HEALTH AND SAFETY ASPECTS OF ARC WELDING

Grant McMillan
Consultant Occupational Physician, 17 Ashburton Road, Alverstoke, Hampshire, UK PO12 2LH, UK

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Summary

Welding is a generic term for any of the processes of joining materials at areas or points softened or liquefied by the application of heat derived in a variety of ways. The most common source is an electric arc. Millions of workers are involved in arc welding of metal, one of the most ubiquitous industrial processes in the world. It can produce a wide range of hazards and associated acute risks to health, safety and wellbeing. The nature and extent of these factors and resulting acute and chronic ill-effects, and the interpretation and assessment of the quality of research reports in this area, are discussed. It is argued that much can be done to control these risks, and thus prevent injury and disease, whilst boosting productivity, by applying available knowledge and experience to greater effect, improving design and organization of welded constructions, and seizing opportunities presented by new technology and production methods including mechanization and automation. Such action is needed urgently to help overcome difficulties in recruiting and retaining suitable workers. Uncertainty surrounding the contribution welding emissions may make to the development of serious diseases such as lung cancer and mood and movement disorders, is discussed. It is put forward that the absence of absolutely definitive information on suspected causation of chronic and malignant disease is neither reason nor excuse for not taking protective action.

1. Introduction

1.1. Definition of Welding

Welding is a generic term for any of the processes of joining materials at areas or points softened or liquefied by the application of heat derived in a variety of ways, with or without the application of pressure and/or the use of filler material, so that an area of coalescence is formed which, when allowed to cool, forms a continuous metallic bond between these points of the component parts. There is usually an emission of particles (fume) and gases as an unwanted by-product. Several sources of heat are used. By far the most common source is an electric arc struck between two electrical conductors. Arc welding of metal is the most ubiquitous of the industrial processes, probably followed by resistance welding. It is the focus of this chapter.

1.2. Welding Processes

The principal categories of activities categorized by The American Welding Society (AWS) as *welding processes* comprise arc, solid state, resistance and oxyfuel welding; brazing and soldering. AWS identifies several *processes allied to welding*. These include thermal spraying; arc, oxygen and thermal cutting; and adhesive bonding. These are mentioned here to emphasize that these are not welding processes. It is emphasized that this chapter focuses on arc welding. There are four main specific arc processes. These are manual metal arc (MMA), metal inert gas (MIG), metal active gas (MAG), and tungsten inert gas (TIG). While these are similar in some respects, each is separate and different from the others in important health-significant ways. Each of these methods may be used manually and all except MMA can be used mechanically. Sources of technical information on these and other joining processes are included in the Bibliography.

1.3. Definition of a Welder

Globally, millions of workers use arc welding as the main or an auxiliary process in their occupation. It is important to be absolutely clear and precise about what work one means when talking about or researching the health and safety aspects of being a “welder”. In that context for the purposes of this chapter a *welder* is defined as a worker who is or has been employed principally in *joining* separate pieces of metal in a continuous metallic bond using arc, oxyfuel, resistance or oxyfuel welding processes. He or she does not use soldering or brazing as the principal joining methods nor are they primarily engaged in cutting metal but rather in joining it. As the hazards vary in nature and extent between and within welding processes, it is vital to the accuracy of risk assessment that the welder’s work title recorded indicates at least the processes he uses or has used e.g. arc welder, oxyfuel or gas welder, resistance welder. To re-emphasize, this chapter deals almost exclusively with arc welding.

1.4. Workers Using Processes Allied to Welding

With the exception of adhesive bonding, the processes allied to welding mentioned in Section 1.2 are used to cut or coat metal rather than for joining it. Men and women who are employed principally using these may choose to describe themselves as “a welder”. In most circumstances it does not matter that this is not a strictly accurate definition. It is, however, very important when assessing the effect of work on health as the emissions, and thus the hazards and derived risks, of these processes may differ significantly from those of welding processes. In such circumstances these workers should not be described as “welding” and if these form the principal or significant part of their work should not be called “welders”. This is not just being pedantic. It would fatally flaw a study of the effects of welding on health if such workers were to be included as subjects. When someone describes themselves as a welder or working with a welder it is very important to clarify and note the processes they use or to which they are exposed. Hazards of processes allied to welding are not considered in this chapter.

2. Hazards of Arc Welding

2.1. Definitions

A hazard is an agent which has the potential to cause harm. Risk is the assessed chance of that agent actually causing harm in given circumstances.

