# WELDING

## 1. Historical Perspectives and Process Description

### 1.1 Introduction

'Welding' is a term used to describe a wide range of processes for joining any materials by fusion or coalescence of the interface. It involves bringing two surfaces together under conditions of pressure or temperature which allow bonding to occur at the atomic level. Usually, this is accompanied by diffusion or mixing across the boundary, so that in the region of the weld an alloy is formed between the two pieces that have been joined. Welding and other methods of joining, such as soldering or brazing, can be distinguished clearly (Lancaster, 1980). In the latter, a low-melting alloy is heated until it flows and fills the gap between the two pieces of metal to be joined; the workpieces do not melt, and there is negligible diffusion or mixing of the metal across the boundaries. Metal can be welded by the application of energy in many forms: mechanical energy is utilized in forge, friction, ultrasonic and explosive welding; chemical energy in oxy-gas and thermit welding; electrical energy in arc welding, various forms of resistance welding and electron beam welding; and optical energy in laser welding. The term 'welding' is applicable equally to metals, thermoplastics and various other materials.

Many of the techniques used in welding can also be used for other purposes. Oxy-gas flames and electric arcs are used for cutting. Various processes, including flame spraying, plasma spraying and manual metal arc and metal inert gas hard surfacing, are used for depositing hard metal surface coatings and for building up worn machine components.

### 1.2 Development of welding in the twentieth century

Welding of metals has its origins in pre-history: at least 5000 years ago, metal was welded by heating and hammering overlapping pieces. The same principles are employed to this day in forge welding and other modern forms of 'solid state welding' (Lancaster, 1980; Lindberg & Braton, 1985). The development of modern welding technology began in the late nineteenth century with the application of oxy-fuel flames, electric arcs and electrical resistance welding. The industrial application of oxy-fuel combustion for cutting and welding was facilitated by the availability of calcium carbide, from which acetylene gas could be generated as required, and by the commercial availability from about 1895 of bottled oxygen produced by the liquefaction of air (Skriniar, 1986). Oxy-fuel welding underwent rapid development in the early years of the twentieth century, and by the middle of the First World War good quality welds could be made in steel plate, aluminium and other metals.

The phenomenon of the electric arc was first discovered in 1802 by Petrov; its first recorded use for welding was in 1882 by Bernardos (Skriniar, 1986), who used an electric arc struck between carbon electrodes to melt ferrous metals to effect repairs and make joints. The results were often brittle and unsatisfactory because of oxidation and nitrogen absorption from the surrounding air, and consequently arc welding developed only slowly at first. To fill larger gaps, metal wire had to be fed by hand into the molten metal of the weld pool. Early attempts to use the filler metal itself as a 'consumable' electrode, and to strike the arc onto the workpiece, produced poor results, largely because of nitrogen embrittlement (Lancaster, 1980). Electrodes consisting of wire wrapped in paper or asbestos string were found to produce better results (Brillié, 1990), and a range of materials was experimented with as 'flux' coatings. Flux compositions gradually evolved, and the resulting weld quality was improved as minerals were added to act as gas and slag formers, deoxidants and scavengers. A variety of binding agents was used to attach the flux coating to the electrode, but water-glass (sodium and potassium silicates) was quickly discovered to be most effective. By about 1930, the modern welding rod had been developed and weld quality was adequate for many structural and manufacturing purposes. The process came to be known as manual metal arc (MMA) (Morgan, 1989) or shielded metal arc welding (Lancaster, 1980). Throughout the 1930s, asbestos continued to be added to a small proportion of electrodes in the form of powder in the flux mixture, or as asbestos string wrapped around the electrodes. This practice declined after the Second World War and ceased in the 1950s.

Electrical resistance welding was also developed before the turn of the century. This process was found to be relatively immune to the embrittlement problems that usually accompanied early arc welding. Spot welding was developed for fastening thin sheet, and butt welding for joining bars and making chains. These and the related process of seam welding, used for making unbroken joints in sheet metal, were well developed by about 1920 (Lancaster, 1980).

Before 1914, welding was not a common industrial process and was often restricted to repair applications. It received a spur during the First World War in armament manufacture. Later, the car industry, particularly in the USA, adopted resistance welding techniques, and these were taken up for other production line manufacture; however, riveting remained the principal method of joining metal plates in buildings, bridges, ships, tanks and armaments until the late 1930s.

