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Occupational Health in Metal Arc Welding

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Abstract
The physical and often acute effects associated with metal arc welding, such as death by electrocution or physical injuries in the workplace are well recognised. Increasingly today, attention is focused upon chronic effects, in particular cancer risks in welders. This review aims to address these concerns; put the risks into perspective and direct the reader to the means of assessment and control. Attention is drawn to the activities of Commission VIII International Institute of Welding which, through its various working groups, is charged with reviewing world-wide publications on health and safety in welding and with the issue of authoritative statements. The mechanism of gas and fume generation from welding processes is described. Fume particle size and morphology in relation to inhalation and effects within the body are addressed. Epidemiology studies on cancer and other risks are reviewed. Strategies for the assessment and control of risks from metal arc welding are considered, taking due note of international movements on legislation and standardisation.

Introduction

Metal arc welding covers a wide range of processes used world-wide and estimated to involve more than 1% of the labour force in some industrialised countries [1]. Statistics concerning work-related injuries are notoriously unreliable, especially where diseases with long latent periods are considered or for diseases which have multiple causes, an important example being cancer. Acute physical injuries such as electrocution or workplace accidents do occur during welding and their causes are usually easily identified. Other physical but more insidious effects such as hearing loss or repetitive strain are less easily identified. Sufficient is known however concerning all of these effects for the risks to be assessed and the means of their control implemented employing design and managerial solutions. Accordingly this review focuses on long-term effects rather than the more readily recognised acute and readily controllable effects. The last 20 years have shown an explosion in concern about long-term health effects in welding. Scientific publications in this area were about 20 in 1970, rising through more than 200 in the early 1980s and Commission VIII reviewed several hundred papers presented during 1995. Commission VIII is charged by the International Institute of Welding (IIW) to monitor publications and national activities in relation to health and safety in welding and to publish guidance as appropriate. The IIW has an international role in respect of all aspects of welding, and is made up of national delegates and experts from over 40 countries.

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Welders siderosis, associated with deposition of iron in the lungs and acute respiratory diseases, has long been recognised, but the focus in recent years has moved to considering cancer, sensitisation, behavioural and musculoskeletal effects. The extent and severity of these health effects are currently being debated. Whilst excess cancers are undoubtedly observed in welders the cause is not established as demonstrated later. Because of the large workforce involved in welding and the economic implications of health risks or controls, even risks of small magnitude need to be seriously addressed. Methods of assessment of risk and control primarily at source by process modification are described. Developments in legislation with concomitant codification of practices and procedures through standard setting bodies are considered. The activities of international bodies especially the IIW relating to health and safety in metal arc welding are outlined.

Arc Welding Processes

Technical details of the many and varied types of arc welding processes are fully described elsewhere and in this paper sufficient is included only to highlight aspects relevant to health and safety [2–4]. The main processes are: Manual Metal Arc (MMA) utilising a metal stick electrode coated with flux; Metal Inert Gas (MIG) utilising a continuous wire electrode and gas shielding; Flux Core Arc Welding utilising a continuous wire having a core containing flux and possibly other metals used with or without gas shielding; and Tungsten Inert Gas (TIG) – the only one of the processes which makes use of a non-consumable electrode (thoriated tungsten) together with a consumable metal rod held in the arc which is surrounded by inert shielding gas.

In metal arc welding the electrode arcs onto the workpiece (which in certain cases may have been treated with metals such as zinc and cadmium contributing to fume) producing temperatures in excess of 10,000 K. Oxides of nitrogen can be produced at the high temperatures involved by reaction between nitrogen and oxygen present in the arc region. Radiation in the infrared region (presenting thermal risks), the optical and the ultraviolet (UV) regions (with possible eye damage) need control. Also, since UV transforms oxygen to the irritant gas ozone, an additional health risk from that gas may be present. Ozone generation, decomposition, assessment and control in welding is an extremely complex subject which can only be briefly touched on here. Close to the arc UV radiation of 120–180 nm is particularly effective in producing ozone, although at greater distances some ozone is produced from the 180–240 nm radiation [5–8]. Simply stated, metal arc weld processes which produce considerable fume may present low ozone risks due to the fume shielding the UV radiation and also assisting in decomposition of the ozone produced. Of the various processes described TIG normally produces least fume and significant amounts of ozone. Metal arc welding of aluminium is often associated with high ozone emissions.