In this article, use of terms “welding” or “welder” without qualification should be taken as meaning arc welding and arc welder unless otherwise specified by another qualifier such as “resistance” or “oxyfuel”.

2.2. Sources of Hazards

Hazards of welding derive from components of the welding processes namely, emissions from the processes, the physical nature of the work environment, environmental contaminants such as asbestos, and manual handling of equipment and materials.

2.3. Emissions from Welding Processes

The emissions from arc welding processes are an unwanted by-product. They comprise:

- hot metal splashes and spatter;
- an often biologically active mixture of particles varying in composition, size and morphology (ie structure) which is collectively termed “welding fume”;
- a mixture of gases; and
- ionizing and non-ionizing radiation.

2.3.1. Sources of Emissions

Emissions arise from and are influenced by many factors including the energy of the arc and thus electrical parameters; shielding gases; materials to be welded and their coatings and contaminants; materials in the filler metal, its core or coating; and reactions of the arc with gases and contaminants of the ambient air.

2.3.2. Particle Emissions

Constituents of particulate emissions derive almost entirely from the filler metal rod or wire and, when present, its flux coating and/or core (see Table 1). These are vaporized or discharged explosively by the intense energy of the arc. The particles formed are then oxidized in the ambient air to form “welding fume”. Consequently, the composition of the filler metal wire or rod, much more than that of the base metal(s) being welded together, usually has the prime effect on the composition of the fume. Surface coatings and contaminants of the base metal also make a contribution when present (see Section 2.3.6). The smallest particles (diameters < 100 nm) are formed by vaporization and homogenous nucleation of particles from the vapor phase. Accumulation occurs as primary particles experience further growth due to collisions with other primary particles as well as particle agglomerates. If the colliding particles are liquid, they will form a single sphere. If the collisions are between solid particles they may be held together by van der Walls bonding, electrostatic or magnetic forces, or they may sinter. Three differentiated types of fume particle morphology result. These are individual spherical particles, individual irregular shaped particles, and agglomerates containing multiple particles of different sizes.

2.3.3. Gas Emissions

As detailed in 2.4.3 below, gaseous emissions from arc welding comprise any shielding gases remaining after they have performed their role; gases formed in the arc and by the action of the arc on the ambient air (Section 2.3.7); and those resulting from combustion or heating of surface coatings (see Section 2.3.6). The number of variables affecting workplace experience means that a wide range of exposures is possible.

2.3.4. Radiation Emissions

Non-ionizing radiation emissions from arc welding comprise UV, IR, visible light and generated electromagnetic fields. It is one of the most potent industrial sources of UV radiation. Industrial radiography and welding with thoriated tungsten electrodes have the potential for damage by ionizing radiation.

2.3.5. Variations in Emissions between and within Processes

The formation and emission rates and the composition of each and all of these pollutants may vary markedly between and even within welding processes; welders using the same process in apparently identical circumstances can have quite different exposures. These variations can be troublesome when designing a sampling strategy, during sampling and when prescribing control solutions. They can, however, be turned to advantage to ensure the maximum reduction of hazardous emissions whilst achieving a weld that is in all respects “fit for purpose”, by selecting, using and perhaps modifying processes from those which are technically acceptable for a given task - and improving the skills of welders through education and training. The individual welder’s skill can be a powerful influence. It should not be forgotten that exposures of individual welders may come from general workshop levels rather than their own work.

2.3.6. Influence of Surface Coatings and Contaminants on Emissions

The composition and amount of fumes and gases produced may be influenced significantly in complexity and potential to cause harm when the metal to be welded has a surface coating applied, e.g. by galvanizing, electro-plating, painting on primer, thermal coating, or is contaminated by materials such as oil, degreasers or the products/by-products of manufacturing process e.g. lead, manganese. It is becoming increasingly common, particularly with resistance welding in the auto and white goods industries, to weld through or close to organic materials such as shop primers, other coatings, adhesives, etc. This can generate a wide range of degradation products. Their composition may be difficult to predict even if knowledge of the composition of the product is available.

