, an average chemical formula can be proposed based on the major elements of which they are composed.

Fumes from soldering are similarly complex, although in this case the metal components come only from the filler (usually tin/copper alloys), as the base metal does not melt, and a variety of other chemicals generated from the flux, usually rosin (with other additives and solvent). Due to the infancy of additive manufacturing technologies there is lack of information on the content of the emissions (and related health impacts), and the fumes may be considered to be similar to those produced by laser welding and based on the alloy being used. However the process itself is enclosed in a chamber protected by inert atmosphere (oxygen free) to protect the printing process from any oxidation.

There are numerous articles available in literature describing particle size distribution, spinel structures, degradation products etc. and how they relate to health effects, which are very detailed and complicated to understand at this high level. However they basically indicate that the structures of the components in welding fumes+ are very diverse and complex, and the relationship with health effects is also not straightforward.

5.2 Welding fumes+ controls

The Chemical Agents Directive (CAD) places responsibility on employers to protect the health and safety of their employees from the risks from all chemical agents in the workplace. This includes chemical agents such as fume generated by processes, and substances that become hazardous because of the way they are used[27].

CAD requires employers to identify, assess and control, by eliminating if possible, or otherwise by minimising such risks. Central to this process is the employer's risk assessment, drawing on information, such as labels, safety data sheets or published guidance, to identify and use control measures appropriate to the way the chemical agent is used in their workplace.

If exposure of employees to hazardous substances cannot be avoided during welding work, appropriate protective measures are required to eliminate or minimise the risk. The measures have to follow the "hierarchy of control" principles, as described by the OSHwiki[28], [29]:

1. Elimination

Employers should assess if it is possible to eliminate the welding hazard, ie means creating a joint between two materials without welding e.g. mechanical joining processes such as clinching, riveting, screwing.

2. Substitution

If elimination is not possible then consider substitution, e.g. using a different welding process that leads to a reduced risk of exposure, such as using TIG instead of MIG/MAG. The TRGS 528 identifies a number of ways to consider substitution from using mechanical joining processes or welding processes which are identified as being in the "low emission group" to optimising parameters that reduce fume emissions, from electrical parameters (welding current, welding voltage) to shielding gas type and composition.

3. Isolation

If elimination or substitution are not possible, and the specific welding process is needed then there are some practical measures to minimise the risk. The first option is "isolation", which means making a separation between the hazard and the risk receptor, Practically, this is achieved by restricting access to the plant or equipment, especially during the period that the welding takes place, or in the case of substances (fillers etc.) locking them away so that only certain authorised workers have access.

4. Engineering controls/measures

This is the subsequent and most effective option in reducing exposure during the welding, by including process enclosures, general ventilation and local exhaust ventilation. Robotic welding is an example of an application that would use process enclosure to protect the operator from potential fume exposure. General ventilation could include using an HVAC system or high-powered fans to move large quantities of air in order to dilute or filter contaminants based on an air change schedule. Local exhaust ventilation includes portable and stationary fume extractors, extraction arms with centralized collectors and fume extraction guns. The extraction of hazardous substances should primarily take place close

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[27] http://ec.europa.eu/social/BlobServlet?docId=6126&langId=en#:~:text=CAD%20places%20responsibility%20on%20employers,the%20way%20they%20are%20used.

[28] https://oshwiki.eu/wiki/Hierarchy_of_prevention_and_control_measures

[29] https://oshwiki.eu/wiki/Prevention_and_control_strategies

to the point of origin (called source capture). Air that has been extracted must only be returned to the working area if it has been sufficiently cleaned.

5. Administrative controls/measures

This includes adopting standard operating procedures or safe work practices or providing appropriate training, instruction or information to reduce the potential for harm and/or adverse health effects. Permit to work procedures are examples of administrative controls and could, for example, include cleaning of the surfaces before welding or using stripping products to remove coatings, which would subsequently reduce the number of contaminants in the fume.

6. Personal protective equipment (PPE)

The last option in the hierarchy of controls is that of personal protective equipment. As a rule, welders wear suitable protective clothing such as a leather apron, welding gloves and protective footwear as well as a welding hood or helmet with suitable radiation protection filters. Depending on the conditions of exposure, suitable respiratory protective equipment may also be required. Ventilated welding helmets/hoods with blowers are available on the market. PPE is the last line of defence and is usually used in conjunction with one or more of the other exposure control measures.

The effectiveness of the protective measures taken has to be checked by means of workplace measurements or other appropriate methods of investigation, prior to their implementation in the workplace, and then periodically. If such a review indicates that exposures are too high (limit values are not complied with) then the implemented measures are insufficient. This leads to a review of the workplace risk assessment, and the initiation of further exposure-reducing measures. Employers must also carry out health surveillance when the fume contains substances such as chromium. In case OELs are exceeded a combination of different STOP measures may be installed to comply with the risk minimisation request. A good example for this kind of approach is the "REarc Welding Initiative" to substantially Reduce Exposures in arc welding e.g. by exploring different layers of minimization:

- Low energy arc processes and parameters (see Table 1 from TRGS 528)
- Optimized chemical composition of process (shielding) gas
- Optimized chemical composition of filler (consumable).

5.3 Summary of welding processes+, generated substances, indication of CMRs and the potential for worker exposure

Table 3: Summary of welding processes+, generated substances, indication of CMRs and worker exposure

		Hazardous substances generated	CMRs (1A/1B) or not	Presence of the hazardous substances is known/proven, possible or exceptional	Workers are likely to be exposed or not
1	**Fusion welding**				
	Gas welding	Metal oxides from the base and filler materials, nitrogen oxides	Yes, depending on the base and filler materials	Base and filler materials: mild steel (Fe, Mn), copper alloys (Cu, Ni, Zn), aluminium (fluorides from the flux)	Yes, usually manual process, but low particle emissions.
	Arc welding - consumable electrode (filler) (MIG, MAG, SMAW, FCAW, SAW, ESW, SW)	Metal oxides mostly from the filler material, nitrogen oxides, carbon monoxide (MAG), ozone (aluminium alloys)	Yes, depending on the filler material, carbon monoxide (MAG)	Base and filler materials: mild steel (Fe, Mn, fluorides), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V, fluorides), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu)	Yes, mainly in the craft sector. Automated processes are often used in industrial applications.
	Arc welding - non-consumable electrode (TIG; PAW)	Metal oxides mostly from the filler material, ozone	Yes, depending on the filler material	Base and filler materials: mild steel (Fe, Mn), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu), titanium alloys (Ti, Al, V), zirconium alloys (Zr)	Yes, mainly in the craft sector. Automated processes are often used in industrial applications.
	Beam welding	Metal oxides from the base material	Yes, depending on the base material	Base materials: mild steel (Fe, Mn), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu), titanium alloys (Ti, Al, V), zirconium alloys (Zr)	Not directly as almost completely automated. However, fume extraction system required to protect workers in the vicinity.

		Hazardous substances generated	CMRs (1A/1B) or not	Presence of the hazardous substances is known/proven, possible or exceptional	Workers are likely to be exposed or not
2	**Soldering**				
	Soft soldering (90°C- 450°C)	Mainly tin and tin oxides (from filler material), aldehydes (from rosin) and hydrogen chloride, evaporating solvents (isopropanol) from fluxes.	No, as long as lead-free due to restriction	Filler materials: mainly tin-based solders (e.g. Sn99Cu1 or Sn95Ag4Cu1) Fluxes: natural resins (e.g. rosin), organic acids (e.g. adipic acid) and chlorides (e.g. zinc chloride or ammonium chloride)	Yes, in the craft sector. Automated processes are often used in industrial applications.
	Hard (silver) soldering (> 450°C, flame brazing)	Copper oxide, zinc oxide, silver oxide, chlorides and fluorides (hydrogen chloride and hydrogen fluoride)	No	Filler materials: brazing solders made of copper-zinc alloys with additives of silver	Yes, in the craft sector. Automated processes are often used in industrial applications.
	Brazing (> 450°C, Laser beam brazing, Brazing with an electric arc (MIG, TIG, plasma)	Copper oxide Exceptionally cadmium oxide	No, with specific exceptions	Filler materials: copper-based alloys (e.g. CuSi3, CuAl8 or CuSn6) Exceptionally in defence and aerospace applications and when used for safety reasons (brazing fillers with cadmium)	Yes, in the craft sector. Automated processes are often used in industrial applications.
3	**Thermal cutting or gouging**	Metal oxides from the base material, nitrogen oxides, ozone	Yes, depending on base materials (e.g. Cr(VI) and Ni)	Base materials: mild steel (Fe, Mn), stainless steel (Fe, Mn, Cr(III), Cr(VI), Ni, Co, V), cast iron (Fe, Mn, Cr(VI), Ni), nickel-based alloys (Ni, Cr(VI), Fe), copper alloys (Cu, Ni), aluminium alloys (Al, Mg, Mn, Zn, Cu), titanium alloys (Ti, Al, V), zirconium alloys (Zr)	Yes, in the craft sector. Automated processes are often used in industrial applications.
4	**Thermal spraying**	Metal oxides from the spray additive, nitrogen oxides	Yes, depending on the spray additives (e.g. Cr(VI), Ni, Co)	Spray additives: boron, cobalt, molybdenum, nickel, chromium, silicon, plastics,	Yes, in the craft sector. For large components open

		Hazardous substances generated	CMRs (1A/1B) or not	Presence of the hazardous substances is known/proven, possible or exceptional	Workers are likely to be exposed or not
		(depending on energy source)		copper, carbides (WC-12Co, WC-27NiCr, WC-14CoCr, WC/Ti-C-17-Ni, Cr_3C_2-25NiCr etc.), steel, aluminium, zinc, bronze (Cu, Sn), tin, Monel (Ni, Cu, Fe), oxide ceramics (Al_2O_3, Cr_2O_3, TiO_2, Y_2O_3, ZrO_2), tantalum	spraying, for small components in spray booths. Automated processes are often used in industrial applications.
5	**Flame straightening**	Nitrogen oxides	No	Nitrogen oxides occur	Yes, usually manual process.
6	**Additive production processes**	Metal powders	No, the substrates do not contain carcinogenic substances. Carcinogenic substances can be formed in the closed installation space (e.g. nickel oxide).	Metal powders, especially iron, titanium, nickel, chromium and aluminium alloys	No, construction occurs inside closed machines.

6. Monitoring exposure

6.1 External exposure

Different strategies for measuring welding fumes+ can be followed. The total amount of fumes can be measured as well as the individual components of the fumes (metal or metal compounds). The gases generated during the welding can also be measured independently.

For the fumes measurement, the principle of most of the methods is trapping the sample on a suitable filter by using a particle sampler (for inhalable or respirable fraction). Then the fumes are measured via the chosen technique (this may involve some sample preparation (e.g. extraction) depending on the analytical technique used. The methods for fumes (for total concentration of fumes) or for individual compounds are summarized in Table 4.

Gravimetric methods for dust (inhalable or respirable) can be used to determine the total concentration of fumes.

Regarding the determination of individual metal (and its compounds), there are different techniques that can be used to measure metals in air. Table 4 covers methods that allow the determination of several metals (and their compounds) in a single analysis, as routine analysis of all metals separately will highly increase the cost and normally will not be justified. However, other techniques could be used in cases where lower concentrations need be achieved or in situations where it is clear that one metal specifically drives the assessment.

The table states whether the method includes sampling of inhalable, respirable fraction or both. When a specific particulate sampler (and its associated flow rate) has been recommended the calculations of the sampling time have used the maximum flowrate recommended by the method. However, the latter does not exclude that the methods have the potential to use other sampler at different flowrates that may allow to achieve lower LOQ or to collect a different aerosol fraction. The methods appearing under "similar methods" have a similar methods principle and analytical technique and may differ in the sample preparation or in details such as the filter, or the sampler used.

Table 4: Methods for fumes

Method /Agent	Analytical technique	LOQ and sampling volume ad time	Similar methods/ comments
NIOSH 0500 {NIOSH, 1994 #451} NIOSH 0600 {NIOSH, 1998 #452} Inhalable or respirable dust (total welding fume)	Gravimetric	0.03 mg/filter (LOD) 0.1 mg/filter (LOQ) Flow rate 2 l/ min 0.2 mg/m3 for a 480 l sample (4 hours) Note: using higher flow rate samplers (10 l/min) the LOD could be further lowered ≈0.04 mg/m3	MDHS 14/3 MétroPol Fiche 002 and INSHT MTA/MA-014/A88
OSHA ID-125G {OSHA, 2002 #457} Metal and metalloids	ICP-AES	Al: 0.05 mg/m^3 Co: 0.008 mg/m^3 Cr: 0.003 mg/m^3 Cu:0.004 mg/m^3 Fe: 0.06 mg/m^3 Mg: 0.01 mg/m^3 Mn: 0.0004 mg/m^3	

Method /Agent	Analytical technique	LOQ and sampling volume ad time	Similar methods/ comments
		Ni: 0.004 mg/m^3 V: 0.004 mg/m^3	
		Flow rate : 2 l/min Sample volume 480l (4 hours)	
MDHS 91/2 {HSL, 2014 #458} Metals and metalloids in air by X-ray fluorescence spectrometry (Inhalable fraction)	X-ray fluorescence spectrometry	Ba: 0.001 mg/m^3 Co: 0.0006 mg/m^3 Cr: 0.0004 mg/m^3 Cu: 0.0004 mg/m^3 Fe: 0.001 mg/m^3 Mn: 0.02 mg/m^3 Ni: 0.0004 mg/m^3 Flow rate : 2 l/min Sample volume 480l (4 hours) Note: using higher flow rate samplers (10 l/min) the LOD could be further lowered approx. by a factor of 5.	A sampler for the respirable fraction could be used if required
IFA 7808	ICP/MS	As: 0.0000014 mg/m^3 Be: 0,00000029 mg/m^3 Cd: 0,000011 mg/m^3 Co: 0,000029 mg/m^3 Ni: 0,00011 mg/m^3 Flow rate: 10 l/min Sample volume: 1200 l (2 hrs)	A sampler for the respirable fraction could be used if required
ISO 15202- parts 1,2, and 3 (ISO, 2020) (Inhalable, thoracic respirable fraction or multifraction)	ICP-AES	Co: 0.0004 mg/m^3 Cr: 0.0006 mg/m^3 Copper: 0.0026 mg/m^3 Mn:0.0002 mg/m^3 Ni: 0.0018 mg/m^3 Flow rate: 2 l/min Sample volume: 480 l (4 hrs)	The standard recommends to use a sampler for the fraction relevant for the metal(s) that fulfils the EN 481 requirements. The LOQ can be lowered by using a sampler that runs at a higher flow rate (e.g. 10 l/min)

(1) Sampling time calculated for the maximum flow of 10 l/min (maximum flow rate for common inhalable and respirable fraction samplers)

For the gases (NOx, CO, O_3 etc) monitoring methods can be sampling and analysis, or direct reading (see Table 5).

Table 5: Methods for gases

Method /Agent	Analytical technique	LOQ and sampling volume ad time
NIOSH 6604 {NIOSH, 1996 #459} Carbon monoxide (CO)	Direct reading monitor	1.14 mg/m^3 (Instrument dependent)
NIOSH 6014 {NIOSH, 1994 #460} NO and NO_2	UV/VIS (1)	For NO: 1.3 mg/m^3 for a 1,5L/ sample (1 hour)
		For NO_2: 1 mg/m^3 for a 3 L/ sample (2 hours)
OSHA ID-214 {OSHA, 2008 #461} O_3	UV/VIS (1)	0.06mg/m^3 for 90 L sample (3 hours)

(1) Visible absorption spectrophotometry

6.2 Biomonitoring of exposure (internal exposure)

There is no biomarker established for welding fumes+ as such. However, biomonitoring can focus on the individual components of the fume. Metals are often biomonitored (see for instance section 8 for BLVs and BRVs established in different MS).

7. Regulation of the substances in welding fumes+ in the EU

7.1 Directive 98/24/EC and Directive 2004/37/EC

The metals and metal oxides contained in welding fumes+ fall within the scope of Directive 98/24/EC and Indicative Occupational Exposure Limit Values (IOELVs) have already been enacted for many lead components, e.g. for manganese and inorganic manganese compounds, silver, inorganic fluorides, barium, chromium and chromium(II) or chromium(III) compounds, carbon monoxide, nitrogen monoxide, nitrogen dioxide.

For carcinogenic metals and metal compounds, Directive 2004/37/EC applies with Binding Occupational Exposure Limit Values (BOELVs) specified therein, such as for chromium(VI) compounds, nickel compounds, cadmium and its inorganic compounds, beryllium and its inorganic compounds. A workplace occupational exposure limit established under either of these directives would apply automatically to welding fumes+.