The Second World War provided a major impetus to the heavy manufacturing industry and heralded the widespread adoption of welding technology. Tanks and heavy armaments were built in large numbers using MMA welding, and this method of assembly was also applied to shipbuilding. Early welded ships were prone to catastrophic fractures due to hydrogen embrittlement, but this was overcome in the early 1940s when basic low-hydrogen MMA electrodes were developed (Lancaster, 1980). Other, newer welding processes also found applications in the war years. In 1936, submerged arc welding was patented in the USA (Skriniar, 1986). This differs from the MMA process in that the electrode is in the form of a continuous wire which is driven mechanically into the arc as it melts. A granulated flux is poured from a hopper so that it surrounds the arc region and melts to form a slag layer over the weld metal. This process was used extensively for the manufacture of tanks in the final years of the war. Tungsten inert gas (TIG) welding (gas tungsten arc welding; Lindberg & Braton, 1985), the first successful gas-shielded welding process, was introduced in 1943 (Lancaster, 1980). In this technique, a non-consumable tungsten electrode is used, and the arc is shielded with argon gas delivered by a nozzle which surrounds the electrode. The process was used initially instead of rivets for the assembly of aluminium and magnesium alloy aircraft frames (Skriniar, 1986). When filler metal was required, wire was fed by hand into the weld pool. A variant of TIG welding, developed in the late 1960s, is the plasma arc process, in which some of the shield gas is forced through the arc and ejected as a high velocity jet of ionized gas (plasma). Plasma arcs can be used either for cutting or welding, and higher welding speeds can be achieved than with TIG welding (Lindberg & Braton, 1985).

After the Second World War, welding became the principal means of joining metal throughout the manufacturing, shipbuilding and construction industries, and welding technology research and development accelerated. Metal inert gas (MIG) welding, the first gas-shielded welding process to involve a consumable metal electrode, was put into use in 1948 (Skriniar, 1986). As in submerged arc welding, the wire electrode is driven mechanically into the arc region at the same rate as it is consumed. The arc region is bathed in an inert gas mixture based on argon or helium to protect the molten weld metal from atmospheric gases. Attempts to use cheaper shield gases such a carbon dioxide were not very successful at first because of weld porosities; however, the development of special welding wires containing antioxidants in the early 1950s overcame this problem. As carbon dioxide cannot be described as an inert gas, the new process was referred to as metal active gas (MAG) welding. The terms MIG and MAG are loosely interchangeable, but, as argon- and helium-based shield gases usually contain some oxygen or carbon dioxide, MAG is the more accurate description. In the USA, both MIG and MAG welding are usually referred to as gas metal arc welding (Lindberg & Braton, 1985).

In the late 1950s, tubular electrodes were introduced for semi-automatic welding. Hand-held tubular electrodes had first appeared in the 1920s and were used to a limited extent after the Second World War for oxy-fuel welding. The new 'flux-cored' tubular electrodes were incorporated into MIG-type welding torches with a carbon dioxide shield gas. Their adoption was gradual, but by the mid 1960s the advantage of flux-cored wires over the solid-wire carbon dioxide process was generally appreciated. The flux contents of tubular wires can be used to control oxidation and alloying of the weld metal and gives it more effective protection during cooling. Tubular electrodes that contained gas-forming compounds and could be used without an external shield gas were introduced in the late 1950s. In the 1960s, such 'self-shielded' flux-cored welding wires rapidly gained popularity in the USA, the USSR and Japan but saw only limited use in Europe until the 1970s and 1980s (Widgery, 1988).

Recent developments in welding technology have involved refinements of the existing welding processes and the introduction of new, often more automated processes. Welding power supplies, once little more than heavy transformers and rectifiers, are increasingly sophisticated (Wilkinson, 1988): since the late 1970s, development of transistorized 'solid state' power sources has been dramatic; voltage and current profiles can be computer-programmed to give precise drop-by-drop delivery of weld metal to the weld pool. This can improve weld quality and productivity in MIG welding and related processes. The 1970s and 1980s have witnessed increasing use of electron beam and laser welding and in particular a marked increase in automated and robot welding. The automotive industry has for many years been highly automated, and few welds on motor vehicles are made by human welders. This type of automation is very inflexible and car production lines are usually built for a single product. Robot automation, in contrast, can be highly flexible and can be used for a variety of products. Computer-aided design and manufacture is now increasing, and this will gradually reduce the number of human welders employed in manufacturing industries in countries with advanced economies.