Oxides of nitrogen and ozone present inhalation risks. Similarly, the production of mixed metal oxides (fume) of particle size within the respirable range presents inhalation risks in metal arc welding which need to be controlled [9–16]. The mechanism of fume formation is extremely complex, but essentially two primary sources can be identified arising from the electrode which typically account for more than 80% of the fume produced. At the high temperature of the electrode metals vaporise dependent on their respective vapour pressures to produce a mixture of metals which condenses, often reacting with oxygen to produce sub-micrometre chains which can coalesce to form larger species (still typically well below 1 μm and hence respirable). This fractionated fume will, because of its means of production, be rich in more volatile constituents of the electrode such as manganese. Physical ejection of discreet (unfractionated) parts of the electrode may also occur – described as spatter. Such ejected spatter undergoes a number of changes including oxidation and eruption from the centre of the particle to produce cenospheres. In addition to the fractionated and unfractionated fume produced from the electrode, there is a contribution from the workpiece and weld pool, typically less than 20% of the total – an exception being when the workpiece is galvanised when zinc emissions can be considerable. The production of fume is clearly dependent upon the presence of oxygen in the arc regions and the ambient environment, so can be considerably influenced by the shielding gases used [17–19].

Chromium in its hexavalent form – Cr(VI) – is produced in metal arc welding by complex routes. In stainless steel welding for example MMA fume may contain 5% total chromium (4% in the Cr(VI) form). Sodium present in the flux as a binder can allow stable hexavalent compounds to exist in the high temperatures of the arc regions. Replacement of sodium by lithium results in Cr(VI) compounds which are much less stable and considerably reduces the concentration of Cr(VI) in the fume. Mechanisms of the formation of Cr(VI) species in MIG have been extensively investigated in the author's laboratories and a mechanism postulated interrelating the generation of UV radiation, the production of ozone and the oxidation of chromium metal to Cr(VI) at some distance from the arc [20–24]. Understanding the mechanism of fume formation and of other associated constituents which may have an impact on health is fundamental to the development of control of hazard by process modification. For example the replacement of sodium by lithium in MMA, noted above, and the minimisation of ozone generation by choice of shielding gas or addition of active metals such as zinc in MIG which have been shown to have a dramatic effect in reducing Cr(VI) in the fume [2, 25–28].

Gases such as oxides of nitrogen and ozone are readily inhaled and their health effects are well documented [9, 14, 15]. The effects of inhaled fume are less well understood. Controls, to avoid untoward health effects, depend upon modification of the process to reduce the emissions at source, ventilation and in extreme cases the use of personal respiratory protective equipment. The effects of the fume and its constituents in the body are extremely complex, depending upon the surface area of the fume and its in vivo solubility and clearance mechanisms. Many studies are now being presented concerning the chemical and physical forms of for example chromium and nickel in welding fumes which throw light on their clinical effects and also allow the interpretation of the results of biological monitoring such as the measurement of metals or metabolites in the urine of welders [29–32].

Under a contract to the American Welding Society, the Mellon Institute Materials Characterisation Centre, USA analysed six welding fumes from a variety of welding rods and wires [33]. Techniques used included X-ray analysis, scanning electron microscopy, and automated electron beam analysis. Four carbon steel fumes, a stainless steel fume and an aluminium fume were tested. Particle average diameters were all in the respirable range between 0.1 and 1 μm. Dependent upon the magnification, the particles appeared as spheres or clusters of spheres. Electron diffraction patterns showed that the fumes contained crystalline material. There was no correlation between the average diameter and particle chemistry or between the average diameter and the fume type. Although to a first approximation such welding fumes may be described as composed of mixed metal oxides, the actual physical and chemical bonding of the individual metals within the fume can be very complex. The bonding is often intermetallic. The chemical form of metals such as chromium can depend upon the presence of other elements such as sodium.

In the 'ferrous' fumes, when large amounts of iron were sent, the main crystalline phase was magnetite and other metals such as chromium or nickel could be found bound as mixed oxide ionic species of the type $(Fe,X)_3O_4$ where X is a non-ferrous metal. The stainless steel welding fume which is a major topic of interest in this review contained, by wet chemical analysis: 5.6% chromium, 0.75% nickel, 10.8% iron, 18.9% potassium, 10.4% sodium, 6.2% manganese, 4.9% silicon plus other elements. Mixed metal oxides were identified. Other chemical structures may be found, for example $K_2(Fe,Cr)O_4$ found in such stainless fumes. The authors of the report describe the possibility of pure oxides of transition metals being present when iron concentrations are very low.