7.2 EU Harmonised Classification & Labelling - CLP (EC) 1272/2008

As pointed out in Section 2, welding fumes+ are complex covering several substances depending on the metal being worked and the process being used, and other factors such as the source of energy. The fumes in this case are process generated and therefore are not subject to the CLP regulation, even if some of the material used in the process may be subject to CLP.. For example the fillers used in brazing could be mixtures or articles under REACH, and if considered mixtures (alloys are special mixtures) they are subject to CLP. Special labelling rules apply to alloys containing cadmium which are intended to be used for brazing or soldering (point 2.7 of Annex II to CLP): [The label on the packaging shall bear the following statement: EUH207 — 'Warning! Contains cadmium. Dangerous fumes are formed during use. See information supplied by the manufacturer. Comply with the safety instructions'].

Looking at some of the substances in Section 2, metal compounds such as beryllium oxide, chromium (VI) compounds and nickel compounds have harmonised classifications. Also some gaseous substances such as carbon monoxide have harmonised classifications.

Although welding fumes+ as such do not have a harmonised classification and labelling for carcinogenic effects under the CLP Regulation, some of the welding fumes+ constituents mentioned in the previous paragraphs (e.g. CrVI compounds) have such a harmonised classification as Carc 1A or 1B and are thus in the scope of CMRD as defined by Article 2 paragraph a(i).

However, the CMRD Article 2 definition of 'carcinogen' includes also paragraph (a)(ii) which concerns *a substance, mixture or process referred to in Annex I to this Directive as well as a substance or mixture released by a process referred to in that Annex*. Welding fumes+ are released by a process.

IARC (2108) considered *welding fumes* carcinogenic to humans (Group 1). It is noted that IARC concluded on *welding fumes* overall without specifying for which type of welding or for which base metal welded the conclusions apply. Some further analysis is presented in Appendix 1 as regards what types of welding or welding fumes were covered by the studies used in that IARC evaluation. Such considerations might be relevant when defining the scope of the welding fumes+ entry in CMD/CMRD Annex I. As explained the exposure concerns specific substances that are already covered by the Article 2 a(i) definition via CLP and the processes which could be covered by Article 2 a (ii).

7.3 REACH Registrations

The substances in welding fumes+ are process generated and thus are not subject to REACH registration. The base metals are part of an article and the filler materials could be articles or mixtures (alloys are special mixtures), and although covered by REACH are not subject to REACH registration. Certain substances in welding fumes+ may be registered due to other uses but this scoping report does not describe the REACH registration data for those substances because the tonnage information would not be useful. For example, although the total registration tonnage of a substance such as nickel could be estimated the amount specifically used for solders cannot, as information on the tonnage per use is not provided in registration data.

7.4 Authorised uses under Annex XIV of REACH

Chromium (VI) is the only substance involved in welding that is included in Annex XIV of REACH ("Authorisation List"). It is still widely used in functional or hard chrome plating and surface treatment, with an annual estimated tonnage of 7,000 tonnes. Chrome plating and surface treatment are done in industrial settings, to add a protective coating to metal parts and products and enhance the strength of the surface as well as wear and corrosion resistance. The treated surface does not contain chromium trioxide, but there is exposure for workers during the plating to the harmful chemical (chromium (VI)) that can cause cancer.

Welding processes do not use chromium (VI) as a starting material, either as a base material or as an additional (filler) material. However, chromium (VI) compounds are formed during certain welding operations, for example, welding of high-alloy steels. In build-up welding, metal mixtures containing chromium can be used as a base material, but not metal mixtures containing chromium (VI).

7.5 Restricted uses under Annex XVII of REACH

No specific entry, also because welding fumes+ are generated upon use and it is not the use of a substance.

8. Existing occupational limit values

At EU level, there is no OEL specific for welding fumes+. However, some Member States have established a specific OEL for welding fumes (for 8 -h TWA).

8.1 OELs

Table 6 presents OEL values for several EU Members States and some values from countries outside the EU.

Moreover, the EU and MS have established OELs for several of the welding metal (possible) components and the associated gases.

For metals, Table 7 summarizes OELs for individual metals most often found in welding. Where several entries per metal where available, the OELs for the metal fumes, metal and inorganic compounds and /or metal oxides have been chosen. See the "remarks" column for more details.

For gases, the OELs for ozone, nitrogen oxides and carbon monoxide are presented in Table 8, Table 9 and Table 10.

The list should not be considered as exhaustive.

Table 6: Existing Occupational Exposure Limits (OELs) indicated as 8-h Time-Weighted Average (TWA) for welding fumes

Country	mg/m^3	Remarks
Austria	5 (R)	Respirable aerosol
Belgium	5	
France	7 (inhalable) 3.5 (respirable)	From July 2023, the following values will apply: 4 (inhalable) 0.9 (respirable)
Denmark	0,5-1,7	Electrode methods - stainless steel 0,5 TIG 1,1 MIG/MAG 1,6 Flame cutting 1,7 Electrode methods - construction steel 1,7
Germany	1.25 (R)	Respirable aerosol. No specific for limit value for "welding fumes", but as a general dust limit value for granular bio-resistant dusts with a mean density of 2.5 g/cm^3.
Ireland	5	
Latvia	4	
Norway	5	
The Netherlands	1	
United Kingdom	[5]	The UK Advisory Committee on Toxic Substances has expressed concern that, for the OELs shown in parentheses, health may not be adequately protected because of doubts that the limit was not soundly-based. These OELs were included in the published UK 2002 list and its 2003 supplement, but were omitted from editions published from 2005 onwards.

Table 7: Existing Occupational Exposure Limits (OELs) for metals (and oxides) common in welding indicated as 8-h Time-Weighted Average (TWA) for welding fumes

Metal	TWA (8 hrs)		STEL (15 min)		Remarks
	EU value (range)^1 mg/m^3	Countries	EU value (range)^1 mg/m^3	Countries	
Aluminium	(1-10) I and R	AT, BE, DE, DK, ES, FI, FR, HU, IE, LT, NO, PL RO, SE	(3-20) I and R	AT, DK, PL, RO	OEL values for metal, metal oxide, fumes …
Barium	0.5 (0.5) I	EU wide	(0.5- 4) I	AT, DE	OEL for Barium soluble compounds EU IOELV
Cobalt	(0.0005-0.5) I	AT, BE, DK, ES, FI, DE, HU, IE, LT, NL, NO, PL, RO, SE	(0.04-0.4) I	AT, DK, DE, HU, RO	OELs values for cobalt and its compounds and cobalt oxides
Chromium metal and Cr (II) /(III)	2 (0.5-2) I	EU wide	(1 -2) I	DK, DE, HU, NL	Chromium Metal, Inorganic Chromium (II)Compounds and Inorganic Chromium (III)Compounds (insoluble) EU IOELV
Hexavalent Chromium (Cr(VI))	0.005 (0.001-0.1) I	EU wide	(0.008 - 0.2) I	AT, DE, FR, HU	Chromium(VI) compounds EU BOELV
Copper	(0.01-0.2) I and R	AT, BE, DE, DK, ES, FI, FR, HU, IE, NO, PL, SE	(0.02-0.4)	AT, DE, DK, HU, PL,RO	OEL for Copper fume
Iron	(2.5- 6) I and R	AT, BE, DK, ES, FI, HU, IE, NO, PL, RO, SE	(5-10)	AT, DK, IE, PL	OEL for iron (III) oxide fume or respirable dust
Magnesium	(0.3 – 10) I and R	BE, DE, DK, ES, FR, HU, IE, NO, PL, RO	(2.4 -24)	DE, DK, HU, RO	Magnesium oxide as Mg or MgO
Manganese	0.2 I (0.1- 5) 0.05 R (0.02-0.05) I and R	EU wide	(1,6-20) I (0.1-0.16)	AT, DK, DE, HU	Manganese and inorganic compounds
Nickel	0.1 (I) 0.006-0.1 I and R	EU wide	(0.048-2) I and R	AT, DE, DK, HU, RO	Until 17 January 2025
	0.05 (I) 0.01(R)	EU wide			From 18 January 2025
Vanadium	(0.005-0.2) I and R	AT, BE, DE, DK, ES, FI, HU, IE,NL, PL, RO, SE	(0.005-0.25)	AT, DE, DK, HU, NL, SE	Vanadium, Vanadium oxide

(1) The range corresponds to the values implemented in the different EU MS.
(2) BOEL is set to 0.025 mg/m^3 for welding and similar processes and 0.01 mg/m^3 for other activities until 2025
I= Inhalable fraction
R= Respirable fraction

Table 8: Existing Occupational Exposure Limits (OELs) indicated as 8-h Time-Weighted Average (TWA) and Short-term exposure (15 min) for Ozone

Country	TWA (8 hrs)		STEL(15 min)		Remarks
	ppm	mg/m^3	ppm	mg/m^3	
Austria	0,1	0,2	0,2	0,4	
Belgium			0,1 (1)(2)	0,2 (1)(2)	(1) Additional indication "M" means that irritation occurs when the exposure exceeds the limit value or there is a risk of acute poisoning. The work process must be designed in such a way that the exposure never exceeds the limit value. For evaluation, the sampled period should be as short as possible. However, the sampled period shall be long enough to perform a reliable measurement. The measured result shall be related to the considered period. (2) 15 minutes average value
Denmark	0,1	0,2	0,1 (1)	0,2 (1)	(1) Ceiling limit value
Finland	0,05	0,1	0,2 (1)	0,4 (1)	(1) 15 minutes average value
France	0,1	0,2	0,2	0,4	
Hungary		0,2		0,2	
Ireland	0,05 (1) 0.08 (2) 0,10 (3) 0,20 (4)				(1) Heavy works (2) Moderate works (3) Light works (4) Heavy, moderate or light works (<= 2h)
Latvia		0,1			
Norway	0,1	0,2			
Poland		0,15			
Romania	0,05	0,1	0,1 (1)	0,2 (1)	(1) 15 minutes average value
Spain	heavy work 0,05	heavy work 0,1			

Country	TWA (8 hrs)		STEL(15 min)		Remarks
	ppm	mg/m^3	ppm	mg/m^3	
	moderate work 0,08 light work 0,1 heavy, moderate and light works < 2 hours 0,2	moderate work 0,16 light work 0,2 heavy, moderate and light works < 2 hours 0,4			
Sweden	0,1	0,2	0,3 (1)	0,6 (1)	
Switzerland	0,1	0,2	0,1	0,2	
The Netherlands		0,12			
USA - NIOSH			0,1 (1)	0,2 (1)	
USA - OSHA	0,1	0,2			
United Kingdom			0,2	0,4	

Table 9: Existing Occupational Exposure Limits (OELs) indicated as 8-h Time-Weighted Average (TWA) and Short-term exposure (15 min) for NOx)

Country	Nitrogen dioxide (NO_2)				Nitrogen monoxide (NO)				Remarks
	TWA (8 hrs)		STEL (15 min)		TWA (8 hrs)		STEL (15 min)		
	ppm	mg/m^3	ppm	mg/m^3	ppm	mg/m^3	ppm	mg/m^3	
Austria	0,5	0,96	1 (1)	1,91 (1)	2	2,5			(1) Ceiling limit value
Belgium	3	5,7	5 (1)	9,5 (1)	2	2,5			(1) 15 minutes average value
Denmark	2 (1)(2)	4 (1)(2)	2 (1)(2) (3)	4 (1)(2) (3)	2 25 (1)	2,5 30 (1)	4 (2) 50 (1)(2)	5 (2) 60 (1)(2)	(1) Skin (2) In mining and tunnel construction, until 21 August 2023 applies to Nitrogen dioxide (3) Ceiling limit value
EU (IOELV)	0,5	0,96	1 (1)	1,91 (1)	2	2,5			(1) 15 minutes average value
Finland	0,5	0,96	1 (1)	1,9 (1)	2	2,5			
France	0,5	0,96	1 (1)	1,91 (1)	2	2,5			

Country	Nitrogen dioxide (NO_2)				Nitrogen monoxide (NO)				Remarks
	TWA (8 hrs)		STEL (15 min)		TWA (8 hrs)		STEL (15 min)		
	ppm	mg/m^3	ppm	mg/m^3	ppm	mg/m^3	ppm	mg/m^3	
Germany (AGS)	0,5 (1)	0,95 (1)	1 (1)(2)	1,9 (1)(2)	2 (1)	2,5 (1)	4 (1)(2)	5 (1)(2)	
Germany (DFG)	0,5	0,95	0,5 (1)	0,95 (1)	0,5	0,63	1,0 (1)	1,26 (1)	
Hungary		9		9		30			
Ireland	3 (1)	5 (1)	5 (1)(2)	9 (1)(2)	25 (1)	30 (1)	35 (1)(2)	45 (1)(2)	
Italy	0,5 (1)	0,96 (1)	1 (1)(2)	1,91 (1)(2)	2 (1)	2,5 (1)			
Latvia	0,5	0,96	1 (1)	1,91 (1)	2	2,5			
Norway	0,5	0,96	1 (1)	1,91 (1)	2	2,5			
Poland		0,7		1,5		2,5			
Romania	0,5	0,96	1 (1)	1,91 (1)	2	2,5			
Spain	0,5 (1)	0,96 (1)	1 (1)(2)	1,91 (1)(2)	2 (1)	2,5 (1)			
Sweden	0,5	0,96	1 (1)	1,9 (1)	2	2,5			
The Netherlands		0,4		1		0,25			
USA - NIOSH			1 (1)	1,8 (1)	25	30	25	30	
USA - OSHA			5	9	25	30	25	30	
United Kingdom	0,5 (1)	0,96 (1)	1 (1)(2)	1,91 (1)(2)	2 *25*(1)	2,5 *30* (1)			

Table 10: Existing Occupational Exposure Limits (OELs) indicated as 8-h Time-Weighted Average (TWA) and Short-term exposure (15 min) for carbon monoxide

Country	TWA (8 hrs)		STEL (15 min)		Remarks
	ppm	mg/m^3	ppm	mg/m^3	
Austria	20	23	60 (1)	66 (1)	(1) 15 minutes average value
Belgium	20	23	100 (1)	117 (1)	(1) 15 minutes average value

Country	TWA (8 hrs)		STEL (15 min)		Remarks
	ppm	mg/m³	ppm	mg/m³	
Denmark	20 25 (1)	23 29 (1)	40 (2) 50 (1)(2	46 (2) 68 (1)(2)	(1) In mining and tunnel construction, until 21 August 2023 applies to Carbon monoxide. (2) 15 minutes average value
European Union	20	23	100 (1)	117 (1)	Binding Occupational Exposure Limit Value (IOELV) (1) 15 minutes average
Finland	20	23	75 (1)	87 (1)	(1) 15 minutes average
France	20	23	100 (1)	117 (1)	Restrictive statutory limit values (1) 15 minutes average value
Germany (AGS)	30	35	60 (1)	70 (1)	(1) 15 minutes average value
Germany (DFG)	30	35	60 (1)	70 (1)	(1) 15 minutes average value
Hungary		33		66	
Ireland	20	23	100 (1)	117 (1)	(1) 15 minutes average value
Italy	20 (1)	23 (1)	100 (1)(2)	117 (1)(2)	(1) For mining and tunnel activities only: the limit value applies from 22 August 2023 (D.I. 02.05.2020; paragraph 1, art. 2 (2) 15 minutes average value
Latvia	17	20	100 (1)	117 (1)	
Norway	20	23	100 (1)	117 (1)	(1) 15 minutes average value
Poland		23		117	
Romania	20	23	100 (1)	117 (1)	(1) 15 minutes average value
Spain	20 (1)	23 (1)	100 (1)(2)	117 (1)(2)	(1) For this agent there is a transitional period, which will end, at the latest, the Member States may continue to apply the national limit value August 21, 2023, for the underground mining and tunnel construction sectors. During this period it will be applicable in these sectors before the end of this period (2) 15 minutes average value
Sweden	20	23	100 (1)	117 (1)	(1) 15 minutes average value
Switzerland	30	35	60	70	
The Netherlands		29			
USA - NIOSH	35	40	200 (1)	229 (1)	(1) Ceiling limit value

Country	TWA (8 hrs)		STEL (15 min)		Remarks
	ppm	mg/m^3	ppm	mg/m^3	
USA - OSHA	50	55			
United Kingdom	20 *30 (1)*	23 *35 (1)*	100 (2) *200 (1)(2)*	117 (2) *232 (1)(2)*	(1) Values in italics are limits applicable to underground mining & tunnelling industries ONLY until 21/8/23 (2) 15 minutes average value

Source: Gestis database (searched November 2021): International limit values for chemical agents (Occupational exposure limits, OELs) (https://www.dguv.de/ifa/gestis/gestis-internationale-grenzwerte-fuer-chemische-substanzen-limit-values-for-chemical-agents/index-2.jsp)

8.2 Biological limit values

There are no BLVs established for welding fumes+ as such. However, several MS have established biological limit values or reference values for some of the possible components of the welding fumes+. Table 11 and Table 12 show BLV established for some of the metals common in welding fumes+ (search based on the metals identified in Table 7).

Table 13 shows the biological limit values established for carbon monoxide.