2.3.7. Influence of Air Contaminants on Emissions

The air in the welding operator’s breathing zone may contain compounds originating from the surrounding workplace atmosphere rather than the welding process. Commonly used solvents found recently included acetone, cyclohexane and dichlormethane as vapor particles having passed from an adjacent tank or remained on metal parts which have just been cleaned but have not yet dried. These may be broken down into new and potentially hazardous substances. For example, formation of potentially hazardous concentrations of the eye and respiratory tract irritants dichloroacetylchloride, hydrochloric acid, chlorine and phosgene have been described in the laboratory and welding workshop as breakdown products resulting from arc-generated UV photo-oxidation of the chlorinated hydrocarbons trichloroethylene, perchloroethylene and/or, to a lesser extent, methyl chloroform. These are not safe solvents in welding environments. They and others which pose degradation hazards should be now only of historical interest through the awareness programs and the introduction of the more informed selection of safer degreasing and other solvent processes and improved separation of processes and engineering controls to contain solvent vapor.

2.3.8. Asbestos as an Environmental Contaminant

The air in the welding operator's breathing zone may contain compounds originating from the surrounding workplace atmosphere rather than the welding process. Commonly used solvents found in the ambient air near welding operations include acetone, cyclohexane and dichlormethane. Some may react with the arc to form other hazards such as phosgene. Many welders have worked in the ship and locomotive industries and others where they may similarly have been exposed to airborne asbestos fibers from materials they used to protect themselves from sparks and, more significantly, from insulation installed in the construction.

2.4. Chemical Hazards

2.4.1. Constituents of Particles

Chemical substances are present in the fume particles as simple oxides and spinels (complex oxides) rather than in elemental forms. Selective distillation can result in the proportions of metal compounds in the fume being significantly different from those in the filler metal from which they are largely derived. Table 1 seeks to identify the chemical constituents which are of some and of the greatest occupational hygiene importance. These are termed principal and key components respectively. The latter tend to present the greater risk of harm and require more stringent control measures to ensure that workers are not exposed to an excessive level of the substance concerned.

Process	Consumable	Typical principal fume components	Other possible principal components	Typical key components*
MMA (SMAW)	Unalloyed and low alloy steel	Fe, Mn, Cr, Cr(VI) Ni, Cu	F	Mn, Cr, CR(VI)
	High alloy steel	Cr, Cr(VI), Fe, Mn, Ni	F	Cr(VI), Ni
	Aluminum	Al, Cu, Mg, Mn, Zn	Be, Cl, F	AL, Mn or Zn
	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	Co, Cr, Cr(VI), Fe, Ni, Mn	Fe	Cr, Cr(VI) or Ni
	Copper-based	Cu, Ni		Cu or Ni
MIG/MAG	Unalloyed and	Fe, Mn, Cr, Cr(VI)		Mn, Cr, Cr(VI)

(GMAW/ GTAW)	low alloy steel	Ni, Cu		
	High alloy steel	Cr, Cr(VI), Fe, Mn, Ni		Cr, Cr(VI) or Ni
	Aluminum alloys	Al, Mg, Mn, Zn		Al, Mn or Zn
	Nickel-based	Co, Cr, Cr(VI), Mn, Ni	Fe	Cr, Cr(VI) or Ni
	Copper-based	Cu, Ni		Cu or Ni
Gas-shielded FCAW	Unalloyed and low alloy steel	Fe, Mn, Cr, Cr(VI) Ni, Cu	F	Mn, Cr, Cr(VI)
	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
	Nickel-based	Co, Cr, Cr(VI). Mn. Ni	Fe	Cr. Cr(VI) or Ni
Self-shielded FCAW	Unalloyed and low alloy steel	Fe, Mn, Cr, Ni, Cu, Al	Ba, F	Mn
	High alloy steel	Cr, Cr(VI), Cr(VI), Fe, Mn, Ni, Al	Ba, F	Cr(VI) or Ni
*Key components tend to present the greater risk of harm and require more stringent control measures to ensure that workers are not exposed to an excessive level of the substance concerned.				

Table 1. Principal and key components of commonly encountered arc welding fumes

2.4.2. Bioavailability of Constituents of Particles

The lung is the principal route for the constituents of these particles to enter the body of an exposed worker. Consequently, the size and structure of particles are critically important in assessing the biological availability and hazardous effect of their constituent compounds. Workplace measurements have demonstrated that most particles in welding fume are in the respirable category i.e., they may reach the deepest areas of the lung. Many particles are so small when they are formed as to be classified as nanoparticles. This may affect their penetration, retention, absorption and biological effect in ways which, as yet, are poorly understood. At the other end of the scale the formation of agglomerates of particles further complicates predictions as it is not known to what extent these persist after inhalation or if the constituent smaller particles separate within the lung – each affecting their depth of penetration and the proportion retained.