In other studies, Hewett [34] measured particle size distributions for four different welding fumes involving mild steel (MS) and stainless steel (SS) in two processes; shielded metal arc (SMAW) (flux coated rod) and gas metal arc (GMAW) (MIG/MAG). The estimated mass distribution geometric means for the SMAW-MS and the SMAW-SS consumables were 0.59 and 0.46 μm aerodynamic equivalent diameter respectively, and 0.25 μm for both the GMAW-MS and GMAW-SS consumables. The bulk fume densities, being the mass in terms of the mean volume of the fume, were $3.4\ g \cdot m^{-3}$ for both the SMAW-MS and SMAW-SS consumables and 5.7 and $5.9\ g \cdot m^{-3}$ for the GMAW-MS and GMAW-SS consumables respectively. The bulk fumes specific surface areas were 18.0 and $19.4\ m^2 \cdot g^{-1}$ for the SMAW-MS and SMAW-SS consumables and 27.2 and $39.6\ m^2 \cdot g^{-1}$ for the GMAW-MS and GMAW-SS consumables respectively. (Hewett [35] uses this information in another paper to estimate the pulmonary deposition of welding fumes.) The importance of flux components in welding fume is stressed since these can cause the fume to be hygroscopic resulting in enhanced total deposition compared to dry fume. He concludes that determination of deposition fractions (and in turn the in vivo effects) are dependent on adequate knowledge of not only the concentrations of fumes and their constituents but also the chemical forms and morphologies [35, 36].

Within the workplace standard occupational hygiene workplace air sampling and analysis protocols are used to assess the emissions from metal arc welding processes. Fumes for example are collected on filters worn on sampling heads within the breathing zone of the welder and are subsequently analysed by atomic absorption spectrophotometry and other methods. The concentration of elements of interest can be compared with the appropriate workplace air quality standard – Threshold Limit Values (TLVs), published by the American Conference of Industrial Hygienists (ACGIH), are used in the USA while many other countries are developing their own lists of occupational exposure standards. The United Kingdom uses two types of standards; Occupational Exposure Standards (OESs), conformity to which should result in no adverse health effects, and Maximum Exposure Limits (MELs) which take into account not only health criteria, but also practicability and socio-economic factors. In effect this means that MELs are set at higher levels than they would be if based only on health criteria. Accordingly, it is illegal to exceed an MEL and exposures must be reduced below the MEL so far as reasonably practicable. Welding fume has an OES of 5 $mg \cdot m^{-3}$, but some constituents of it have lower MELs – for example, Cr(VI) compounds with an MEL of 0.05 $mg \cdot m^{-3}$. The standards for such individual components must be met as well as that for the total fume. Within the European Union the situation is complex and, for example, Criteria Documents are developed for toxic substances which in due course lead to the promulgation of Indicative Limit Values to which member states conform. Biological monitoring protocols and standards are being widely developed, although the correlation between workplace air concentrations with the results of biological measurements is often poor [29, 32, 37, 40]. The ACGIH Biological Exposure Indices are based on equivalence with TLVs but other countries use different approaches. Standard setting bodies such as CEN and ISO are active in workplace sampling and also in the development of standardised methods for measurement of emissions of gases and particulates from welding. Protocols have been developed for generation of fume within boxes in which the fume can be collected in order to calculate the fume formation rate – the weight of fume produced in a given time – or the fume generation rate – the amount of fume produced per unit weight of electrode consumed. There is no simple relationship between such data and the exposure of the welder in the workplace due to a variety of factors including the effects of local exhaust ventilation in the workplace; nevertheless measurement of fumes and gases under controlled conditions within boxes have a number of advantages. The results allow comparison between different types of electrode and/or different manufacturer's products so that the least hazardous can be selected [3, 8, 33, 56]. Also information regarding fume emissions can form part of the information used by occupational hygienists in assessing workplace risk. Formal procedures for assessment of risk in welding processes to permit the selection of appropriate controls have been developed in some countries, including the UK [31, 38, 39].