Table 11: Overview of existing occupational BLVs and reference values for the general population (not occupationally exposed) for metal compounds in urine

Metal	Country/ Organisation	Metal in urine	Specifications
Aluminium	Germany	50 µg/g creatinine	BAT (1) Sampling time: for long-term exposures: at the end of the shift after several shifts
	Finland	3 µmol/L (i.e. 80 µg/L)	BAL Sampling time: before the first shift after 2 days without exposure
	Germany	15 µg/g creatinine	BAR (general population) sampling time not relevant
Barium	Germany	10 µg/L	BAR (general population) sampling time not relevant
Cobalt	France	5 µg/g creatinine	VLB Sampling time: end of exposure week
	ACGIH	15 µg/L	VLB Sampling time: end of exposure week
	Germany	Range of values starting from value of 3 µg /l urine for an external concentration of 0.005 mg/m3 in air	EKA value Sampling time: for long-term exposure: at the end of the shift after several shifts
	Finland	130 nmol/L (i.e 7,7 µg/L) e	BAL : end of exposure week
	Spain	15 µg/L	VLB Sampling time: end of exposure week

	Germany	1,5µg/L	BAR (general population) sampling time not relevant
Hexavalent Chromium(Cr(VI))	France	2,5 µg/L (1,8 µg/g creatinine)	VLB Sampling time: end of exposure week
	ACGIH	0,7 µg/L	VLB Sampling time: end of exposure week
	Finland	0,2 µmol/L (i.e. 10,4 µg/L) With a target of 0,01 µmol/L (i.e. 0,52 µg/L).	VLB Sampling time: end of exposure week
	Spain	10 µg/L	VLB Sampling time: beginning and end of exposure week (value refer to the difference between the two points)
		25 µg/L	Sampling time: end of exposure week
	France	0,65 µg/L (0,54 µg/g. creatinine)	VBR (general population)
Nickel	Germany	Insoluble compounds Range of values starting from value of 15 µg Ni/l urine for an external concentration of 0.1 mg/m^3 in air	EKA value
	Germany	3 µg/L	BAR (general population)
	Finland	Soluble compound 0,2 µmol Ni /L urine (12 µg/L) Insoluble compound 0,1 µmol/L urine (6 µg/L)	BAL Sampling time: end of exposure week

BAT: Biological tolerance value (for occupational exposure)
BAL: Biological Action Levels (for occupational exposure)
BAR: Background level of a substance which is present concurrently at a particular time in a reference population of persons of working age who are not occupationally exposed to this substance
VLB: Biological limit value (for occupational exposure)
VBR : valeurs biologiques de référence (general population)

Table 12: Overview of existing occupational BLVs and reference values for the general population (not occupationally exposed) for metal compounds in blood

Metal	Country	Metal in blood	Specifications
Cobalt	Spain	1 µg/L	VLB Sampling time: end of exposure week

Table 13: Overview of existing occupational BLVs and reference values for the general population (not occupationally exposed) for carbon monoxide

Country/ Organisation	Biomarker and value	Specifications
Germany	Carboxyhemoglobin in blood=5% (for non-smokers)	BAT Sampling time: end of shift
ACGIH	Carboxyhemoglobin in blood=3,5%	VLB Sampling time: end of shift
Finland	Carboxyhemoglobin in blood=4%	BAL Sampling time: end of shift
Spain	Carboxyhemoglobin in blood=3,5% Carbon monoxide on exhaled air=20ppm	VLB Sampling time: end of shift

BAT: Biological tolerance value (for occupational exposure)
VLB: Biological limit value (for occupational exposure)
BAL: Biological Action Levels (for occupational exposure)

9. Health Effects

The potential health effects of welding fumes+ are dependent on the sites of deposition of the inhaled particles in the respiratory tract as well as the clearance mechanisms involved in removing the particles from the lungs (Antonini, 2014). The total volume deposited in the lung cells and the aerosol surface are also important factors for the induced pathological reactions. Insoluble particles deposited in the lung are scavenged by alveolar macrophage cells. The ability of these cells to clear the lung is affected by the total deposited volume of the aerosols. Potential health effects also depend on where in the respiratory tract (nasal/head airways, tracheobronchial region (upper airways), and alveolar region (lower airways)) the particles deposit. Welding particles that deposit in the nasal/head airways may have access to the central nervous system and the brain. A potential route of delivery of metals and ultrafine particles is uptake by olfactory neurons in the nose that can directly transport inhaled material to specific areas of the central nervous system. Particles that deposit in the tracheobronchial region are quickly removed by a lung clearance mechanism referred to as the mucociliary escalator. Inhaled particulates that have deposited in this region encounter a layer of mucus and become entrapped. The entrapped particles are moved by beating cilia up the mucociliary escalator and out of the trachea, where the material is swallowed and excreted from the body via the gastrointestinal tract. The majority of particles in the size range 0.20 and 0.50 µm deposit in the alveolar lung region (Antonini, 2014), the deepest region of the lungs, where rapid clearance mechanisms are not as effective. These particles are most likely engulfed and cleared by a mobile, phagocytic white blood cell called the alveolar macrophage. Particles can remain in macrophages in the lungs and body's lymphatic systemic for extended periods of time.

Bearing in mind that welders commonly use different types of welding processes on many different materials during their professional career, considering the health effects based on single substance exposures is not appropriate. The SLIC Guidance and TRGS 528 categorise the health effects from exposure to welding fumes+ on the (respiratory) system in similar ways:

- acute (short-term) respiratory health effects
- chronic (long-term) respiratory health effects
- other health effects

Due to improved exposure control and other preventive measures some known or suspected health effects of welders mentioned in Sections 9.1 to 9.3 have become rarer. However, no comprehensive literature search was performed in the context of this scoping study to assess how common the below health effects are under current welding circumstances and what are the effect concentrations/exposure-risk-relationships for them. Such considerations would become actual when drafting the scientific rationale for the OEL(s) themselves.

9.1 Acute respiratory health effects

The HSE identifies 4 categories of acute health effects[30]:

Irritation to the throat and larger airways in the lungs: Gases and fine particles in welding fumes+ can cause dryness of the throat, coughing or tightness in the chest. The effects tend to be short-lived. Ozone in particular can cause this when tungsten inert gas (TIG) welding stainless steels and aluminium. High exposures to nitrous oxides, generated during some welding processes like gas welding, gas spraying and gas cutting (including flame straightening), plasma cutting (when nitrogen is used as the plasma gas), can also cause irritation. Toxic pulmonary oedema (fluid on the lungs) has been described, particularly in oxyacetylene welding, and in some cases has been fatal after indoor flame straightening. Extreme ozone exposure can pose the same hazard, but in practice no toxic pulmonary oedema has been described in welders exposed to ozone.

Acute irritant-induced asthma: Very high levels of exposure to inhaled irritants can cause asthma to develop, but this is not common. This condition used to be known as reactive airways dysfunction syndrome (RADS). After long-term exposure to irritants below the level of acute irritant-induced asthma, a chronic obstructive airway disease may result (low level RADS). The symptoms are mostly not as direct as acute irritant-induced asthma, but show some correlation with the exposure over time; often, at weekends, on vacation e. g. there is a significant relief of the symptoms. It is to be noted that irritant mechanism may also increase asthma risk at lower and more continuous exposures than the traditional RADS (Maestrelli et al. (2020), (Tarlo and Lemiere, 2014), (Tarlo, 2014)). The mechanisms of metal-induced asthma and occupational asthma in welders remain largely unknown (see Section 9.2).

Metal fume fever: Many welders get flu-like symptoms after welding. The effects are often worse at the start of the working week and it is also called "Monday morning syndrome". Metal fume fever is a relatively poorly understood condition (Antonini et al., 2003). Metal fume fever is usually linked to welding or hot work on galvanised metals, typically inhalation of freshly formed zinc oxide fumes during the joining or cutting of galvanized zinc-coated steel, but also by inhalation of other metal oxides present in welding fumes+, e.g. copper (Antonini et al., 2003). High exposures to mild steel weld fume can also cause this illness. Metal fume fever does not usually have any lasting ill effects. It often starts a few hours after exposure begins and carries on for a while after exposure ends.

Acute pneumonia: Welders are at an increased risk of developing severe pneumococcal pneumonia. It has been suggested that the fumes may increase the susceptibility to infection in welders. However, limited data exists which examines the immunosuppressive effects of fume inhalation, although there is some evidence from animal studies suggesting that soluble metals and fluxing agents present in welding fumes+ may suppress antibacterial defenses of the lungs, thus increasing the susceptibility of welders to lung infection (Antonini et al., 2003). According to the HSE welders are particularly prone to a lung infection that can lead to severe and sometimes fatal pneumonia. Pneumonia kills about 2 welders a year. It can affect young welders as well as older people. Exposure to welding fume in the past does not increase the chances of you getting pneumonia now. A vaccination is available to reduce the risk of pneumonia if you are a welder. However, the vaccination is not a substitution for good exposure control.

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[30] https://www.hse.gov.uk/welding/health-risks-welding.htm

The SLIC Guidance describes other (non-respiratory system) acute health effects (sometimes fatal) that may result from exposure to welding gases, including:

- headache, dizziness and nausea: due to overexposure to carbon monoxide which impairs the oxygen carrying capacity of the blood by the formation of carboxyhaemoglobin;
- asphyxiation (suffocation from lack of oxygen): may result from accumulation of shielding gases (such as argon, helium and nitrogen, or argon-based mixtures containing carbon dioxide, oxygen or both) in confined and enclosed spaces.

The SLIC Guidance also notes a temporary reduction in lung function i.e. overall lung capacity and the ease of breathing out (peak flow) can be affected by exposure to welding fume. This is normally seen in the context of Occupational Asthma (see below).

In high concentration, nitrogen oxides from welding processes may lead to a pulmonary oedema, which can sometimes be fatal ((Amaducci and Downs, 2022), (Safe-Welding)).

9.2 Chronic respiratory health effects:

The HSE also identifies 4 categories of chronic health effects[31]:

Lung cancer: although this is associated with exposure to specific metals e.g. chromium, nickel, many studies report increased risk of lung cancer in welders or other workers exposed to welding fumes+. The International Association for Research on Cancer (IARC 2018) conclude that all welding fume can cause lung cancer and may cause kidney cancer, classifying all welding fume as Group 1 carcinogenic substances. While IARC (2018) could identify some specific established carcinogens (e.g. CrVI) that can increase the risk of lung cancer in welders, IARC was not able to conclude that such specific exposures explain fully the increased risk observed. Certain aspects of the IARC (2018) evaluation are further described in Appendix 1 and summarised in Section 9.4.

Chronic obstructive pulmonary disease (COPD): current evidence suggests that exposure to welding fumes+ may cause COPD, but there is not enough evidence to prove a definitive link. Normally seen in smokers, lung function can decline more quickly than expected, and fume may contribute to this decline. Established COPD causes progressive shortness of breath, chest tightness and wheeze. It may also cause fatigue. If the illness does progress, workers can become very severely incapacitated.

Welder's lung: normally describes metal deposition in the lung from exposure to welding fume. It is thought to be a benign type of pneumoconiosis, also known as siderosis. On its own, the welder may not complain of health problems. Most of the deposited iron oxide particles are present in alveolar macrophages without thickening of the alveolar septa or the presence of alveolitis. In addition, pulmonary function in welders with siderosis has been reported to be within normal limits and not significantly different from matched, non-welding controls (Antonini et al., 2003). In the context of the scoping study it was not further analysed how welder’s lung / siderosis might affect symptoms or lung function of workers with an already existing lung disease. In rare cases, after high and long exposures to steel welding fumes, lung fibrosis may result in welders (siderofibrosis) ((Oh et al., 2018), (Billings and Howard, 1993)). In aluminium welders, after high and long exposures lung disorders in the sense of an aluminosis may occur, but the condition is rare (Feary et al., 2020).

Occupational asthma: can be caused in rare cases by metals in the welding fume, for example by hexavalent chromium, nickel and cobalt. Stainless steel welding fume will contain these metals and some types of welding, for example MMA lead to more of these in the fume. Occupational asthma symptoms include episodes of severe shortness of breath, wheezing, coughing and chest tightness. It usually involves a latency period of a

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[31] https://www.hse.gov.uk/welding/health-risks-welding.htm

few months to a few years between first exposure to a respiratory sensitiser in the workplace, and symptoms starting. Welders with occupational asthma can also develop a short-term temporary reduction in lung function. This is sometimes also seen in welders without asthma.

The underlying mechanism involved in occupational asthma caused by nickel and chromium salts has not yet been fully elucidated (Fernández-Nieto et al., 2006). In some cases, specific IgE antibodies against conjugates of these metallic salts with human serum albumin have been described.

Occupational asthma due to nickel compounds was recently discussed in the context of RAC Opinion on OEL of Nickel and nickel compounds (see section 7.5 of ECHA (2018)). Nickel sulphate is an established cause of occupational asthma, although based on a low number of confirmed cases, the data are lacking for other nickel compounds. In any case occupational asthma from nickel compounds seems rare.

Occupational asthma due to chromium(VI) compounds is also rare (Baur and Bakehe (2014), Fernandez-Nieto et al., (2006). Occasional occupational asthma cases have been described in welders of special stainless steels (Hannu et al., 2005) and more generally among welders welding stainless steel (Hannu et al., 2007). However, the specific causative agents remain largely unknown, and no comprehensive epidemiological follow-up is available to reliably estimate the incidence rate. Both high level short duration exposures and longer/repeated lower level exposures of irritants may play a role (see Section 9.1. and RADS for references).

The SLIC Guidance notes that in addition to these effects, exposure to welding fumes can induce chronic inflammation and impairment of the immunological response; for this reason, the risk of other bronchial and pulmonary conditions such as pneumonia may be increased in welders. Certain chronic lung conditions such as COPD and lung cancer are also adversely influenced by tobacco smoking.

Welding activities on surfaces with coatings, debris and residual degreasing agents will generate other hazardous substances with a range of health effects, e.g. phosgene, aldehydes, amines, isocyanates (allergens).

9.3 Other health effects

Exposure to welding fumes+ may also cause:

- **Skin effects:** Airborne allergic contact dermatits may potentially be caused from nickel or chromium in fumes, but such effects are usually not seen in welders..
- **Neurological effects**: exposure to manganese can lead to neurological symptoms, similar to Parkinson’s disease. These symptoms include speech and balance disorders. However, as explained at the beginning of section 9, no comprehensive assessment of current occurrence and risk of historically observed conditions was performed in this scoping study. This applies also to manganese exposure related clinical and subclinical neurological effects.
- **Ototoxic effects:** some studies have shown that workers exposed to both manganese and noise seemed to have accelerated hearing impairment compared with those exposed to manganese alone.
- **Reprotoxic effects:** a lot of epidemiological studies have shown reproductive disorders among welders. Chromium is present in stainless steels (at least 10%), and usually welding using the TIG process. It is reprotoxic through various mechanisms: decreases testosterone secretion, disturbs the movements of spermatozoids, decreases the concentration of spermatozoids and oxidative stress[32]. Nickel, cadmium, manganese

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[32] https://www.atousante.com/en/reproductive-disorders-occupational-exposure-male-welders/

and carbon monoxide are also known to be potentially reproductive toxic, however the evidence is mixed and inconclusive[33]. Overall although some epidemiological studies have shown reproductive disorders in welders, the overall data situation is heterogeneous and inconsistent regarding the underlying causes and fume components.

- According to IARC (2018) there is sufficient evidence in humans for the carcinogenicity of ultraviolet radiation from welding an ultraviolet radiation from welding causes ocular melanoma. It is noted, however, that the necessary preventive actions for this hazard are other than setting an OEL.

9.4 Summary of the IARC evaluation and latest meta-analyses in terms of types of welding

This section focuses on lung cancer. This is because lung cancer is a very common cancer and thus the populations included in welding related lung cancer studies have the largest number of cases and are thus the studies that more likely than others have been able to assess the risk by different types of welding. Such information on types of welding was considered useful given the scoping purpose of this exercise in view of input for drafting a welding related entry in CMRD Annex 1. A comprehensive carcinogenicity assessment in terms of other types of cancer or quantitative exposure risk relationships for welding fumes or its components was beyond the scope of this study while such a comprehensive assessment would be necessary in a scientific evaluation proposing the actual OEL(s) or ERR(s).

IARC (2018) (summarised also in Guha et al. (2017)) considered *welding fumes* carcinogenic to humans (Group 1). It is noted that IARC concluded on *welding fumes* overall without specifying for which type of welding or for which base metal welded the conclusions apply. The IARC evaluation and its conclusions are taken at face value. However, some further analysis is presented in Appendix 1 as regards what types of welding or welding fumes were covered by the studies used in that evaluation. Such considerations might be relevant when defining the scope of the welding fumes entry in CMD/CMRD Annex I. In summary, the human cancer studies evaluated by IARC cover welders predominantly or exclusively exposed in steel welding and the animal studies evaluated cover exclusively (stainless) steel welding fumes. However, it is not possible to judge to which extent some welders that predominantly welded steel also welded other metals (e.g. aluminium), welded alloy steels that contained other metals or performed other activities similar to welding.

Nonetheless, solderers as a specific occupation were explicitly excluded from the human studies evaluated by IARC. Furthermore it is noted that additive processes as 3D printing are not mentioned by the IARC assessment and as stated above no specific results are mentioned for non-steel welding that would allow conclusions.