## 1.3 Description of major welding processes

### (*a*) *Introduction*

Despite the many different types of welding process that have been developed, the large majority of welding still involves MMA, MAG, TIG, flux-cored and submerged arc processes (Stern, 1983; Lindberg & Braton, 1985). MMA has been the dominant welding process since the 1930s but is now declining in importance (Wilkinson, 1988). Since the late 1970s, the market for MMA electrodes in Europe has fallen markedly, partly due to the recession in heavy industry and the reduction in shipbuilding and off-shore construction, but also because of increasing use of other welding processes, particularly MIG. Cored wires have been important in the USA since the 1960s and are of rapidly increasing importance in Japan and the newly industrialized nations of the far east (Widgery, 1988).

Although welding is a recognized profession, many other workers, not employed specifically as welders, also carry out some welding. Most welders are familiar with the majority of the common industrial welding processes but usually have extensive work experience with only a few. Most welders have experience with MMA and many are also experienced with MIG. Fewer have much experience with TIG, submerged arc and the many other forms of welding. Some welders use a wide range of processes routinely, while others are employed to specialize in certain welding processes, such as TIG, and many specialize in welding certain types of metal such as stainless-steel and aluminium.

The fabrication of large structures, such as ships and heavy bridge girders, can involve long periods of continuous welding. Small, intricate assemblies require more manipulation of the workpieces and shorter, more intermittent periods of welding. Before a workpiece is welded, it usually requires some preparation including cutting, shaping and grinding of the edges to be joined. Such preparation is not usually carried out by welders; however, they might have to spend time positioning the parts to be joined and tacking them at intervals along the seam prior to welding, again reducing the overall arcing time. The proportion of the working day involved in arcing is sometimes referred to as the 'duty cycle'. Duty cycles rarely exceed 70% of the day and can be very much less. For MMA welding, the average duty cycle rarely exceeds 50% on average, and a figure of 20% is reported to be typical (Widgery, 1986).

The speed with which a weld can be made is determined by many factors, including the rate at which weld metal can be deposited. Metal deposition rates depend upon the type of welding process being used, the welding current, electrode diameter and characteristics, and upon the position of the weld being made. For all welding processes, the highest rates of deposition are achieved when horizontal welds are made from above (downhand welding). Vertical, overhead and other 'positional' welding require lower welding speeds to avoid sagging of the weld metal (Widgery, 1986). It is often necessary to finish the weld by chipping away residual flux or grinding away excess weld metal. Sometimes it is necessary to cut out areas of weld metal that contain flaws such as cracks and flux inclusions. This can be done by grinding, but often an electric arc gouging process is used. The most common of these is arc-air gouging which involves a carbon arc and a compressed air jet to blow away the molten metal.

Welding can be carried out in almost any setting, including under water and in hyperbaric conditions. It is often carried out on benches in engineering workshops, but much structural welding is done outdoors; some assemblies, such as ships, boilers, tanks and pipes, often require welding in confined spaces.

(*b*) *Manual metal arc welding*

MMA (or shielded metal arc) welding equipment is relatively simple, consisting of a heavy source of electric current, such as a transformer, transformer-rectifier or generator, and a simple spring-loaded holder for the electrode (welding rod). A heavy cable carries the current to the electrode holder, and a similar cable provides a return or earth connection which is clamped to the workpiece or to a heavy metal bench on which the workpiece is placed. The welder strikes an electric arc between the tip of the electrode and the workpiece by brief contact and then withdraws the electrode tip several millimetres to maintain an arc gap, which must be adjusted continually as the electrode is consumed. Each electrode must be replaced after only a few minutes. The weld that is produced by the MMA process is covered by a layer of slag resulting from the flux coating on the electrode. This must be removed before the work is completed or before another layer of weld metal can be laid to build up a large joint, usually by use of a chipping hammer. Some types of slag systems are designed to peel off the weld easily, while other types adhere strongly and must be chipped vigorously. This cleaning task further slows the welding operation. The metal deposition rates achieved by MMA welding during continuous arcing are usually in the range 1-3 kg/h, although higher rates can be achieved with some electrodes. MMA electrodes in a wide range dimensions and compositions are available for welding different types of metal and for obtaining different mechanical and corrosion resistant properties. Most metals are welded with electrodes of similar composition; for example, stainless-steel electrodes are used to weld stainless-steel components. A notable exception to this general rule is the use of nickel consumables to weld cast iron. Three types of MMA flux system are commonly used: cellulosic — containing mostly cellulose, rutile (titanium dioxide) sand and magnesium silicate; rutile — containing mostly rutile sand and calcium carbonate plus a small amount of cellulose; and basic — containing mostly calcium carbonate. Many other ingredients are added to fluxes, including calcium fluoride (Brillié, 1990), sodium and potassium silicates and iron powder (Lancaster, 1980).