Medical and Epidemiological Studies

Physical injury from heavy equipment, electrocution, eye injuries from projectiles and radiation, exposure to solvents from degreasing, working in hot environments or those contaminated by other substances hazardous to health such as asbestos, need to be taken into full account in assessing health and safety in metal arc welding. The focus in this review is primarily on fumes and gases and their primary route of exposure through inhalation. Transfer of substances produced during welding through the skin is not normally a problem unless the skin is damaged, but account must be taken of ingestion risks, especially where for example soluble residues from fluxes containing barium are encountered in the workplace. The airborne risks will depend upon the composition, concentration and duration of exposure. Exposure to gases is usually associated with irritation of the respiratory tract, with associated changes in lung function and in extreme cases oedema. Metal fume fever, which presents as the symptoms of influenza some time after the exposure, may be caused by inhaling many freshly formed metal oxides such as zinc, cadmium, copper, etc., the greatest risk arising from the welding of galvanised steel. Systemic poisoning can result from exposures to fluorides, chromium, lead, barium, etc. Inhaling welding fumes has long been recognised as leading to benign X-ray changes referred to as siderosis. Evidence from a group of UK experts to the UK Industrial Injuries Advisory Council in 1989 identified, at that date, abundant evidence for acute respiratory diseases in welders – metal fume fever, pneumonitis and irritative effects, but the causes of observed chronic diseases including bronchitis, emphysema, asthma were not clear in view of confounding factors such as smoking [15]. The debate continues today [9, 10, 46–48]. The focus of current concerns is on the long-term effects of fume constituents such as Cr(VI) compounds and nickel which in other industries have been demonstrated to be carcinogenic (table 1) [41–45].

The proportion of inhaled gases exhaled depends to a certain extent upon their solubility in vivo. Particulate materials within the respirable range may also in part be exhaled, or trapped within the nasal region and prevented from reaching the vulnerable lung tissue by complex mucociliary clearance mechanisms. In the latter, ciliated cells and rising mucous transports inhaled particulates up the respiratory system to the throat where they are swallowed. Particulates which escape these clearance mechanisms may dissolve or may be engulfed by macrophage cells for transport up the mucociliary escalator and eventual elimination from the body from the gastro-intestinal tract in urine and to a lesser extent faeces. Notwithstanding, high concentrations of weld fume constituents can be found in the lungs of welders many years after exposure and their health effects are not fully understood. Deposited materials and some gases can damage the lung and result in the build-up of collagen in the lung tissue, a process described as fibrosis, which can interfere with the gas exchange capacity and elasticity of the lung.

Acute medical effects from welding are usually due to gross, readily avoidable exposures. Several deaths have occurred, however, due to asphyxia of welders working in confined spaces especially with inert shielding gases and where the oxygen is depleted below the level necessary for respiration. Throughout the world there is an increase in reported asthma and the suggestions that much of this is due to pollution from the environment or the workplace. Attention has been focused upon nickel and Cr(VI) as potential respiratory sensitisers, but firm evidence of, for example, occupational asthma in stainless steel welders remains a subject for study [13, 46–48]. Suggestions of effects on reproduction and of neurological manifestations (which are known to be associated with solvent use in other industries) have been made. Many of the studies of welders are confounded by the complex nature of the processes and also because the reported health effects can arise from many other causes apart from the specific welding process concerned. Welders often have to work in unhealthy and inhospitable working environments where they may be exposed to a variety of adverse substances and conditions. As a group, welders smoke more than many others [11, 12].

Confounding factors are important in the ongoing and important studies of cancer risks in welders and their causes. There are now details in the literature of the many studies conducted, in particular, over the last 20 years. Before this time, excess lung cancers in chromite ore processors had been identified and an association with Cr(VI) compounds of intermediate and low solubility had been suggested. In 1976 in the USA NIOSH, largely based upon these studies, proposed new workroom air standards of 0.025 $mg \cdot m^{-3}$ for soluble Cr(VI) and 0.001 $mg \cdot m^{-3}$ for insoluble Cr(VI) compounds [44]. These proposals (which have not been adopted) were several orders of magnitude more stringent than those in many countries and could have profound implications for the welding industry world-wide.