The lung cancer risk estimates vary quite widely in the epidemiological studies assessed by IARC. However, IARC did not perform a meta-analysis to combine these risk estimates to a meta-relative risk (mRR) estimate that would overcome the statistical variation in the individual, sometimes relatively small, study populations. Nor did IARC assess potential variation of risk between types of welding (e.g. mild vs stainless steel or method of welding). However, parallel to the IARC evaluation such a meta-analysis was performed with a literature search, inclusion and exclusion criteria agreed in full consensus with the IARC Working Group (Honaryar et al., 2019).

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[33] https://oshwiki.eu/wiki/Reproductive_effects_caused_by_chemical_and_biological_agents#Welding

The studies represented a total of 16 485 328 participants from the cohort studies, and 137 624 cases and 364 555 controls from the case-control studies. The mRR estimate for lung cancer for 'ever' compared with 'never' being a welder or exposed to welding fumes was 1.43 (95% CI 1.31 - 1.55). The mRR estimate was reduced to 1.17 (95% CI 1.04 - 1.38) for studies that adjusted for smoking and asbestos exposure simultaneously. Mild steel welders (mRR = 1.44; 95% CI 1.07 - 1.95) had approximately the same magnitude of lung cancer risk as stainless steel welders (mRR = 1.38; 95% CI 0.89 - 2.13). These estimates were not adjusted for asbestos and smoking. Risk estimates for exclusively gas welding (mRR, 1.71; 95% CI 1.10 - 2.66) were higher than for exclusively arc welding (mRR, 1.36; 95% CI 0.70 - 2.67). These estimates were not adjusted for asbestos and smoking.

As regards the lack of difference in lung cancer risk between mild steel and stainless steel welders Honaryar et al. (2019) noted that, *exposure to chromium and nickel compounds, which are well-established lung carcinogens present in much higher concentrations in stainless steel compared with mild steel, did not completely explain the total increased lung cancer risk found in welders. The mRR for mild steel welders was slightly higher than that for stainless steel welders, although the CIs overlapped. Mild steel is commonly welded with high emission techniques that generate higher mass concentrations of particulate matter than welding stainless steel, which could explain the difference in risk estimates. Exposure misclassification could be another possible explanation for the difference in risk estimates, as some of the mild steel welders could have been exposed to stainless steel welding fumes from another worksite; however, the misclassification would be expected to be non-differential and bias risk estimates towards the null.*

The results of Honaryar et al. (2019) are quite similar to those earlier reported by Ambroise et al. (2006) who performed a meta-analysis on largely the same studies and found a mRR of 1.26 (95% CI 1.20 – 1.32) for lung cancer among welders with little difference between shipyard, mild steel, stainless steel or unspecified welders (mRRs 1.32, 1.32, 1.31 and 1.24, respectively). Kendzia et al. (2013) pooled 16 case-control studies with 568 lung cancer cases and 427 controls ever worked as welders and found an odds ratio (OR) of developing lung cancer of 1.44 (95% CI 1.25 - 1.67). The OR increased by number of years in welding from 1.14 (95% CI 0.80 – 1.61) for 1-3 years to 1.77 (95% CI 1.31 – 2.39) for > 25 years (p for trend < 0.0001).

A meta-analysis of respiratory tract cancer risk from welding fumes is also ongoing in the context of WHO/ILO Global Burden of Disease project, but only methods, not yet any results have been published (Pega et al., 2020).

Similar to IARC (2018) assessment, the meta-analyses reported above, did not cover soldering, brazing or additive processes like 3D printing. Nor did they report estimates for welding according to any other base metal than mild steel or stainless steel. As regards the magnitude of lung cancer risk, the meta-analyses above indicate a statistically significantly increased, 1.3 to 1.4 fold risk, which however is reduced when adjusted for past exposure to asbestos and for smoking. The meta-analyses also indicate that the risk increases with increasing duration of exposure to welding. However, the effect of potential confounding by asbestos and smoking was not adjusted for in the mRR estimates that apply to different strata by duration of exposure.

9.5 Summary

In addition to health hazards falling under the scope of CMD/CMRD, exposure to fumes, dusts and gases from welding and similar activities is associated with a number of other adverse health effects. The causal mechanisms are not all fully established and for many of them specific exposures (e.g. certain metals or metal compounds) are relevant, while for others the associations have been established at more general level (e.g. exposure to irritative substances or dust). This applies also to exact causal mechanisms of welding related lung cancer excess where it seems necessary to control both welding related specific exposures (e.g. CrVI) and more generic exposures to ensure adequate prevention.

As regards specific causative agents, e.g. metals and metal compounds or certain gases, exactly the same adverse health effects can result from exposure both from welding and from totally different exposure settings. This would support applying the same limit values in all exposure settings without differentiating welding from other circumstances (See further Section 10).

As regards more generic exposures, e.g. dust it is not clear if the effects observed in welders fall under the general concept of poorly soluble low toxicity dusts or something specific to welding.

The focus of the further work on the above depends also on the preferred option taken on the overall approach (see Section 10).

Table 14: Overview of health effects /diseases and their causal agents

	Health effects/diseases	Causal agents
Acute	Irritation to the throat and larger airways in the lungs	Gases (nitrous oxides, ozone) and fine particles
	Acute irritant-induced asthma	Higher levels of exposure to gases (nitrous oxides, ozone) and fine particles
	Metal fume fever	Zinc oxide from welding galvanised metals (mild steel), also from zinc and/or copper oxides (e. g. brass, bronze, copper alloys)
	Acute pneumonia (bacterial, mainly pneumococcal)	Welding fume containing metals (mainly: iron)
	Pulmonary oedema	Nitrous oxides
Chronic	Lung cancer	Chromium VI, nickel oxides
	Chronic obstructive pulmonary disease (COPD)	Welding fume (chronic exposure), not specific to any substance
	Welder's lung / welder’s fibrosis	Iron dust (iron oxide particles); Aluminium dust (aluminium containing particles)
	Occupational asthma	Chromium, nickel, cobalt; lower levels of exposure to gases (nitrous oxides, ozone) and fine particles
Other	Neurological effects	Manganese
	Ototoxic effects	Manganese (and noise)
	Reprotoxic effects	Inconsistent results

10. Approaches for controlling exposure to welding fumes+[34]

10.1 Existing national approaches

10.1.1 Germany (TRGS)

Depending on the welding process and the base and additional materials used, the composition of welding fumes is highly heterogeneous. For this reason, there is no comprehensive limit value for “welding fumes” in Germany. The toxicologically relevant constituents of welding fumes are determined and assessed in each case. The basis for this is laid out in “Technical Rule for Hazardous Substances” (TRGS) 528 "Welding Work" which has to be followed in Germany, in particular Section 5 “Effectiveness check” with the associated Annex 4 “Notes for measurements”. As a result of this assessment, protective measures have to be implemented by employers to minimise exposure, in line with the hierarchy of control.

In Germany, the general limit value for respirable dust (A-dust fraction) of 1.25 mg/m³ must be complied with in any case for welding work. The limit value for inhalable dust (E-dust fraction) of 10 mg/m³ must also be observed.

10.1.2 France (ANSES)

ANSES also looked at a variety of welding processes, materials used and energy sources, and recommended that work involving exposure to welding fumes or metal fumes from related processes including hard soldering, gouging, oxy-cutting, thermal spraying, and hardfacing should be included in the Ministerial Order establishing the list of carcinogenic substances, mixtures and processes.

The WG issued 2 additional recommendations for:

- protecting and raising awareness of workers potentially exposed to carcinogenic metal fumes;
- improving knowledge on the carcinogenic risk associated with exposure to metal fumes.

To achieve the above the ANSES WG also recommended:

- carrying out an assessment at least annually of the risk of carcinogenicity for the various personnel involved, to implement adequate preventive and protective measures;
- establishing the monitoring of occupational exposure, in particular by carrying out atmospheric metrological monitoring as well as biological monitoring of exposure, and developing the associated tools;
- informing exposed personnel of the carcinogenic risk associated with exposure to welding fumes or metal fumes and train them;
- informing and training employers, encouraging them to use the most appropriate and less emissive processes according to the welding operations to be performed.

Additionally to improve knowledge on the carcinogenic risk of exposure to metal fumes by the WG recommended:

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[34] As national approaches (e.g. in France or Germany) do not set an OEL, the original title was amended. We also note that even the approach to make an entry to Annex I of CMRD is not setting an OEL. Consequently these approaches are about controlling exposure to welding fumes+.

- carrying out epidemiological studies on the risk of cancer, especially cancers other than bronchopulmonary cancer and laryngeal cancer, associated with exposure to metal fumes;
- to specify at best, in these epidemiological studies, the details of the processes, metals and alloys used and associated exposures.

10.2 Relevant EU legislation

The most relevant EU-legislation for this report is Council Directive 98/24/EC, (Chemical Agents Directive, CAD) and Council directive EU 2004/37/EC (Carcinogens and Mutagens Directive, CMD). The amendment with Directive 2022/431/EU also brought reprotoxic substances within the scope of the directive, changing the original title to the protection of workers from the risks related to exposure to carcinogens, mutagens or reprotoxic substances at work and (CMRD).

Hazardous chemical agents are subject to the requirements under CAD and CMRD on the protection of the health and safety of workers from the risks related to chemical agents at work. CAD and CMRD both state that employers have a duty to determine whether any hazardous chemical agents are present in the workplace, to eliminate the use of these and, where this is not possible, to assess the risks to which they may give rise. This includes hazardous substances that are produced/generated as a by-product of any process.

10.2.1 Generic description for Annex I of CMRD

Article 2 of Directive 2004/37/EC defines carcinogens, mutagens and reproductive toxicants. In addition to carcinogenic substances covered by Art 2 (a) (i) and (ii), the section (iii) defines as carcinogens substances, preparations and processes listed in Annex I of CMRD. Annex I currently has the following entry:

- Work involving exposure to dusts, fumes and sprays produced during the roasting and electro-refining of cupro-nickel mattes

It may be necessary to revise that entry.

10.2.2 Relevant for CMRD

CMRD aims to protect workers against health and safety risks from exposure to carcinogens, mutagens or reproductive toxicants at work. To this end, it sets out the minimum requirements for protecting workers who are exposed to carcinogens and mutagens, including the so-called Binding Occupational Exposure Limit Values (BOELVs). For each BOELV, Member States are required to establish a corresponding national occupational limit value (OEL), from which they can only deviate to a lower but not to a higher value.

CMRD applies to a substance or mixture that meets the criteria for classification as a Category 1A or 1B carcinogen or Category 1A or 1B germ cell mutagen or Category 1A or 1B reproductive toxicant set out in Annex I to the CLP Regulation. In addition, it applies to carcinogenic substances, mixtures or processes referred to in Annex I to the Directive, as well as a substances or mixtures released by a process in that annex.

With Directive 2022/431 of 9 March 2022, Directive 2004/37/EC also applies to substances toxic to reproduction (e.g. a BOELV was established for inorganic lead and its compounds and for carbon monoxide). In addition, a BOELV was established for nickel compounds.

Welding fumes containing carcinogenic, mutagenic or reproductive toxic components, such as chromium(VI) compounds, nickel compounds, cadmium and its inorganic compounds, beryllium and inorganic beryllium compounds, inorganic lead and its compounds, cobalt and carcinogenic cobalt compounds, as well as carbon monoxide produced during welding are regulated by the CMRD. This is due to specific constituents of the fume being classified under CLP (as per the above examples) and consequently there is no legal ambiguity as regards their inclusion in the scope of the directive.

However, the Commission, as expressed in its mandate to ECHA, wishes to explore the possibility of a generic entry in annex I of CMRD to include work involving exposure to welding fumes+ within the scope of the directive. The scope of such an entry in Annex I of CMRD would take into account the scientific and technical considerations of how fume is generated and is effects on workers' health. However, given the variability of the processes and nature of the fumes generated the discussions on a robust wording for an entry into annex I of CMRD will need to take account also of policy considerations.

10.2.3 Relevant for CAD

The CAD aims to lay down minimum requirements for the protection of workers from risks to their safety and health arising, or likely to arise, from the effects of chemical agents that are present at the workplace or as a result of any work activity involving chemical agents.

CAD provides for the drawing up of indicative and binding occupational exposure limit values as well as biological limit values at Community level.

Welding fumes+ and gaseous hazardous substances released during the welding process are regulated by the CAD as a whole, not only when metals such as nickel, cobalt or manganese are present.

10.3 Potential entry into Annex I of CMRD

The request from the Commission indicates defining the scope of the substances and processes to be included in an entry to Annex I of the CMRD that would cover the exposure from welding fumes and fumes from other processes that generate fume in a way that is similar to welding.

10.3.1 Need for and entry in Annex I

It can be debated if an entry in Annex I of CMRD is needed or is the best way to address worker exposure from welding fumes+, and below are a number of considerations to support the decision-making.

Advantages of an Annex I entry:

- Welding can be a relatively safe activity if all the safety and exposure control measures are in place and the hierarchy of controls followed. However, it remains a prominent concern that welders are at high risk from various diseases, including cancers, which seems to indicate that more needs to be done to ensure that the needed measures are in place. In case some employers are not doing enough to protect the health of their employees, an entry brings some prominence to this issue, that welding is an activity/ process that merits specific attention.
- An entry brings clarity about employers' duties and which measures have to be taken under CMRD and under CAD (even though the principles to protect workers are similar).
- An entry defining the welding and other processes and corresponding (hazardous) welding fumes+, and what is included (or not) brings clarity and simplicity about duties.

Note: the entry itself has to be in a simple and clear language, so additional information must be provided in another way, than in the entry itself.

Disadvantages of an Annex I entry:

- The majority (but not all) of the relevant substances are already covered by entries in Annex III. If all the relevant substances were in Annex III (so any missing were added as a priority) then would this Annex I entry be needed?

- Welding processes are very heterogeneous, so is it appropriate to have a single entry that covers worker exposure from the various fumes?
- Reprotoxic substances are not covered: Annex I is for carcinogenic substances category 1A or 1B, so how to address reprotoxic substances (if there are any like silver (in soldering) that in the future may become classified as reprotoxic (and remain not carcinogenic)
- If the entry is not clear enough (including the supporting information) it could lead to more confusion. A particular concern if is the entry is too broad, and not clear enough on which processes and substances are in and which are out.

In addition there are some possible complications with an entry. Annex I of CMRD is for carcinogenic substances and mixtures only, so how should potential reprotoxic substances in welding fumes (that are not also carcinogenic) be considered. This may need a future extension of Annex I to include reprotoxic and mutagenic substances and mixtures.

There is also a relationship with Annex III of CMRD, which lists the majority of the metals and metal compounds (with a limit value) that are both carcinogenic and present in welding fumes. Any remaining carcinogenic (and reprotoxic) substances in welding fumes that are not in Annex III (such as cobalt compounds) should be prioritised for an entry.

A point to note that carbon monoxide is also listed in Annex III (with limit values) as a reprotoxic substance. Technically it is not part of the particulate fume, but a welding gas. None of the other welding gases have been identified as being classified as CMR. From the welding gases perspective the situation seems well-controlled, and it is the particulate fume that remains the concern.

10.3.2 What would an entry in Annex I look like?

To avoid additional confusion an entry into Annex I in CMRD should be written as simply and clearly as possible, while providing additional information such as definitions of the processes and substances elsewhere.

The entry should take the form of (several options are provided for discussion):

- ‘work involving exposure to fumes from welding (and similar) processes that contain substances that fall within the scope of the CMRD’;
- ‘work involving exposure to fumes from welding (and similar) processes that contain substances that meet the criteria for CMR Category 1A or 1B set out in Annex I to the CLP Regulation’;
- ‘work involving exposure to fumes from fusion welding, brazing, thermal cutting or gouging and thermal spraying that contain substances that fall within the scope of the CMRD.’
- ‘work involving exposure to fumes from fusion welding, brazing, thermal cutting or gouging and thermal spraying that contain substances that meet the criteria for CMR Category 1A or 1B set out in Annex I to the CLP Regulation.’

The following information is provided to support the entry:

Definition of the welding process: welding is a manufacturing or fabrication process whereby two or more parts are fused together by means of heat, pressure or both forming a join as the parts cool. For this entry the parts to be joined are made of metal.

The parts that are joined are known as **base** (or parent) material/metals. The material added to help form the join is called **filler** (or consumable), which can be in the form of a rod, wire, tape or powder.

Definition of welding fumes: these are formed when metals (base and/or filler) are heated above their boiling point (vapourised) and their vapours rapidly condense into very fine particles (solid particulates). The particulate matter is the metals and their oxides, including spinels (complex structures of metals with different valences with oxygen, silicon and/or fluorine).

Excluded from the definition of welding fumes: exposure to various gases can also occur during welding which may include gases produced during the welding (e.g. nitrogen oxides, carbon monoxide and ozone) or gases used for shielding (e.g. argon, helium and nitrogen). These gases are called welding gases and if they were considered part of the welding fume the situation would become even more complicated than it already is, and therefore it is proposed that they are not part of the welding fume, which is only the particulate matter.