The morphology of individual particles may have a significant effect on chemical bioavailability. A varying proportion of the spherical particles, especially the larger ones, have their potentially biologically-active metallic compounds contained within a core surrounded by a relatively impervious, and thus possibly protective, silica-rich shell derived from components of the consumable. The particle cores generally consist of a complex amalgam of iron-rich oxides containing iron, manganese, potassium, chromium and oxygen in different ratios depending on the type of consumable. This core and shell structure may reduce the absorption of the core materials so that this may differ significantly from that anticipated from an analysis of the particle composition.

2.4.3. Constituents of Gaseous Emissions

The principal gases generated in the welding process are ozone, oxides of nitrogen (NO_x) and carbon monoxide. Harmful concentrations may accumulate in the absence of effective ventilation. The arc plays a key role in their formation. When arcing is not continuous, for example in manual processes, formation and emission of these gases peak during arcing and diminish or are absent between arcing. Accordingly, welders may be exposed for repeated short periods to concentrations very much higher than those indicated by an averaging sampling and measuring technique. Shielding gases may also be emitted.

2.4.4. Ozone

It has been said that exposure to ozone is currently a major occupational hygiene problem with almost all gas shielded arc welding processes and that, in recent years, the increasing use of aluminum and stainless steels, along with raised productivity, has increased the likelihood of unacceptable welder exposure. This appears to be related more to achieving control down to at least within national occupational exposure limits, many of which have been reduced in recent years, than to there being evidence in the literature of exposures to ozone in workplaces causing ill health in welders – as this has not been found (see later). The possibility of there being as-yet-undetected harm occurring in welders cannot be ignored – and so exposure to ozone must be minimized to at least within the national standards.

The generation of ozone is due to photo-dissociation of molecular oxygen in the ambient air around the welding process under the influence of direct or reflected UV radiation emitted from the arc. The gas forms in two distinct regions; approximately half within a 10-15 cm radius of the arc by the action of UV in the 130-175 nm range and the remainder in relatively low concentrations further from the arc, up to a meter, due to UV of wavelengths 175-240 nm. It decomposes when subjected to higher wavelengths. Usually the ozone reaches the breathing zone in a few seconds after the arcing starts and the concentration returns to the background level almost within the same time after arcing has ended.

The concentration of ozone is affected by the number of welders at work (as several together can build up significant concentrations during welding in an inadequately ventilated space), the welder’s care and skill, and any of the large number of other variables which influence the rate of formation and decomposition of the gas produced by each operator. These include the magnitude of the UV in the critical ranges for production – and beyond for decomposition of the gas once formed; the presence of fume particles, dust or other gases; the composition of the filler wire; the welding process and its parameters; and, often most complex and variable, the shielding gas. Together these, and the need for specialized equipment based on chemiluminescence, make measuring welders’ exposure problematic.

Process selection is a powerful influence on control of ozone emission and exposure. All else being equal, ozone concentration is greatest in processes with low fume emission and vice versa as it reverts to oxygen in contact with particles. For example, there tends to be a very fierce arc in TIG welding and so a lot of ultraviolet radiation and much ozone are produced, particularly when welding on aluminum and stainless steel. Process modification may be useful in reducing ozone levels, at least experimentally, as small changes to the process and its parameters can have disproportionate effects.

2.4.5. Oxides of Nitrogen

Oxides of nitrogen or nitrous gases (nitrogen monoxide, dioxide and peroxide) are generated as by-products in most arc welding, cutting and heating processes as a result of heating the air in the arc or flame region. Emission rates during arc welding are very low compared to allied processes especially plasma cutting and oxyacetylene processes. The hazard is increased in confined spaces with poor ventilation.

The first stage in the formation of these NO_x is oxidation of atmospheric nitrogen to nitrogen monoxide, a gas of very low toxicity. This occurs in contact with the very hot gas emanating from the arc and weld pool. 75-97% of the oxides of nitrogen emitted may be nitrogen monoxide. Its rates of formation and emission peak during arcing as the temperature goes above 500-1000ºC. They then fall, sometimes dramatically, as the NO is diluted by the ambient air and cools to its temperature whereupon it oxidizes, at rates dependent on concentration and temperature, to the biologically more active gases nitrogen dioxide and peroxide which have the potential to cause harm. The ratio of nitrogen monoxide and dioxide can change if ozone or other oxidants are present in the air. In gas shielded arc welding, because of ozone formation by the UV of the arc, almost all of the total oxides of nitrogen generated is nitrogen dioxide. The very low emission rates during arc welding compared to processes such as plasma cutting or oxyacetylene burning where much higher rates may be encountered, may be of practical importance for occupational physicians and epidemiologists when seeking to select samples of workers for research studies as mixing those with superficially similar jobs may result in mixing those with notably different potential exposures to these gases, e.g. arc welders (low NO_x) and flame burners (higher NO_x).