Epidemiological studies on welders exposed many years ago consistently show excess cancer risks (mainly lung). For most cohorts including those mainly doing mild steel, stainless steel or both types of welding, published reports suggest more than a 30% excess risk [41, 45, 49, 50]. It is important in these retrospective studies to note that, because of the long latent period, exposure to the causal agents should be looked for 20–30 years previously. All of the historical studies recognise the lack of reliable exposure data at the times concerned. Also recognised are the important confounding factors of smoking and exposure to asbestos in the working environment (which are firmly demonstrated as causes of cancer). Therefore, in reviewing these studies it is vital to keep a clear sight of the three questions:

(1) Do welders show an excess number of cancers compared to a control population? (2) Can identified cancers be causally related, specifically to metal arc welding? And, if so, (3) can particular components such as nickel or Cr(VI) compounds (as for example produced in stainless steel welding) be positively identified as the cause?

In general, epidemiological studies have attempted to separate stainless steel welders from mild steel welders and to tackle with varying degrees of success questions of confounding factors such as smoking, asbestos exposure and the lack of precise data on the exposure to welding fumes during the period of interest. Only partial answers to the questions can be given in the present state of our knowledge.

The International Agency for Research on Cancer (IARC) published in 1990 an evaluation of carcinogenic risks from chromium, nickel and welding [43]. In respect of welders, the most comprehensive cohort described in the IARC report is a European one drawn from 135 companies. In descriptions of this cohort, as in others in the

Table 1. Some health effects and their reported causes in welders

Acute effects
Metal fume fever (Zn, etc.)
Irritation of eyes, respiratory tract; fibrosis (O_3)
Irritation of eyes, respiratory tract; oedema (NO_x)
Chronic effects
Irritation: possible long-term effects (F)
Behavioural diseases (Pb, Mn)
Siderosis (Fe)
Pulmonary function effects; possibly associated with fibrosis and chronic bronchitis (various causes)
Cancer (unknown; Cr(VI), Ni, etc. suspected)

report, note is taken of the uncertainties concerning smoking. Age and sex specific national mortality reference rates were computed using the WHO data bank and additionally national incidence reference levels were used for the four Nordic countries involved. Statistically significant increases in both the incidence of and mortality from lung cancer was demonstrated, but there was no consistent difference in cancer risk amongst stainless welders as compared to mild steel welders or shipyard welders. Taking into account this and other studies, IARC in 1990 concluded that there was limited evidence in humans for carcinogenicity of welding fumes and gases and the overall evaluation was that welding fumes are possibly carcinogenic to humans (Group 2B).

Several of the cohorts in the IARC study have been followed in more recent years. A subgroup from the European study comprising 2,721 welders in France and appropriate controls took into account the smoking habits of 87% of the study population and were able to contrast mild steel welders, stainless steel welders and stainless steel welders predominantly exposed to Cr(VI) compounds. Comparison of welders with controls is expressed in terms of standardised mortality ratios – SMR with the corresponding 95% confidence intervals which, it will be noted, are in all cases statistically non-significant. Overall mortality (at corresponding ages) was slightly higher for welders than controls. For lung cancer the SMR was 1.24 (0.75–1.94) for welders and SMR 0.94 (0.68–1.26) for controls. The SMR for lung cancer was 1.59 among non-shipyard mild steel welders (0.73–3.02). This contrasts with the results for all stainless steel welders: SMR 0.92 (0.19–2.69), and for stainless steel welders predominantly exposed to Cr(VI): SMR 1.03 (0.12–3.71). Moreover, SMRs for lung cancers for mild steel welders tended to increase with duration of exposure and time since first exposure, leading to significant excesses for durations greater than 20 years and latency greater than 20 years. Such a pattern was not found for stainless steel welders. The conclusion reinforces that from the European study in failing to show that the risk for lung cancer is higher for stainless steel welders than mild steel welders notwithstanding the confirmation that welders as a group show an excess cancer risk compared to controls [50]. Other epidemiological studies and investigations continue and other conclusions will be presented in some of these [45].

The IIW Commission VIII reviewed all studies available up to 1992 and issued an authoritative statement concluding that 'On the balance of the evidence from these studies, welders as a group have a slightly greater risk of developing lung cancer than the general population. This risk, though slight, cannot be neglected. The cause of the excess risk has not been completely identified. While tobacco smoking and asbestos exposure, often more common in the welders studied than in general, are known causes of lung cancer they do not provide a complete explanation. The role of the welding process must be considered. The studies do not show welding processes in general or of specific type to be a definitive cause of the excess.' The statement continues by drawing attention to the known lung cancer risk in processes other than welding and that it is sensible to draw on knowledge from these other processes to the benefit of welders – leading to the recommendation of good occupational hygiene practice for the assessment and control of welding fume especially those containing chromium and nickel [51].