Looking at processes where there is exposure to fumes generated in a way that is similar to welding, would involve the vaporisation and rapid condensation of metals (that are CMR) to particulate matter leading to worker exposure. For additive manufacturing processes there is no exposure as the melting/vaporisation occurs in an inert atmosphere inside a closed machine. Fumes from processes such as soldering and the majority of brazing applications do not arise from CMR substances as classified under CLP, however, the filler may sometimes contain antimony, silver, or brass (zinc oxide) which are potentially reprotoxic (they are suspected but do not have a harmonised classification under CLP). It should be noted that there are a limited number of specific uses where brazing fillers containing cadmium can still be used for safety reasons, as well as the derogation allowing their use in the defence and aerospace sector. Another issue is that while nickel is classified as carcinogenic Category 2 (so does not come under Annex I of CMRD), nickel oxide (as well as other more complex spinel structures) can be produced in the fume, and nickel oxide is carcinogenic Category 1A.

In practical terms in order to produce a welding fumes+ that would be covered by the CMRD the parent and/or filler material has to contain a CMR[35] substance as set out in Annex I to the CLP Regulation. The majority of the metals of concern used in welding processes are already included in the CMRD Annex III, with a limit value, which can be applied to welding fumes+. Any remaining metals (e.g. cobalt) should be prioritised for an entry into Annex III.

Welding fumes+ that contain substances that lead to health effects other than CMR would be controlled under CAD.

10.4 Other options to control exposure

The following options may be considered to set limit values or take other actions.

10.4.1 Set a generic occupational exposure limit (OEL) for inhalable and respirable dust.

This could either be specific to welding fumes or a generic limit for dust. Some Member States have established a specific OEL for welding fumes (see Section 8) but an EU-wide limit does not exist. If an EU-wide generic dust limit is set it should be complemented with monitoring of the gaseous phase for the relevant gases as it would be difficult to define a generic gas exposure metric.

Advantages

i. Allows a limit to be established which would cover a large number of substances in the welding fume (metals and their oxides, including spinels which may not be exactly identified), without setting individual limits for each substance.

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[35] Nickel is classified as carcinogenic 2 so does not come under Annex I of CMRD, while nickel compounds such as nickel oxide are category 1 carcinogens, so the nickel compounds in the fume would be covered by an entry in Annex I of the CMRD

ii. Ensures to establish a relationship between particle size distribution and deposition of the inhaled particles in different parts of the respiratory tract (in turn leading to potential health effects).

Disadvantages

i. Concommittent substance-specific approach for gases (based on OELs of those gases overall, not only for welding) and generic approach for particulate matter, although particulate matter can contain some known specific carcinogens.

ii. Low confidence in such a limit:

   a. Not specific enough: values for dust concentrations and particle sizes at individual workplaces differ very widely because of differences in the mechanism of dust formation, the kind of dust and the measures taken to reduce dust exposure. The type of substances in the contents of the dust also varies a lot.

   b. Underestimation: the establishment of a generic OEL for dust would likely be based on static area dust sampling data. The actual concentrations in the air inhaled by the exposed persons (determined more accurately by personal sampling) tend to be higher.

10.4.2 Specific OELs could be complemented with a generic dust metric (an inhalable limit and a respirable limit)

Certain substances (metals, ozone etc.) as described in Section 8 already have an EU OEL, either indicative or binding. Such specific OELs could be complemented with a generic dust metric (an inhalable limit and a respirable limit) as described in bullet 1 (above).

At national level this seems to be the approach in Germany with generic dust OELs that apply to all dusts (i.e. similar/alike to Poorly Soluble Low Toxicity (PSLT) derived limits, not specific to welding). France has a similar approach. The substance specific OELs would apply to all exposure circumstances, not only welding, and would be reviewed according to the overall priorities.

Advantages

i. Every welding relevant substance specific OEL would similarly apply to welders and other workers exposed to this substance. These substance specific OELs would also have considered non-cancer hazards. Also the generic dust limits (respirable and inhalable) would be uniform across industries/workers.

Disadvantage:

i. The hazard properties of welding fumes, due to their very complex composition, could be somehow different to either how generic dust acts or how the specific substances act, so the limits derived from non-welding data might not be protective in welding. However, there is, at least currently, no scientific data indicating this.

10.4.3 Monitor those welding related specific substances that are established carcinogens

A narrow approach would be only monitoring those welding related specific substances that are established carcinogens, i.e. to apply a BOEL for each of them under CMRD.

Advantages

i. In Annex I of CMRD it is just needed to define the scope of processes that would be covered under “Welding+”, and then indicate that all substance specific limits apply.

Disadvantages

i. As described in Section 9 although IARC concludes that there is sufficient evidence in humans for the carcinogenicity of welding fumes, IARC was unable to conclude that the cancer excess observed in welders is explained solely by exposure to such established specific carcinogens.

ii. Some of the established carcinogens' BOELs may need to be updated based on newer data (if they were established some time ago).

10.4.4 Mandatory protective/control measures for welding techniques that lead to greater emissions of welding fumes, or promoting of low-emission techniques

Other options could be to consider mandatory protective/control measures (e.g. enclosures, source extraction) for those welding techniques that lead to greater emissions of welding fumes (such as MAG), or to promote substitution to low-emission processes (such as TIG).

Advantages

i. Aiming for a reduction in emissions (exposure minimisation approach), directly reduces worker exposure without the need for a limit value for all welding fumes or individual components.

Disadvantages:

i. Without a limit value it is difficult to say with certainty that there is no harm caused by the welding fume, that additional control measures need to be implemented, or that the worker (welder) needs to be removed to do other work before any health effects are observed.

10.4.5 Health Surveillance Programmes for welders under certain conditions

The TRGS 528, HSE and SLIC all refer to a Health Surveillance Programmes for welders under certain conditions. This could be done in addition to any other option.

Some further considerations on this are included in section 10.5.3.

Advantages:

i. Enables the collection of data to detect or evaluate health hazards

ii. Helps protect employees' health by early detection of changes or disease (e.g. the early detection of reduced lung function or increased breathing problems could prevent further damage to the lungs)

iii. Data can be used to evaluate the effectiveness of control measures

Disadvantages:

i. Cost to the employers,

ii. Health records will need to be kept, potentially for decades, although there are services to support this in a cost-efficient way with minimal effort, while taking data protection into account.

10.5 Additional considerations

10.5.1 Generic dust limits

It is to be noted, that as regards the generic dust limits that would apply to welding, it would most likely not be possible to derive an exposure risk relationship (ERR) that would correlate to the exposure level to the excess risk of cancer: this is due to lack of data. It is very likely that if there was not enough data for IARC to characterise qualitatively the cancer (lung cancer) hazard related to such exposures, it does not seem probable to be able to establish a quantitative ERR for them. One of the main reasons for this is that for such process generated general exposures, there is usually no animal data that can be used, and the available human epidemiological data has already been scrutinised recently by IARC. This of course needs to be verified more thoroughly, but that is not under the scope of this exercise. If that proves to be true, then the generic dust limits would need to be set based either on hazard endpoints other than cancer (e.g. irritation, inflammation, chronic bronchitis) or on technical feasibility or best practice considerations.

10.5.2 Combined Exposure

OELs are usually established for single substances. When two or more harmful substances, which act upon the same target organ, are present, their combined effect should be considered. One of the issues with welding fumes+ is that they are generated from metal alloys, so depending on the process the fumes can contain multiple metals (and metal oxides), which may have a combined effect.

Some of these metals already have existing OELs (see section 8). So in that case could a OEL be set for a mixture (welding fume) containing metals (and oxides) to take account of a combined effect. A formula has been proposed:

$$C_1/OEL_1 + C_2/OEL_2 + C_3/OEL_3 + \ldots. = 1/OEL_{mixture}$$

Where Ci represents the air concentration of agent i, while OELi is the limit value of agent i.

A similar formula is described referring to a "Hazard Index" (HI) (Gunnar Damgård Nielsen, 2008). Where the hazard index of each compound is described by

$$H.I.(i) = [(\text{Concentration of compound } (i))/TLV(i)])$$

and the TLV of the mixture is considered exceeded if the sum of the hazard indices exceeds one: (Sum (H.I. (i)) > 1).

The same reference discusses that the additive approach is considered reasonable for sensory irritants. However, if one compound inhibits the metabolism of another compound in a mixture (toxicokinetic interaction) and the effect is due to a systemic effect, the effect of the mixture may exceed the effect estimated from the H.I.

The Canadian Centre for Occupational Health and Safety also describes the same formula[36] and states that this formula should not be used for:

- mixtures of substances with toxicological effects that are not additive (individual toxicological effects and target organs are different),
- mixtures of substances which inhibit each other's effect,
- substances that may have a synergistic effect,
- carcinogens (exposure to mixtures of carcinogens should be eliminated or as low as possible), and
- complex mixtures (e.g., diesel exhaust).

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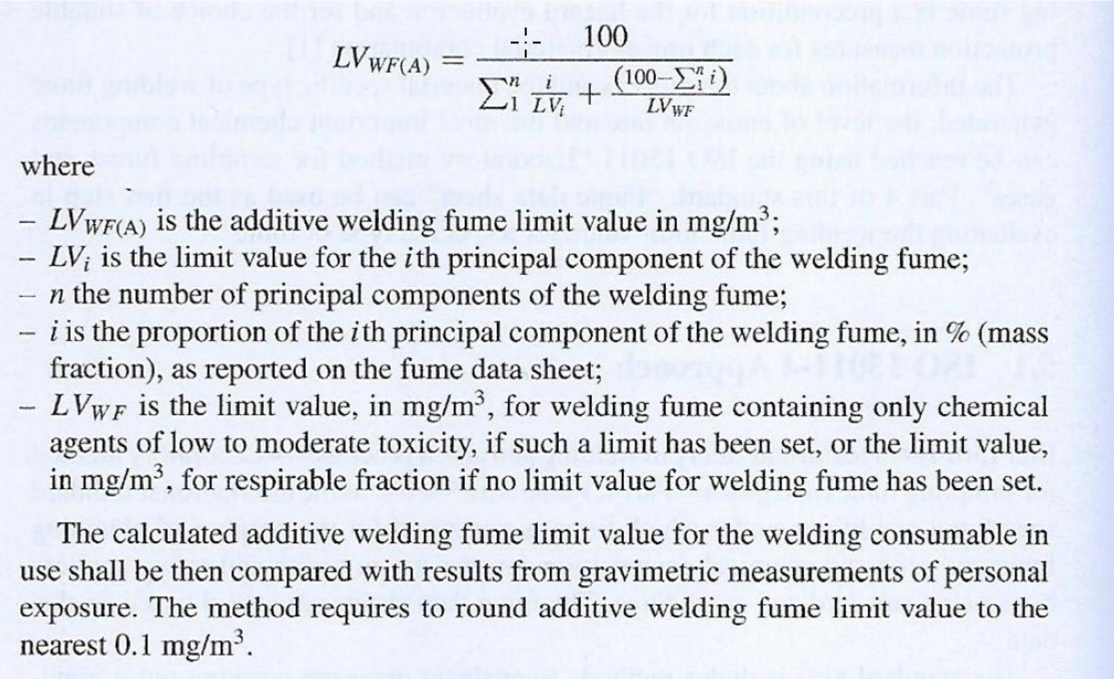
[36] https://www.ccohs.ca/oshanswers/hsprograms/occ_hygiene/occ_exposure_limits.html

Coming from another direction, the ISO 15011-4 proposes a method to calculate an additive welding fume limit value (Figure 3).

Figure 3: A method to calculate an additive welding fume limit value proposed by ISO 15011-4



$$LV_{WF(A)} = \frac{100}{\sum_1^n \frac{i}{LV_i} + \frac{(100-\sum_1^n i)}{LV_{WF}}}$$

where

- $LV_{WF(A)}$ is the additive welding fume limit value in mg/m^3;
- LV_i is the limit value for the ith principal component of the welding fume;
- n the number of principal components of the welding fume;
- i is the proportion of the ith principal component of the welding fume, in % (mass fraction), as reported on the fume data sheet;
- LV_{WF} is the limit value, in mg/m^3, for welding fume containing only chemical agents of low to moderate toxicity, if such a limit has been set, or the limit value, in mg/m^3, for respirable fraction if no limit value for welding fume has been set.

The calculated additive welding fume limit value for the welding consumable in use shall be then compared with results from gravimetric measurements of personal exposure. The method requires to round additive welding fume limit value to the nearest 0.1 mg/m^3.

However the ISO standard also states that it should not be used for complex substances.

The issue with welding fumes is that they are complex, containing diverse metal compounds (spinels), and the interaction between these compounds can itself be complex and difficult to predict so they can inhibit each other's effect or have synergistic effects.

This aligns with the approach in Germany, where the topic is regulated in TRGS 402 (section 5.2.1 and section 5.3 para. 5): No assessment index is formed for a mixture of carcinogenic substances, i.e. carcinogenic substances are assessed individually and no mixture assessment is made, with the reasoning that too little is known about the combined effects of carcinogenic substances and additive, synergistic and antagonistic effects are possible.

Therefore while there might be scope to consider combined exposure in some circumstances, those circumstances would be very limited with regard to welding fumes, and not be applicable in the majority of cases.

10.5.3 Health surveillance

The overall relative risk of lung cancer in welders, especially when adjusted for smoking and asbestos, is not as high as in some other risk occupations e.g. among workers with heavy past exposure to asbestos, it seems quite consistent (see section 9.4). It is also worth noting that welding is associated with an increased risk of several non-cancer health effects (See section 9). All this underlines a need for health surveillance of welders.

It is noted that Article 14 of CMRD stipulates that *The Member States shall establish, in accordance with national laws and/or practice, arrangements for carrying out relevant health surveillance of workers for whom the results of the assessment referred to in Article 3(2) reveal a risk to health or safety*. Article 14 includes further provisions concerning the health surveillance and Annex II of CMRD contains practical recommendations for that health surveillance of workers. These refer e.g. to the health surveillance to be *performed* *according to the principles and practices of occupational medicine.* Similar considerations are included in Article 10 of CAD, although with different wording.

In conclusion, it seems warranted to offer health surveillance for welders and this health surveillance should cover prevention of both (lung) cancer and non-cancer effects. How this is covered under CMRD and/or CAD is a question of legal drafting. The organisation of the health surveillance remains an obligation of the Member States and the content of that surveillance should follow the principles and practices of occupational medicine. It is beyond the scope of this scoping study to give further recommendations on those aspects.

REFERENCES

AMADUCCI, A. & DOWNS, J. W. 2022. *Nitrogen Dioxide Toxicity. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan. 2022 Apr 30.* *https://www.ncbi.nlm.nih.gov/books/NBK554539/#article-43019.s3*.

AMBROISE, D., WILD, P. & MOULIN, J. J. 2006. Update of a meta-analysis on lung cancer and welding. *Scand J Work Environ Health,* 32**,** 22-31.

ANTONINI, J. M. 2014. 8.04 - Health Effects Associated with Welding, Editor(s): Saleem Hashmi, Gilmar Ferreira Batalha, Chester J. Van Tyne, Bekir Yilbas,. *Comprehensive Materials Processing***,** 49-70.

ANTONINI, J. M., LEWIS, A. B., ROBERTS, J. R. & WHALEY, D. A. 2003. Pulmonary effects of welding fumes: review of worker and experimental animal studies. *Am J Ind Med,* 43**,** 350-60.

AUSTIN, H., DELZELL, E., LALLY, C., ROTIMI, C. & OESTENSTAD, K. 1997. A case-control study of lung cancer at a foundry and two engine plants. *Am J Ind Med,* 31**,** 414-21.

BAUA, C. O. H. S.-A. M.-. 2021. Technical Rules for Hazardous Substances (TRGS) 528 - Welding Work.

BAUR, X. & BAKEHE, P. 2014. Allergens causing occupational asthma: an evidence-based evaluation of the literature. *Int Arch Occup Environ Health,* 87**,** 339-63.

BECKER, N. 1999. Cancer mortality among arc welders exposed to fumes containing chromium and nickel. Results of a third follow-up: 1989-1995. *J Occup Environ Med,* 41**,** 294-303.

BÉMER, D., RÉGNIER, R., SUBRA, I., SUTTER, B., LECLER, M. T. & MORELE, Y. 2010. Ultrafine Particles Emitted by Flame and Electric Arc Guns for Thermal Spraying of Metals. *The Annals of Occupational Hygiene,* 54**,** 607-614.

BILLINGS, C. G. & HOWARD, P. 1993. Occupational siderosis and welders' lung: a review. *Monaldi Arch Chest Dis,* 48**,** 304-14.

BRENNER, D. R., HUNG, R. J., TSAO, M. S., SHEPHERD, F. A., JOHNSTON, M. R., NAROD, S., RUBENSTEIN, W. & MCLAUGHLIN, J. R. 2010. Lung cancer risk in never-smokers: a population-based case-control study of epidemiologic risk factors. *BMC Cancer,* 10**,** 285.