2.4.6. Carbon Monoxide

This gas is generated by thermal decomposition of carbon dioxide in metal active gas welding shielded by that gas and by the incomplete combustion of flux materials containing carbonates and/or cellulose in all or almost all processes. The amounts of carbon monoxide generated by fluxed arc welding processes are small and, generally, the risk of over-exposure is low.

2.4.7. Shielding Gases

Shielding gases used in processes such as TIG, MIG/MAG and FCAW may be inert such as argon, helium or nitrogen, or active argon-based mixtures containing carbon dioxide, oxygen or both. Helium may be added to argon/carbon dioxide mixtures to improve productivity. Carbon dioxide may be used on its own. None of the gases can be seen and none has a smell – though a method for odorization for safety purposes was described two decades ago. Their presence in hazardous concentrations is difficult to detect without prior knowledge or measuring equipment. The main hazard arising from shielding gases is asphyxiation (see Section 3.2.1).

2.5. Radiological Hazards

2.5.1. Non-Ionizing Radiation Emissions Including EMF

Arc welding emits UV, IR, and visible light and generates electromagnetic fields (EMF). As mentioned earlier, it is one of the most potent industrial sources of UV radiation. UVB radiation is emitted over the full UV spectrum (UVA, UVB, and UVC). The amount and the spectrum vary between processes and the materials being welded. Much UV is produced by TIG welding, especially on aluminum and stainless steel. The possible hazard of exposure to EMF, a non-ionizing radiation, is one of the most recent subjects of special interest as a hazard to the health of welders.

Although arc welding uses relatively low voltages it requires high current. This flows through welding electrical equipment and cables generating significant magnetic fields. Unless care is taken these induce strong fields close to the body. The arc welder's exposure to EMFs depends on the current intensity and welding process, waveform and type of power source, workshop design and the position of welding cables with respect to the body. Gas metal arc welding probably gives the highest potential for exposure. In resistance welding the highest magnetic field is generated in the electrodes. If the welding equipment is close to the welder and/or the welding cables are wrapped over or in direct contact with the body, as is often observed, then the welder may be exposed to relatively high intensities of field compared to other occupations. With cables coming up from the ground the standing welder will get the highest dose in the legs and, as he holds the gun in front of him, the abdomen.

2.5.2. Ionizing Radiation Including Risks from Thoriated Tungsten Electrodes

This may be introduced into the welding scenario through ancillary processes such as non-destructive testing radiography. Rarely and now quite unnecessarily, the hazard may occur as a consequence of the continued use of thoriated tungsten electrodes in TIG welding and, to a lesser extent, in plasma cutting. Tungsten is used in these processes because it can withstand very high temperatures with minimal melting or erosion. Performance is further improved by alloying the tungsten with small quantities of oxides of other metals. One such additive is thorium oxide which is radioactive, emitting mainly alpha particles. The main source of danger is in the ingestible and respirable dust produced during periodic grinding of the electrodes to maintain the necessary sharp point – but there is also a small external radioactive hazard.

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Biography Sketch

Grant McMillan is a practicing consultant in occupational medicine. His deep interest in the health of welders began in 1975. He has conducted original research, completed a doctoral thesis, and published scientific papers and book chapters on this topic. His work has been recognized by national and international awards including the French Rene Barthe Prize 1984, UK Gilbert Blane Medal 1987 and American Welding Society Health and Safety Prize 1994. From 1996 until its work was completed in 2003 he was the physician member of the Metal Fume Research Group at the University of Bradford where he was Visiting Professor of Occupational Health. He was a member of the UK Delegation to IIW (The International Institute of Welding) from 1984-2007 and Chairman of the IIW Commission on Health and Safety 1997-2006. His research interests continue in his work as an Honorary Senior Clinical Lecturer at the University of Birmingham where with colleagues he is advising on studies of occupational influences on movement and mood disorders such as Parkinson's disease. Dr McMillan has served HM The Queen as an Honorary Physician for seven years. He is a Member of Council and Trustee of The Royal Society of Medicine, a member of the Research Committee of the Chartered Institution of Occupational Safety and Health, and a Justice of the Peace.