In view of long-standing concern about the potential risk from ionising radiation arising from the use of thorium which is incorporated into tungsten electrodes used in TIG welding, Commission VIII has also reviewed this matter and made recommendations for the exercise of control of thorium dust during the grinding of electrodes and for the proper disposal of any waste produced [52].

Increasingly, ergonomic aspects of welding are being considered. Attention has been given to welding torches themselves, especially those for MIG which can be heavy and unwieldy. Developments, especially in Scandinavia, have centred around stationary welding workplaces where both movements of the welding torch and the workpiece are facilitated, taking into account good ergonomic practice. Attention to these factors, to good posture and the avoidance of repetitive handling of heavy weights can result in a considerable reduction of the risk of musculoskeletal damage [54].

Assessment of Risk

A proper risk assessment allows the selection of the appropriate control measures to ensure that the risk is reduced to an acceptable level. If the balance between such controls and risk is incorrect, unnecessary expendi ture on the controls can ensue, or inadequate controls ca be specified which could lead to worker ill-health. There i a common confusion in differentiating risk from hazard the latter refers to the innate ability of the substance cause harm. As demonstrated above, welding fumes a gases are hazardous, but the probability (i.e. the risk) th harm will be caused to the welder depends upon wh and how the welding is carried out, the use of ventilat controls and other factors which need to be assessed. R assessment follows long established occupational hygiene practice, but increasingly formal protocols outlining the decision taking sequential steps are being published and used (table 2) [38, 56].

The first stage of an assessment involves collecting relevant information concerning the type of welding to be carried out, the expected fume constituents and their toxicity and the likely fume formation rate. Such information is readily available in hazard data sheets from the welding consumables manufacturers. In many countries the supply of such information is mandatory. Generic information on the hazard, likely emissions and probable controls needed for various welding processes, is available through the fume information sheets from the IIW and other sources [38, 55]. The assessor should then take note of the particular workplace, collecting any information available on previous workplace monitoring, sickness absence or other factors and noting the availability and use of enclosures, ventilation and respiratory protective equipment. The next stage involves observing the welding and the effectiveness of fume and gas control. This may involve tests of ventilation and of workplace air for comparison with published standards such as TLVs. Note should be taken not only of the normal welding process but of any unusual factors such as confined spaces or the potential for accidents. Finally, judgements can be made of the risk and the need for any further controls above those which are being used or proposed. Requirements for health surveillance or further exposure monitoring would also be made at this stage.

Traditionally an important component of risk assessment concerning exposure to fumes from welding has been sampling of the fume to which the welder is exposed using a personal sampling head and filter positioned within the welder's breathing zone. In simple cases gravimetric measurement of total fume can provide adequate information, but for processes which give rise to fume containing toxic constituents having low occupational limit values it is necessary to carry out comprehensive analysis. Welding fume is by its nature complex both physically and chemically and questions have been raised as to the suitability of using single-substance occupational exposure limits. Process-dependent workplace exposure standards have been proposed in some countries which, based upon knowledge of the fume composition from different types of welding, allow measurement of a marker substance or sometimes gravimetric measurement of total fume to be used as an indicator of exposure risk. Cr(VI) for example is a useful indicator for monitoring in stainless steel welding.

Table 2. Assessment of welding fume

List substances present and their chemical/physical form
Obtain hazard data sheets
Plan of workplace and description of each welding process
Obtain air sampling, plant breakdown, accident data
Identify operators and others – maintenance, visitors
Note control measures and how they are used
Assess exposure under normal and emergency conditions
Consider the need for further information
Write conclusions
Further information may be needed:
Toxicity data for new substances in the consumables or those produced during process
Occupational exposure limits in house
Novel process factors which may influence exposure
Hypersensitive, untrained or unusual workforce
Expert evaluation of control measures
Air sampling
Health information

Although inhalation is often the major route of exposure, note must be taken of risks of ingestion and of physical factors in the overall risk assessment concerning metal arc welding. Clearly the assessor must have the appropriate education, training and access to proper documentation – the skills required from an assessor are often underestimated.