COMITÉ D'EXPERTS SPÉCIALISÉS VALEURS SANITAIRES DE RÉFÉRENCE, G. D. T. P. C. 2021. Identification de travaux ou de procédés à inscrire à l'arrêté fixant la liste des substances, mélanges et procédés cancérogènes.

CORBIN, M., MCLEAN, D., MANNETJE, A., DRYSON, E., WALLS, C., MCKENZIE, F., MAULE, M., CHENG, S., CUNNINGHAM, C., KROMHOUT, H., BLAIR, A. & PEARCE, N. 2011. Lung cancer and occupation: A New Zealand cancer registry-based case-control study. *Am J Ind Med,* 54**,** 89-101.

DANIELSEN, T. E., LANGÅRD, S. & ANDERSEN, A. 1996. Incidence of cancer among Norwegian boiler welders. *Occup Environ Med,* 53**,** 231-4.

DANIELSEN, T. E., LANGÅRD, S. & ANDERSEN, A. 2000. Incidence of cancer among welders and other shipyard workers with information on previous work history. *J Occup Environ Med,* 42**,** 101-9.

DANIELSEN, T. E., LANGÅRD, S., ANDERSEN, A. & KNUDSEN, O. 1993. Incidence of cancer among welders of mild steel and other shipyard workers. *Br J Ind Med,* 50**,** 1097-103.

DUNN, J. E., JR. & WEIR, J. M. 1968. A prospective study of mortality of several occupational groups. Special emphasis on lung cancer. *Arch Environ Health,* 17**,** 71-6.

ECHA 2018. *ANNEX 1. Background Document in support of the Committee for Risk Assessment (RAC) for evaluation of limit values for nickel and its compounds in the workplace. ECHA/RAC/A77-0-0000001412-86-189/F*.

FEARY, J., PARFREY, H., BURGE, S., NICHOLSON, A. G., DEVARAJ, A. & CULLINAN, P. 2020. Interstitial Lung Disease (ILD) in aluminium welders. *European Respiratory Journal,* 56**,** 3167.

FERNÁNDEZ-NIETO, M., QUIRCE, S., CARNÉS, J. & SASTRE, J. 2006. Occupational asthma due to chromium and nickel salts. *Int Arch Occup Environ Health,* 79**,** 483-6.

FLOROS, N. 2018. Welding fume main compounds and structure. *Welding in the World,* 62**,** 311-316.

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. In: Sunderman FW, editor. Nickel in the human environment. Lyon, France: International Agency for Research on Cancer. IARC Scientific Publication No. 53, pp. 105–115.*

GUHA, N., LOOMIS, D., GUYTON, K. Z., GROSSE, Y., EL GHISSASSI, F., BOUVARD, V., BENBRAHIM-TALLAA, L., VILAHUR, N., MULLER, K. & STRAIF, K. 2017. Carcinogenicity of welding, molybdenum trioxide, and indium tin oxide. *Lancet Oncol,* 18**,** 581-582.

GUNNAR DAMGÅRD NIELSEN, S. Ø. 2008. Background, approaches and recent trends for setting health-based occupational exposure limits: A minireview. *Regulatory Toxicology and Pharmacology,* Volume 51**,** Pages 253-269.

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**,** 32-40.

HANNU, T., PIIPARI, R., KASURINEN, H., KESKINEN, H., TUPPURAINEN, M. & TUOMI, T. 2005. Occupational asthma due to manual metal-arc welding of special stainless steels. *Eur Respir J,* 26**,** 736-9.

HANNU, T., PIIPARI, R., TUPPURAINEN, M., NORDMAN, H. & TUOMI, T. 2007. Occupational asthma caused by stainless steel welding fumes: a clinical study. *Eur Respir J,* 29**,** 85-90.

HONARYAR, M. K., LUNN, R. M., LUCE, D., AHRENS, W., T MANNETJE, A., HANSEN, J., BOUAOUN, L., LOOMIS, D., BYRNES, G., VILAHUR, N., STAYNER, L. & GUHA, N. 2019. Welding fumes and lung cancer: a meta-analysis of case-control and cohort studies. *Occup Environ Med,* 76**,** 422-431.

IARC 2018. *IARC Moographs on the Evaluation of carcinogenic risks to humans. Volume 118. Welding, Molybdenum trioxide, and Indium tin oxide. International Agency for Research on Cancer.*

ISO 2020. ISO 15202-1:2020. Workplace air — Determination of metals and metalloids in airborne particulate matter by inductively coupled plasma atomic emission spectrometry— Part 1: Sampling.

J BLUNT, N. C. B. 2002. *Health and Safety in Welding and Allied Processes*.

JÖCKEL, K. H., AHRENS, W., POHLABELN, H., BOLM-AUDORFF, U. & MÜLLER, K. M. 1998. Lung cancer risk and welding: results from a case-control study in Germany. *Am J Ind Med,* 33**,** 313-20.

KENDZIA, B., BEHRENS, T., JÖCKEL, K. H., SIEMIATYCKI, J., KROMHOUT, H., VERMEULEN, R., PETERS, S., VAN GELDER, R., OLSSON, A., BRÜSKE, I., WICHMANN, H. E., STÜCKER, I., GUIDA, F., TARDÓN, A., MERLETTI, F., MIRABELLI, D., RICHIARDI, L., POHLABELN, H., AHRENS, W., LANDI, M. T., CAPORASO, N., CONSONNI, D., ZARIDZE, D., SZESZENIA-DABROWSKA, N., LISSOWSKA, J., GUSTAVSSON, P., MARCUS, M., FABIANOVA, E., T MANNETJE, A., PEARCE, N., TSE, L. A., YU, I. T., RUDNAI, P., BENCKO, V., JANOUT, V.,

MATES, D., FORETOVA, L., FORASTIERE, F., MCLAUGHLIN, J., DEMERS, P., BUENO-DE-MESQUITA, B., BOFFETTA, P., SCHÜZ, J., STRAIF, K., PESCH, B. & BRÜNING, T. 2013. Welding and lung cancer in a pooled analysis of case-control studies. *Am J Epidemiol,* 178**,** 1513-25.

KJUUS, H., SKJAERVEN, R., LANGÅRD, S., LIEN, J. T. & 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**,** 193-202.

MAESTRELLI, P., HENNEBERGER, P. K., TARLO, S., MASON, P. & BOSCHETTO, P. 2020. Causes and Phenotypes of Work-Related Asthma. *Int J Environ Res Public Health,* 17.

MATRAT, M., GUIDA, F., MATTEI, F., CÉNÉE, S., CYR, D., FÉVOTTE, J., SANCHEZ, M., MENVIELLE, G., RADOÏ, L., SCHMAUS, A., WORONOFF, A. S., LUCE, D. & STÜCKER, I. 2016. Welding, a risk factor of lung cancer: the ICARE study. *Occup Environ Med,* 73**,** 254-61.

MEGUELLATI-HAKKAS, D., CYR, D., STÜCKER, I., FÉVOTTE, J., PILORGET, C., LUCE, D. & GUÉNEL, P. 2006. Lung cancer mortality and occupational exposure to asbestos among telephone linemen: a historical cohort study in France. *J Occup Environ Med,* 48**,** 1166-72.

MELKILD, A., LANGÅRD, S., ANDERSEN, A. & TØNNESSEN, J. N. 1989. Incidence of cancer among welders and other workers in a Norwegian shipyard. *Scand J Work Environ Health,* 15**,** 387-94.

MERLO, F., COSTANTINI, M. & DORIA, M. 1989. Cause specific mortality among workers exposed to welding fumes and gases: a historical prospective study. *J uoeh,* 11 Suppl**,** 302-15.

MILATOU-SMITH, R., GUSTAVSSON, A. & SJÖGREN, B. 1997. Mortality among Welders Exposed to High and to Low Levels of Hexavalent Chromium and Followed for More Than 20 Years. *Int J Occup Environ Health,* 3**,** 128-131.

MOGHIMIAN, P., POIRIÉ, T., HABIBNEJAD-KORAYEM, M., ZAVALA, J. A., KROEGER, J., MARION, F. & LAROUCHE, F. 2021. Metal powders in additive manufacturing: A review on reusability and recyclability of common titanium, nickel and aluminum alloys. *Additive Manufacturing,* 43**,** 102017.

MOULIN, J. J., WILD, P., HAGUENOER, J. M., FAUCON, D., DE GAUDEMARIS, R., MUR, J. M., MEREAU, M., GARY, Y., TOAMAIN, J. P., BIREMBAUT, Y. & ET AL. 1993. A mortality study among mild steel and stainless steel welders. *Br J Ind Med,* 50**,** 234-43.

OH, S. J., HWANG, K. E., JEONG, E. T. & KIM, H. R. 2018. A case of pulmonary siderosis misdiagnosed as pneumonia. *Respir Med Case Rep,* 25**,** 58-60.

PARK, R., KREBS, J. & MIRER, F. 1994. Mortality at an automotive stamping and assembly complex. *Am J Ind Med,* 26**,** 449-63.

PEGA, F., CHARTRES, N., GUHA, N., MODENESE, A., MORGAN, R. L., MARTÍNEZ-SILVEIRA, M. S. & LOOMIS, D. 2020. The effect of occupational exposure to welding fumes on trachea, bronchus and lung cancer: A protocol for a systematic review and meta-analysis from the WHO/ILO Joint Estimates of the Work-related Burden of Disease and Injury. *Environ Int,* 145**,** 106089.

POLEDNAK, A. P. 1981. Mortality among welders, including a group exposed to nickel oxides. *Arch Environ Health,* 36**,** 235-42.

PUNTONI, R., MERLO, F., BORSA, L., REGGIARDO, G., GARRONE, E. & CEPPI, M. 2001. A historical cohort mortality study among shipyard workers in Genoa, Italy. *Am J Ind Med,* 40**,** 363-70.

RINSKY, R. A., MELIUS, J. M., HORNUNG, R. W., ZUMWALDE, R. D., WAXWEILER, R. J., LANDRIGAN, P. J., BIERBAUM, P. J. & MURRAY, W. E., JR. 1988. Case-control study of lung cancer in civilian employees at the Portsmouth Naval Shipyard, Kittery, Maine. *Am J Epidemiol,* 127**,** 55-64.

SAFE-WELDING. *Nitrous gases in welding fumes What dangers are faced when welding.* *https://safe-welding.com/nitrous-gases-in-welding-fumes-what-dangers-are-faced-when-welding/* [Online]. [Accessed 31 May 2022].

SIEW, S. S., 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**,** 444-50.

SIMONATO, L., FLETCHER, A. C., ANDERSEN, A., ANDERSON, K., BECKER, N., CHANG-CLAUDE, J., FERRO, G., GÉRIN, M., GRAY, C. N., HANSEN, K. S. & ET AL. 1991. A historical prospective study of European stainless steel, mild steel, and shipyard welders. *Br J Ind Med,* 48**,** 145-54.

SØRENSEN, A. R., THULSTRUP, A. M., HANSEN, J., RAMLAU-HANSEN, C. H., MEERSOHN, A., SKYTTHE, A. & BONDE, J. P. 2007. Risk of lung cancer according to mild steel and stainless steel welding. *Scand J Work Environ Health,* 33**,** 379-86.

SOSKOLNE, C. L., JHANGRI, G. S., PAGANO, G., BOTTE, G., DI CINTIO, P. & CLAUDIO, L. 2007. *Using established occupational respiratory cancer risk factors for assessing the internal validity in an unmatched case-control study in the Campania Region of Italy, 1988–1990. Eur J Oncol, 12:23–9.*

STEENLAND, K. 2002. Ten-year update on mortality among mild-steel welders. *Scand J Work Environ Health,* 28**,** 163-7.

T MANNETJE, A., BRENNAN, P., ZARIDZE, D., SZESZENIA-DABROWSKA, N., RUDNAI, P., LISSOWSKA, J., FABIÁNOVÁ, E., CASSIDY, A., MATES, D., BENCKO, V., FORETOVA, L., JANOUT, V., FEVOTTE, J., FLETCHER, T. & BOFFETTA, P. 2012. Welding and lung cancer in Central and Eastern Europe and the United Kingdom. *Am J Epidemiol,* 175**,** 706-14.

TARLO, S. M. 2014. Irritant-induced asthma in the workplace. *Curr Allergy Asthma Rep,* 14**,** 406.

TARLO, S. M. & LEMIERE, C. 2014. Occupational asthma. *N Engl J Med,* 370**,** 640-9.

TSE, L. A., YU, I. T., QIU, H., AU, J. S. & WANG, X. R. 2012. Occupational risks and lung cancer burden for Chinese men: a population-based case-referent study. *Cancer Causes Control,* 23**,** 121-31.

VALLIÈRES, E., PINTOS, J., LAVOUÉ, J., PARENT, M., 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**,** 47-58.

VAN LOON, A. J., KANT, I. J., SWAEN, G. M., GOLDBOHM, R. A., KREMER, A. M. & VAN DEN BRANDT, P. A. 1997. Occupational exposure to carcinogens and risk of lung cancer: results from The Netherlands cohort study. *Occup Environ Med,* 54**,** 817-24.

VUORISTO, P. 2014. 4.10 - Thermal Spray Coating Processes,

Editor(s): Saleem Hashmi, Gilmar Ferreira Batalha, Chester J. Van Tyne, Bekir Yilbas,. *Comprehensive Materials Processing***,** 229-276.

YIIN, J. H., SCHUBAUER-BERIGAN, M. K., SILVER, S. R., DANIELS, R. D., KINNES, G. M., ZAEBST, D. D., COUCH, J. R., KUBALE, T. L. & CHEN, P. H. 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**,** 603-13.

YIIN, J. H., SILVER, S. R., DANIELS, R. D., ZAEBST, D. D., SEEL, E. A. & KUBALE, T. L. 2007. A nested case-control study of lung cancer risk and ionizing radiation exposure at the portsmouth naval shipyard. *Radiat Res,* 168**,** 341-8.

Appendix 1. Summary of IARC (2018) evaluation of Welding fumes

For cancer in humans IARC concluded:

- There is *sufficient evidence* in humans for the carcinogenicity of welding fumes. Welding fumes cause cancer of the lung. Positive associations have been observed with cancer of the kidney.
- There is *sufficient evidence* in humans for the carcinogenicity of ultraviolet radiation from welding. Ultraviolet radiation from welding causes ocular melanoma.

For cancer in experimental animals IARC concluded:

- There is *limited evidence* in experimental animals for the carcinogenicity of gas metal arc stainless steel welding fumes.

Overall IARC conclusion:

- Welding fumes are carcinogenic to humans (Group 1).
- Ultraviolet radiation from welding is carcinogenic to humans (Group 1).

It is noted that IARC concluded on welding fumes overall without specifying for which type of welding or for which base metal welded the conclusions apply.

Below is a summary assessment of the data set assessed by IARC. This summary is based on data tabulated by IARC for human, animal and other studies and the textual description and assessment of those studies by IARC (2018)). The original studies were not reviewed. The assessment includes only the human epidemiological cancer studies and animal and other toxicological assays evaluated by IARC.

I - Coverage of different types of welding

Human data

For cohort studies IARC considered that *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 Job Exposure Matrices (JEM) (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.*

For case-control studies IARC considered that *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.*

For the purposes of this mapping exercise, ECHA concurs that exposure assessment based on job title only is not very informative as it does not characterise the type of welding. ECHA notes also that IARC found the evidence of carcinogenicity of welding fumes in humans robust for lung cancer.

The focus in the present mapping is to screen which types of welding were covered by the studies evaluated by IARC. Therefore, this analysis summarises:

- those cohort studies (industrial and population-based) included in the IARC evaluation that reported lung cancer risk estimates (and used a more robust exposure assessment than job title alone);
- those lung-cancer case-control studies that used a welding specific questionnaire (and did not heavily rely on proxy-respondents).

The tables annexed indicate, for which types of welding, lung cancer risk estimates were separately reported by IARC as regards industrial cohorts (Table 15), population-based cohorts (Table 16) and case-control studies (Table 17). All studies for which IARC reported more specific results by base metal welded, the metal is either mild steel or stainless steel. In some studies more specific results were presented by industry, e.g. shipyard welders, boiler welders, building welders. In such industries steel welding is concerned at least during majority of time.

In some studies results are presented also by some metric of likelihood of chromium(VI) or nickel present in the welded material (from stainless steel welding) but no other metal-specific results are described.

For some studies also specific results by welding technique are reported, but they seem to concern those techniques during steel welding activities. For a number of studies the results reported by IARC concern only "welders" without further granularity. However, the description of the recruitment of study subjects indicates that those welders were selected from industries like shipyard, boiler-making, manufacture of vehicles etc, where the welding activities typically concern steel (mild or stainless).

As explained, the above analysis was based on reporting the individual studies in IARC (2018) without reviewing the individual study reports. It is, however, noted that IARC (2018) evaluation included one large multicentre cohort study by Simonato et al. (1991) with individual cohorts from Denmark, England, Finland, France, Germany, Italy, Norway, Scotland and Sweden and one large pooled case-control study covering 16 individual studies from Europe, Canada, China and New Zealand by Kendzia et al. (2013). The original articles of Simonato et al. (1991) and Kendzia et al. (2013) were reviewed and it was confirmed that they do not contain further details as regards specific types of welding in comparison to what is reported in (see Table 15 and Table 17).

In summary: the epidemiological studies included in IARC (2018) provided lung cancer risk estimates for welding fumes that come from populations of welders predominantly or exclusively exposed in welding of steel. When more specific risk estimates are presented, they concern typically stainless steel (ever, or predominantly) or mild steel (only, predominantly, ever) or specific industries like shipyards etc or metrics of presence of chromium (VI) or nickel in the welding fumes.

However, it is not possible to judge to which extent some welders that predominantly welded steel, also welded other metals, alloy steel that contained other metals or performed other activities (e.g. gouging, brazing, carbon arc or plasma arc cutting, and soldering). For soldering in its introduction to evaluation of human studies (section 2.1) IARC (2018) states *Studies or risk estimates of occupations which may involve unspecific and infrequent welding (such as pipefitters, plumbers, and solderers), are excluded from this review; the frequency of welding in these occupations is not normally clear, and the groupings are too broad to meaningfully evaluate exposure as a welder.*

This means that solderers were not in the scope of IARC evaluation of human studies, nor were soldering fumes assessed in any of the animal studies evaluated by IARC (see below), nor are soldering fumes listed in Table 1.1 of IARC which lists welding fume related exposures that have been assessed in previous IARC monographs.

An additional problem is that IARC was unable to assign the increased risk of lung cancer due to welding fumes to certain specific constituents apart from Cr(VI) and some other metal compounds explaining part of the risk. This would make it challenging to assess soldering-related lung cancer risk with only a comparison of compositions of steel welding fumes and soldering fumes.

Animal data

Only a few relevant animal studies were available to IARC, and mostly short-term studies. All these studies concerned welding fumes resulting from stainless steel welding, either with gas metal arc, metal inert gas or manual metal arc techniques. Thus, as described in IARC (2018) table 3.1, the exposure to metal compounds concerned mostly of Fe, Cr, Mn and Ni with only trace amounts of other metals.

Other data

IARC also evaluated *in vitro* and *in vivo* toxicological and mechanistic approaches. Only mild and stainless steel welding fumes and mild and stainless steel welders were covered by those studies. From these studies, IARC concluded that such welding fumes may lead to oxidative stress, inflammative and immunosuppressive activities *in vitro* and in welders.

Summary

The human epidemiological studies evaluated by IARC (2018) and providing risk estimates for lung cancer, concerned populations of welders predominantly or exclusively exposed in welding of steel. When more specific risk estimates were presented, they concerned typically stainless steel or mild steel welding, or welding in specific industries or occurrence of specific components of steel welding fumes. However, it is not possible to judge to which extent some welders who predominantly welded steel also welded other metals (e.g. aluminium) or performed other activities (e.g. gouging, brazing, carbon arc or plasma arc cutting, and soldering). However, solderers as such were explicitly excluded from the human studies evaluated by IARC. Furthermore it is noted that additive processes such as 3D printing are not mentioned in the IARC assessment and no specific results are mentioned for non-steel welding that would allow any conclusions. All the animal studies evaluated by IARC (2018) concerned welding fumes from stainless steel welding.

II- Notes on the main results

As explained in Section 9.4. of this report?, the lung cancer risk estimates vary quite widely in the epidemiological studies assessed. IARC did not perform a meta-analysis to combine these risk estimates to a meta-relative risk estimate (mRR) that would overcome the statistical variation in the individual, sometimes relatively small, study populations. Nor did IARC (2018) assess with a meta-analysis the potential variation of risk between type of welding (e.g. mild vs stainless steel or method of welding). Some such meta-analyses have been published separately and are described in Section 9.4.

IARC (2018) also did not explicitly identify any of the individual epidemiological studies as key studies for their evaluation of the strength of association. However, in the summary report of the IARC evaluation Guha et al. (2017) wrote that *exposure–response associations with indices of longer or greater cumulative exposure to welding fumes were also reported in several studies, some of which were large, high-quality studies ('t Mannetje et al. 2012, Matrat et al. 2016, Sorensen et al. 2007, Siew et al. 2008).* Guha et al (2017) further wrote that in these same studies *asbestos exposure and tobacco smoking, which are important potential confounders, could not explain the observed excess lung cancer risk in welders. Positive associations persisted after adjusting directly or indirectly for smoking, asbestos co-exposure, or both.* Some key results of those studies are described below.

- Siew et al. (2008) followed for lung cancer incidence in 1971-1995 the cohort of 1.2 million economically active Finnish men who participated in the 1970 national census. The Finnish job-exposure matrix (FINJEM) was linked to the occupation held for the longest time up to 1970 to assess cumulative exposure to welding fumes, iron fumes, asbestos, silica, chromium, nickel, lead, benzo[a]-pyrene, and smoking. Relative risks adjusted for age, smoking, socioeconomic status, and exposure to asbestos and silica were estimated. The standardized incidence ratio of cancer of the lung was 1.31 (95% CI 0.84–1.95) among welders in the building industry, 1.05 (95% CI 0.69–1.55) for welders in shipyards, 1.39 (95% CI 1.14–1.69) among welders not otherwise specified, and 0.95 (95% CI 0.78–1.15) among stainless steel welders. The risk for cancer of the lung increased with the cumulative exposure to welding fumes: those with low (0.1–9.9 mg/m^3-years), medium (10–49.9 mg/m^3-years) and high exposure (≥50 mg/m^3-years) had relative risks of 1.09 (95% CI 1.05–1.14), 1.16 (95% CI 1.03–1.31) and 1.15 (95% CI 0.90–1.46) respectively. Exposures to iron fumes, chromium, nickel, lead, and benzo[a]-pyrene were so strongly correlated with exposure to welding fumes that they could not be included in the same statistical model. To assess any potential confounding effect, additional analyses excluding workers with exposures to moderate or high levels of iron fumes, chromium, nickel, lead, and benzo[a]pyrene were performed. These exclusions did not markedly change the estimated risks associated with exposure to welding fumes.

- Matrat et al. (2016) performed a case-control study of 2276 lung cancer cases and 2780 controls in France. Men aged 18–75 yr were included. Exposure was based on information gathered by face-to-face interviews that included a lifelong occupational history, including job periods, and 20 job-specific questionnaires. A detailed 4-page supplementary questionnaire was used if a respondent declared that more than 5% of his working time was devoted to welding, brazing, or gas cutting. Regular welders were defined as participants who reported being employed as a welder for at least one job period. The smoking- and asbestos-adjusted odds ratio (OR) for regular welders (which corresponds to ever being employed as a welder) compared with non-welders was 1.66 (95% CI, 1.11–2.49). The adjusted odds ratios for being a regular welder for less than 10 years was 1.53 (95% CI 0.91–2.55) and for 10 years or more was 1.96 (95% CI, 0.98–3.92) (p for trend, 0.02).
- 't Mannetje et al. (2012) conducted a multicentre case-control study in eastern Europe and the UK, in which occupational histories were collected by face-to-face interviews. There were 15 483 lung cancer cases of which 568 had worked as welders, compared to 18 388 controls of which 427 had ever worked as welders. A total of 70 agent exposures were assessed by experts for each job regarding the expert's confidence in the presence of the exposure (possible, probable, certain), the percentage of working time exposed (1–5%, > 5—30%, > 30%), and the intensity (low, medium, high) according to a common protocol. Odds ratios (OR) were reported adjusted for asbestos, smoking, and other occupational exposures such as chromium and nickel. The OR for ever working as a welder or flame–cutter, adjusted for asbestos, silica, and metal exposure (e.g. Cr) and smoking, was 1.36 (95% CI 1.00–1.86).
  It is to be noted that in these analyses adjusting the OR among welders, only metal exposure in an occupation other than welding was adjusted for. The similarly adjusted OR for ever exposure to welding fumes was 1.18 (95% CI 0.84–1.66). Subsequently, models were adjusted also for exposure to metals occurring as a result of welding (welding-related exposures). Adjustment for chromium reduced the risk estimate for welding fumes by 40% to 1.11 (95% CI 0.93, 1.32). Adjustment for welding-related nickel and cadmium did not appreciably further change this odds ratio. The OR with lifetime exposure expressed in cumulative welding hours for 1–2520 hours, 2521–28 900 hours, and more than 28 900 hours were 0.94 (95% CI 0.73–1.21), 1.27 (95% CI 0.99–1.43), and 1.09 (95% CI 0.84–1.43), respectively (p for trend, 0.19). In these analyses, ORs were adjusted for asbestos smoking, silica and chromium exposure (both Cr related to welding and non-welding exposure). The duration-response association was studied separately for welding fume exposure with and without chromium exposure. Welders without welding-related chromium exposure had a lower lung cancer risk (OR = 1.14, 95% CI 0.95 - 1.36) compared with welders with chromium exposure

(OR = 1.34, 95% CI 1.04 - 1.71). In these analyses an association with duration of exposure to welding fumes was observed for the welders without chromium exposure, with the most pronounced effect observed for those with more than 25 years of exposure (OR = 1.48, 95% CI 1.11 - 1.97). The risk for welding with chromium exposure was elevated for all duration strata, with no apparent duration-response association (ORs 1.47, 1.28, 1.28 for 1-8, 9-25 and > 25 years, respectively).

- Sorensen et al. (2007) followed 4539 male Danish welders for cancer incidence in 1968-2003. Exposure was assessed based on a welding exposure matrix (including > 1000 measurements) for welding fume particulates combined with questionnaire data on welding characteristics. Information on exposure to asbestos and smoking habits were also collected with a questionnaire. Hazard rate ratios (HRR) were adjusted for age, asbestos and smoking. In analyses according to cumulative exposure to welding dust (mg/m^3-years) among stainless steel welders the HRR increased by increasing exposure and reached statistical significance (HRR = 2.34, 95%CI 1.03 - 5.28) in the highest exposure category (> 11 mg/m^3-years), while in mild steel welders without stainless steel welding exposure, there were no clear indications of exposure–response relationships according to cumulative exposure.

Table 15: Summary of industrial cohort studies reporting lung cancer risk estimates and based on more refined exposure assessment than only job title (from IARC table 2.3)

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
Simonato et al. (1991) Europe, multicentre (Denmark, England, Finland, France, Germany, Italy, Norway, Scotland, Sweden) Enrolment and follow-up different between countries Cohort	11 092 welders (164 077 person-yr); workers employed as shipyard, MS, or SS welders by 135 companies; different inclusion criteria for each national cohort Exposure assessment method: expert judgement; welding process exposure matrix developed to estimate exposure levels for total welding fumes, total Cr, Cr(VI), and Ni (described in Gérin et al. (1993))	Welders (in general) Shipyard welders Mild steel welders Stainless steel ever welders Stainless steel predominantly welders. In addition risk estimates by cumulative exposure to Cr(VI) and Ni for stainless steel welders (ever or predominantly)
Moulin et al. (1993) France Enrolment 1975–1976/follow-up 1975–1976 to 1987–1988 (depending on the factory) Cohort Partial overlap with the IARC study, Simonato et al. (1991)	2721 welders, 6683 controls; all male workers employed as welders at the beginning of the follow-up in 13 factories; internal comparison group: 6684 manual workers (excluding boilermakers, foundry workers, painters, or cutters) randomly selected among non-welders in the same factories; restricted to workers employed for at least 1 yr Exposure assessment method: records of welding processes, types of metal, and percentage of working time available at the individual level in eight factories and at the workshop level in five factories; smoking habits from medical records (recorded by the occupational physician once a year); information on asbestos available on factory level only so not relevant for the statistical analysis (it only accounted by separating shipyard from non-shipyard welders	Welders (in general) Shipyard welders Mild steel welders Ever stainless steel welders Predominantly Cr (VI)
Milatou-Smith et al. (1997) Sweden Enrolment 1950–1965/follow-up 1955–1992 Cohort Partial overlap with the IARC study, Simonato et al. (1991)	233 welders (high exposure cohort); 208 welders (low exposure cohort); two cohorts of welders, employed for at least 5 yr during 1950–1965: one of SS welders exposed to high levels of Cr(VI), and one of railway track welders exposed to low levels of Cr(VI) Exposure assessment method: records of information on average levels of exposure to Cr from Swedish measurements in 1975 (SS welders 110 μg/m3, railway track welders 10 μg/m3); no or minimal asbestos exposure (company statements)	Welders exposed to high levels of Cr (stainless steel welders) Welders exposed to low levels of Cr (mild steel welders)
Becker (1999) Germany Enrolment 1950–1970/follow-up 1950–1995 Cohort Partial overlap with the IARC study, Simonato et al. (1991)	1213 SS welders, 1688 turners (internal reference group); arc welders exposed to Cr and Ni and turners employed for at least 6 mo during 1950–1970 at 25 factories of the metal-processing industry Exposure assessment method: exposure duration from companies records; assessment of welding exposure characteristics (welding procedure, percentage of working time) and smoking habits at the individual level by interview of the foremen and superiors; average duration of exposure of the welders was 18.3 yr	Stainless steel elders Coated electrodes welders Coated electrodes or MIG-MAG/WIG welders, Exclusively MIG-MAG/WIG welders
Sørensen et al. (2007) Denmark	4539 welders; male production workers, employed for at least 1 yr at 74 SS or MS companies (shipyards, apprentices, and craftsman excluded), alive at 1 April 1968, born	Mild steel, never stainless steel welders Stainless steel welders

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
Enrolment 1964–1984/follow-up 1968–2003 Cohort Partial overlap with the IARC study, Simonato et al. (1991)	before 1965, who answered the questionnaire in 1986; study population restricted to ever welders who started in 1960 or later Exposure assessment method: welding exposure matrix (based on > 1000 measurements) for welding fume particulates combined with questionnaire data on welding characteristics; questionnaire for asbestos exposure and smoking; next-of-kin questionnaire for the subgroup of deceased	Ever welding Ever stainless steel welding Ever MMA-stainless steel Never MMA-stainless steel Ever mild steel, never stainless steel
Merlo et al. (1989) Genova, Italy Enrolment 1930–1980/follow-up 1960–1981 Cohort Partial overlap with the IARC study, Simonato et al. (1991)	527 welders: 274 oxyacetylene (MS); 253 electric arc welders (SS); all male shipyard workers employed for at least 6 mo as a welder; electric arc slowly replaced oxyacetylene welding over time (1940s: 66% oxyacetylene; 34% electric arc; 1986: 44% oxyacetylene; 56% electric arc). Exposure assessment method: records of job title (electric arc workers: open spaces, lower levels of gases and fumes; oxyacetylene workers: inside oil tankers, higher levels of gases and fumes); air samples during cutting in oil tankers: B[a]P (3–22 µg/m3), NOx (3–8.5 ppm), dust (9–27 mg/m3); higher Ni and Cr(VI) found in SS and MIG welding; asbestos fibres not detected	Shipyard welders (all) Shipyard welders (oxyacetylene) Shipyard welders (electric arc)
Puntoni et al. (2001) Italy Enrolment 1960–1980/follow-up 1960–1995 Cohort	3984 male shipyard workers (267 electric arc welders and 228 gas welders); male shipyard workers (whole cohort) employed at the harbour of Genoa Exposure assessment method: records of individual data on job titles from the personnel department; coding the most prevalent job for individuals with different job titles	Shipyard welder, electric arc Shipyard welder, gas
Melkild et al. (1989) Norway Enrolment: 1946–1977/follow-up: 1953	4778 male shipyard workers (783 MS workers); male workers first employed at shipyard on southwest coast of Norway for at least 3 mo during the enrolment period; MMA-MS welding predominant until 1970; SS welding did not become common until the mid-1970s; gas-shielded welding introduced in the 1960s Exposure assessment method: questionnaire and company records, classifying job titles within 10 categories; 1973 survey: total fumes 7.3 mg/m3 (3.6–23.6); Ni: 0.34 mg/m3 (0.11–1.97); Cr: 0.12 mg/m3 (0.03–0.65); personal protection equipment and ventilation provided to shops in early 1970s; asbestos used until early 1970s	Welders (in general)
Danielsen et al. (1993) Norway Enrolment 1940–1979/follow-up 1953–1990 Cohort	4571 male shipyard workers (623 MS welders); identified by personnel register with information regarding name, start, and end dates; mainly MMA welding performed on MS Exposure assessment method: records of interviews with retired workers; high-exposure welders were defined as welders employed ≥ 3 yr and identified as a welder by veteran workers; very high exposure was defined as a subgroup employed ≥ 5 yr as a welder and followed up from the 5th year of employment Environmental monitoring data: total dust 2.5 mg/m3 (0.8–9.5 mg/m3)	Shipyard welders
Danielsen et al. (2000) Norway Enrolment 1945–1980/follow-up 1953–1995	4480 male shipyard workers; 861 welders; 908 welded some time; 24 welders in machinery production (SS); workers identified by personnel register with information regarding name, start, and end dates; mainly MS welders	Shipyard welders