Control Strategies

Good control starts at the design stage. Substitution of a less hazardous process or substance should be the first consideration. In metal arc welding there are in fact many possibilities of influencing the fume formation rate and the concentration of toxic constituents by process modifications. Leading consumables manufacturers are increasingly giving attention to the development of less hazardous products. These developments depend upon fundamental knowledge of the mechanisms of fume formation and the influence that parameters such as voltage, shielding gas composition, etc., can have on the amount and toxicity of fume. The references [17–19, 26–28, 53] may be consulted for details but, summarising from these and other studies, some process modification strategies are listed in table 3.

Table 3. Some options for control by process modification

MIG
Select welding mode (voltage) to minimise spatter
Select shield gas to facilitate smooth metal transfer
Use modern power sources allowing good control of electrical parameters
High purity wires including surface (avoid sodium lubricants)
Optimise oxygen in primary shield gas
Minimise oxygen in macro-environments
Optimise gas flow rate
Minimise UV and hence ozone and Cr(VI)
Have essential toxic volatile metals in workpiece not electrode
MMA
Take note with modifications of principles above
Adjust power sources and parameters to minimise spatter
Use minimum practicable current and voltage
Select fluxes which ensure minimum oxygen in micro- and macro-environments
Use stable fluxes of low toxicity (eliminate Ba, F, etc.)
Eliminate sodium from flux (use other cations in binders)
Note: enhanced fume and Cr(VI) with sodium

Table 4. Control strategies

Substitute or use process modification
Optimise welding parameters and procedures
Design working environment to avoid other workers' exposure
Totally enclose process
Efficient local exhaust close to welding
On-torch extraction
Good general dilution ventilation
Clean well maintained workplace
Personal protective equipment – but RPE as a last resort

The welder can have a significant effect on his exposure and it is essential that he adopts the right posture, good working practices (including making full use of protective equipment), and that he selects the correct parameters for the process concerned and is in all respects trained and informed. Once substitution and process modification have been properly addressed, options for control can be followed (table 4). These will be dictated by the process and location concerned. Automated welding processes may be totally enclosed, but this practice is not usually practicable for non-routine production. Widespread use is made of partial enclosures with local exhaust ventilation (LEV) [16, 39]. It should be appreciated that the efficiency of exhaust ventilation falls off dramatically with distance from the source – at a distance of 1 duct diameter the air velocity is only 10% of that in the duct face. The exhaust duct must be as close as possible to the weld in order to capture and remove fumes. Flexible ducts are often used for this purpose. On-torch local exhaust extraction may also be used. Care is needed to ensure that LEV does not interfere with shielding gas so as to affect the quality of the welding. Good general ventilation is necessary in any workshop where welding is carried out but is not a substitute for capture at source by LEV. It can be useful in diluting low concentrations of fumes and gases. The effectiveness of LEV can be considerably improved by the end design of the duct – slot, fishtail and flanged hoods may be advantageous. Collected fumes should be safely discharged out of the workplace and filter systems may be necessary to ensure minimal environmental emissions. Routine inspection, maintenance and testing of ventilation systems is necessary. Particular problems of ventilation occur when welding is carried out in confined spaces. It is clearly essential to ensure not only that fume and gas emissions are reduced to an acceptable level but that sufficient air is maintained within the enclosed space to satisfy the welder's breathing requirements [57].

Face shield, eye protection and protective clothing are always necessary during welding. Respiratory protective equipment (RPE) however should not be necessary since control should be primarily achieved by the other control methods described above. Notwithstanding there are some situations, especially in confined spaces, where respiratory protective equipment is essential. Specialist guidance on selection of the appropriate RPE and proper training of the welder will be required.

Conclusions

Metal arc welding presents a wide variety of health and safety hazards. There is imperfect knowledge of the causal links between welding and identified health effects – especially asthma and cancer. More information is needed on the effects of adverse ergonomic conditions. Based on fundamental studies on the mechanisms of fume and gas production and their chemical compositions, hazards can be reduced at source by selection of consumables and process parameters. Sufficient is now known to control risks to within internationally accepted standards – however, to achieve such control depends on proper assessment, provision of equipment and training of the welder. Worker's increased expectations and regulatory changes can be expected to continue and reinforce the need for vigilance to ensure the health and safety of welders.

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