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
Cohort	Exposure assessment method: records of job title and work history. Welding fumes (mg/m3): MS, 14.5 (1973) and 1.87 (1989); SS, 1.5 (1977) and 7.0–38 (1989); SS grinders, 25.5 (1977). Information on employment outside the shipyard (prior to or between jobs) available from the early 1950s; average length of employment 10.1 yr	
Yiin et al. (2005) USA Enrolment 1952–1992/follow-up 1952–1996 Cohort	13 468 workers; men and women, all races, employed as civilian workers at Portsmouth Naval Shipyard for at least 1 d and monitored for radiation Exposure assessment method: expert judgement; exposure to welding fumes and asbestos (0, none; 1, possible; 2, probable) assigned to each job title/shop combination by an expert panel; cumulative exposure score calculated as the sum of the duration of exposed jobs, weighted by exposure probability	Shipyard welders
Yiin et al. (2007) USA Enrolment 1952–1992/follow-up 1952–1996 Nested case–control	Cases: 1097 deaths from lung cancer Controls: 3291 risk-set-matched controls (3 per case, randomly selected by incidence density sampling) Exposure assessment method: expert judgement; intensity and frequency of exposure to welding fumes (as Fe2O3 fumes) and asbestos assessed by an expert panel of 3 industrial hygienists for 3519 job/shop/period combinations. Good concordance, weak inter-rater agreement. Cr and Ni content of welding fumes were also assessed (not used in the analysis). 53% of the study subjects were ever exposed to welding fumes; 64% to asbestos, 8% to Ni and 6% to Cr	Shipyard welders
Rinsky et al. (1988) Kittery, Maine, USA 1952–1977 Nested case–control	Cases: 405 white male deaths from malignant neoplasm of bronchus, trachea. or lung; diagnosis based on death certificates Controls: 1215 selected from the same cohort, matched by date of birth, year of 1st employment, and duration of employment 3:1 Exposure assessment method: personnel records indicating the specific shops to which a person had been assigned; job classification and date of each change in employment were used to code work history	Shipyard welders (by exposure to welding fumes and exposure to asbestos)
Park et al. (1994) USA Enrolment 1966–1989/follow-up 1978–1988 Cohort	16 197 hourly workers (76% assembly plant, 24% stamping plant); 3887 stamp workers; all hourly employees who worked ≥ 2 yr at 2 automotive assembly plants and a metal stamping plant before 1989 Exposure assessment method: records of six process-related categories for stamping plant; ~25 of the decedents worked in more than one exposure category; welding was performed on sheet metal	Welders in stamping or assembly plant
Steenland (2002) Illinois, USA Enrolment 1950s–1980s/follow-up mid-1950–1998 Cohort	4459 welders; 4286 never welders; hourly male (90% white) workers with ≥ 2 yr of experience as a production arc welder or welder helper at 3 heavy equipment manufacturing plants Exposure assessment method: records of person monitoring available from 1974 to 1987; smoking data available for subset of workers; TWA geometric mean across plants (particulate levels, 5.5–7.4 mg/m3; Fe2O3, 3–4.1 mg/m3); average duration of welder 8.5 yr	Mild steel welders
Danielsen et al. (1996) Norway	2957 male welders; 606 SS welders; members of the National Registry of Boiler Welders from 385 different businesses who registered before 1981 with information on	Boiler welders Stainless steel welders

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
Enrolment 1942–1981/follow-up 1953–1992 Cohort	DOB; foreigners without permanent addresses in Norway excluded; most registered welders welding on MS; MMA welding predominant method in early years Exposure assessment method: records of welder registration information contained the method of welding for certification and information on previous work experience	
Meguellati-Hakkas et al. (2006) France Enrolment 1978–1994/follow-up 1978–1996 Cohort	34 305 men ever employed as telephone linemen in 1978 and new hires from 1978 to 1994 Exposure assessment method: expert judgement; semiquantitative assessment based on expert assessment of job tasks for specific calendar/time periods; exposure duration was estimated for welding; highest category was 0.04 yr or more	Welders (in general)
Dunn and Weir (1968) California, USA Enrolment 1954–1957/follow-up 1954–1962 Cohort	68 153 men in all occupations; 10 233 welders and burners; male workers aged 35–64 employed in 14 selected occupational groups were selected from union mailing lists and questionnaires Exposure assessment method: questionnaire; occupational title, employment duration, working conditions, type of welding, and specific exposures associated with particular occupations	Welders and burners (in general)
Polednak (1981) Tennessee, USA Enrolment 1943–1974/follow-up 1974 Cohort	1059 white male welders employed at Oak Ridge nuclear facilities during the enrolment period; two subgroups of welders: (1) 536 welders at K-25 Ni alloy pipes (MS and Ni); and (2) 533 welders at Y-12 and X-10 plants conducting various types of welding (SMA, TIG, MIG) Exposure assessment method: records of personal air monitoring (Ni and Fe2O3) for different welding procedures: Fe2O3, 0.18–0.47 mg/m3; Ni (mg/m3) was highest for MIG/Ni (0.57), intermediate for SMA/Ni (0.13) and MIG carbon steel (0.25), and lowest for TIG welding with Ni (0.04) or carbon steel (0.08). Biomonitoring data (metals) among 33 Ni welders in K-25 facility (0.053 mg/L Ni). Information on smoking available for 33% of workers	Welders in K-25 Ni alloy pipes (MS and Ni) Other welders (Y-12 and X-10 plants conducting various types of welding (SMA, TIG, MIG))
Austin et al. (1997) Ohio, USA 1970–1987 Nested case–control	Cases: 231 deaths from lung cancer Controls: 408 selected from the same cohort matched by race, sex, and year of birth using density sampling Exposure assessment method: records of complete work history from plant personnel files; telephone interview for lifestyle characteristics	Welding (in general)

B[a]P, benzo[a]pyrene; Cr, chromium; Cr(VI), hexavalent chromium; d, day(s); DOB, date of birth; Fe2O3, iron oxide; h, hour(s); IARC, International Agency for Research on Cancer; MAG, metal active gas; MIG, metal inert gas; MMA, manual metal arc; mo, month(s); MS, mild steel; Ni, nickel; NOx, nitrogen oxides; SMA, shielded metal arc; SS, stainless steel; TIG, tungsten inert gas; TWA, time-weighted average; vs, versus; wk, week(s); WIG, Wolfram-Inert-Gas welding; yr, year(s)

Table 16: Summary of population based cohort studies reporting lung cancer risk estimates and based on more refined exposure assessment than only job title (from IARC table 2.1)

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
van Loon et al. (1997) Netherlands Enrolment September 1986/follow-up September 1986–1990	Case–cohort analysis: 524 lung cancer cases, 1630 men in the subcohort; general population cohort of 58 279 men aged 55–69 yr; study restricted to subjects who reported a complete job history Exposure assessment method: expert judgement from a self-administered questionnaire; assessment of probability of exposure to welding fumes, asbestos, paint dusts, and PAHs Cumulative score calculated as the sum of the duration of exposed jobs, weighted	Welders (in general)
Siew et al. (2008) Finland Enrolment 1970/follow-up 1971–1995	1.2 million men; 30 137 lung cancer cases; all economically active Finnish men born during 1906–1945 who participated in the 1970 population census Exposure assessment method: expert judgement; FINJEM linked to the longest-held job in 1970 to assess exposure to welding fumes, iron fumes, asbestos, SiO2, Cr, Ni, Pb, B[a]P, and smoking; exposure estimates based on the judgment of ~20 experts at the Finnish Institute of Occupational Health	Welders and flame cutters (stainless steel >10%) Welder, shipyard Welder, building Welder, not elsewhere classified

B[a]P, benzo[a]pyrene; Cr, chromium; FINJEM, Finnish job-exposure matrix; Ni, nickel; PAH, polycyclic aromatic hydrocarbon; Pb, lead; SiO2, silicon dioxide

Table 17: Summary of lung cancer case-control studies that used a welding specific exposure questionnaire (and not only job title) and did not rely importantly on proxy respondents (from IARC table 2.4)

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
Gerin et al. (1984) Montreal, Canada 1979–1982 Overlaps with the study of Vallières et al. (2012) and therefore also with the SYNERGY pooling study (Kendzia et al., 2013)	Cases: 246 male cancer cases aged 35–70 yr from entire Montreal population at major hospitals for 12 tumour sites identified through hospital pathology department (1343 patients of whom 246 were diagnosed with lung cancer) Controls: 1241, 144 general population healthy subjects and all cases of the remaining 11 tumour sites Exposure assessment method: questionnaire; individual expert assessment of exposure (focusing on Ni and Cr) based on job histories and a semi-structured probing section	Welders (in general) Welders with Ni exposure Welders without Ni exposure
Kjuus et al. (1986) SE Norway 1979–1983	Cases: 176 male incident lung cancer cases of age < 80 yr, admitted to the medical ward with the recent diagnosis of lung cancer Controls: 176 age-matched controls (± 5 yr) selected from the same ward; chronic obstructive lung diseases and conditions, implying physical or mental handicaps not eligible Exposure assessment method: questionnaire; subjects were interviewed at the bedside to obtain complete work history since 14 yr of age; job title and detailed information on relevant exposure factors were ascertained	Welding (in general) Welding (stainless steel, acid proof)
Jöckel et al. (1998) West Germany 1988–1993 Included in the pooled SYNERGY study (Kendzia et al., 2013)	Cases: 1004; 839 men and 165 women from hospitals (females excluded from analysis) Controls: 1004 randomly drawn from a sample of mandatory residence registries, matched for region, sex, and age (±5 yr) Exposure assessment method: questionnaire; welding assessment for all workers reporting welding, regardless of job title, based on a welding-specific supplementary questionnaire; quantification of duration and frequency of each welding task; assessment of welding technique and type of metal; detailed quantitative assessment of asbestos exposure based on several job-specific questionnaires and a case-by-case expert assessment	Welder or burner Oxyacetylene welding Welding fumes (in general) Gas shielded welding Iron and steel welding Welding in air/spacecraft welding
Gustavsson et al. (2000) Stockholm, Sweden 1985–1990 Included in the pooled SYNERGY study (Kendzia et al., 2013)	Cases: 1042 men aged 40–75 yr with diagnosis of lung cancer Controls: 2364 randomly selected from the general-population registry, frequency-matched to the cases in 5-yr groups and year of inclusion (1985–1990); additional matching for vital status to balance cases and controls with regard to being alive at data collection Exposure assessment method: expert judgement; postal questionnaire on lifetime occupational history, residential history since 1950, and smoking habits, as well as on some other potential risk factors for lung cancer; completion by telephone interview; occupational history supplemented by detailed questionnaire on work tasks, frequency, and location(s) for occupations involving potential exposure to motor exhaust; next-of-kin questionnaires for deceased cases/controls	Welding fumes (in general)
Soskolne et al. (2007) Campania region, Italy 1988–1990	Cases: 168 patients with respiratory tract cancers (lung n = 111, larynx n = 35, nasal/pharynx n = 22) Controls: 247 unmatched patients without any respiratory, bladder, or oral cavity cancers, including patients having any other reason for hospitalization; hospital-based case control study	Welding fumes (in general)

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
	Exposure assessment method: expert judgement; occupational history; exposure to 20 agents classified by the industrial hygienist	
Brenner et al. (2010) Toronto, Canada 1997–2002 Included in the pooled SYNERGY study (Kendzia et al., 2013)	Cases: 445 incident cases of cancer of the trachea, bronchus, or lung diagnosed in men and women of age 20–84 yr from four major tertiary care hospitals in metropolitan Toronto Controls: 948 (425 population; 523 hospital); population-based controls were randomly sampled from property tax assessment files (n = 425), hospital-based controls were sampled from patients seen in the Mount Sinai Hospital Family Medicine Clinic (n = 523), frequency-matched with cases on sex and ethnicity Exposure assessment method: detailed questionnaire administered via interview either in person or over the telephone	Exposure to welding equipment (i.e. not only welders but also non-welders exposed to welding fumes)
Corbin et al. (2011) New Zealand 2007–2008 Included in the pooled SYNERGY study (Kendzia et al., 2013)	Cases: 457 incident cases of lung cancer aged 20–75 yr identified through the cancer registry; 53% of those eligible participated Controls: 792 controls selected from electoral rolls and recruited in two waves; frequency-matched for age distribution for lung cancer and three other cancer sites; 48% of those eligible participated Exposure assessment method: questionnaire; complete occupational history by telephone interview except for 432 controls who were interviewed face-to-face	Welders and flame cutters
t Mannetje et al. (2012) UK, Romania, Hungary, Poland, Russian Federation, Slovakia, and Czech Republic 1998–2001 Included in the pooled SYNERGY study (Kendzia et al., 2013)	Cases: 2197 incident lung cancer (age, < 75 yr) Controls: 2295 frequency-matched on study area, sex, age (within 3 yr) and selected from hospital patients Exposure assessment method: expert judgement; face-to-face interview, and expert assessment of 70 agent exposures	Worked as welder/flame cutter, analyses by duration Also analyses by duration of: Arc welding Gas welding Gas and arc welding Exposure to welding fumes without Cr Exposure to welding fumes with Cr
Tse et al. (2012) China, Hong Kong SAR 2004–2006 Included in the pooled SYNERGY study (Kendzia et al., 2013)	Cases: 1208 male histologically confirmed lung cancer cases aged 35–79 yr Controls: 1069 male randomly selected referents living in the same districts as the cases, identified from telephone directories, frequency matched to cases (5-yr age groups); excluding subjects with a history of physician-diagnosed cancer at any site (48% participation) Exposure assessment method: questionnaire; cases were interviewed within 3 mo of the diagnosis of lung cancer; occupational history of jobs held at least 1 yr (industry, job title, specific tasks performed, beginning/end dates of each job period); job titles/ industries coded according to ISCO/ISIC	Welding fumes (in general)
Vallières et al. (2012) Montreal, Canada	Cases: 857 (Study I), 736 (Study II) men, incident, histologically confirmed lung tumours, aged 35–75 yr Controls: 1066 (Study I), 894 (Study II); population controls randomly selected from electoral rolls, matched by age and area of residence	Arc welding fumes Gas welding fumes

Reference, location, enrolment period/follow-up, study design	Population size, description, exposure assessment method	Types of welders for which lung cancer risk estimates were presented separately
Study I: 1979–1986; Study II:1996–2001 Included in the pooled SYNERGY study (Kendzia et al., 2013)	Exposure assessment method: expert judgement; supplementary questionnaire for welding, including questions on the type of gases used, metal welded, and h/wk and wk/yr of exposure	
Kendzia et al. (2013) Europe, Canada, China, and New Zealand 1985–2010 SYNERGY: pooled analysis of 16 studies; overlapping studies: Jöckel et al. (1998), Gustavsson et al. (2000), Richiardi et al. (2004), Brenner et al. (2010), Corbin et al. (2011), Guida et al. (2011), ’t Mannetje et al. (2012), Vallières et al. (2012), Tse et al. (2012)	Cases: 15 483; 568 cases had worked as welders Controls: 18 388; 427 controls had ever worked as welders Exposure assessment method: questionnaire; occupational and smoking histories were assessed in face-to-face interviews (81%); subjects considered exposed if job title was (1) ‘welder’ for ≥ 1 yr or (2) considered as potentially and occasionally involving welding activities	Welder (in general) Welder in: Shipbuilding and repair Construction and related building services Manufacture of machines, equipment, appliances Manufacture of motor vehicles and motor bikes Repair of transport equipment
Matrat et al. (2016) France 2001–2007 ICARE study. Complements earlier study by Guida et al. (2011) and presents additional analyses beyond pooled study of Kendzia et al. (2013).	Cases: 2276 population-based histologically confirmed, incident primary lung cancer cases in men aged 18–75 yr, identified through 10 of 11 cancer registries Controls: 2780 population controls from the same administrative department using random digit dialling, frequency-matched with cases for sex (only men) and age; additional statistical analysis on SES also performed Exposure assessment method: questionnaire; face-to-face interviews using standardized questionnaire, recording details of each occupation lasting ≥ 1 mo, with 20 job-specific questionnaires; asbestos exposure assessed by both a task-exposure matrix and a job exposure matrix	Regular welders (in general) Regular welders, Gas welding Regular welders, Arc welding Regular welders Spot welding Regular welders, Other Also some further analyses by presence of coating in the welded material or type of cleaning applied before welding coated material

As, arsenic; CCR, Californian Cancer Registry; Cd, cadmium; CI, confidence interval; Cr, chromium; d, day(s); h, hour(s); ICIT, Index de la Classification Type; ISCO, International Standard Classification of Occupations; ISIC, International Standard Industrial Classification; mo, month(s); NOx, nitrogen oxides; Ni, nickel; NR, not reported; NSCLC, non small cell lung carcinoma; OR, odds ratio; Rn, radon; SAR, Special Administrative Region; SBA, steel beam assembly; SCC, squamous cell carcinoma; SES, socioeconomic status; SiO2, silicon dioxide; SS, stainless steel; wk, week(s); yr, year(s)