(*c*) *Metal inert gas welding*

MIG/MAG (or gas metal arc) welding equipment is considerably more complicated than MMA equipment and consists of a special power source, an automatic wire feed unit and a gas-shielded welding torch. The welding wire is stored coiled on a drum and is fed automatically to the welding torch by a 'wire feed unit'. The power source is usually a 'constant potential' transformer-rectifier designed to provide a welding current proportional to the rate of consumption of the welding wire. A heavy cable carries the current to the torch, where it is delivered to the welding wire by a tubular copper 'contact tip' through which the wire passes. A heavy return cable is used, as in the MMA process. The power supply is activated by a trigger-like switch on the torch, and the arc is struck between the wire tip and the workpiece after a brief contact. At the same time, the shield gas flow and the wire feed unit are activated. Shield gases may be based on carbon dioxide, argon or helium; pure inert gases are rarely used as they do not result in a stable arc, and shield gases usually contain small amounts of carbon dioxide or oxygen. Because the welding wire must be replaced only occasionally and there is no slag to remove from the weld, duty cycles for MIG welding may be considerably longer than for MMA. Metal deposition rates may also be higher — from about 1 to 10 kg/h or more (Widgery, 1988). Some welding torches are water cooled to permit continuous operation at high power.

(*d*) *Flux-cored wire welding*

Flux-cored wire welding involves almost the same type of equipment as MIG welding, and the processes are technically similar. Self-shielded tubular electrodes do not need a shield gas, but a shield gas must be used for those flux-cored wires that do not contain gas-forming agents. In Japan, carbon dioxide is the gas most commonly used for this purpose, whereas in Europe argon-rich gas mixtures are preferred. The slag layer that is left on the weld is usually self-detaching or is relatively easy to detach mechanically. Flux-cored wires are easier to use in vertical welds because the slag can help to support the molten weld metal. Duty cycles are comparable with those of MIG welding, but weld metal deposition rates can be higher, particularly in positional welding. Deposition rates considerably in excess of 10 kg/h are possible in downhand welding (Widgery, 1988). A variety of fluxes is used in tubular electrodes including many (such as rutile sand) that are used in MMA electrodes. Self-shielded tubular electrodes frequently contain barium carbonate or barium fluoride (Dare *et al.*, 1984), but these are not usually found in gas-shielded flux-cored welding wires.

(*e*) *Tungsten inert gas welding*

TIG (or gas tungsten arc) welding involves use of a gas-shielded welding torch with a tungsten electrode. As the melting-point of tungsten is nearly 3500 °C, the electrode does not melt during welding, provided that a high frequency alternating current is used or that a negative electrode is used in direct current welding. The arc region is shielded by argon, helium or a mixture of the two. The TIG process can be used for spot welding, or a filler wire can be used to produce larger welds. In simple TIG welding, a filler wire can be fed by hand into the molten weld pool. To obtain higher rates of metal deposition, mechanical wire feed units are used similar to those used in the MIG process. Higher heat inputs can be obtained by attaching a second power supply to deliver current to the filler wire. This process, sometimes referred to as 'hot wire TIG' is in fact a combination of the TIG and MIG processes (Lindberg & Braton, 1985). TIG welding gives high quality welds and is suitable for a wide range of metals including stainless-steel, aluminium, magnesium alloys and titanium.

(*f*) *Submerged arc welding*

In the submerged arc process, the welding arc and the still molten weld metal are entirely buried in granulated flux. The welding wire is delivered mechanically by a wire feed unit mounted directly above the welding torch, and the flux is fed continuously from a hopper ahead of the advancing arc. Loose flux granules are usually recovered by a vacuum attachment which follows the torch and recycled to the flux hopper. The welding torch, wire feed unit, flux hopper and vacuum unit are all mounted on a carriage which travels on wheels along the length of the weld. Metal deposition rates of several tens of kilograms per hour can be attained with a single torch and wire feed unit. Sometimes, several wires are used in line to give multiple weld layers at one pass. Submerged arc welding is almost automatic, and the welders' task is to set up the equipment to make each joint and to ensure weld quality with minimal intervention. Because the equipment must be repositioned to make each weld, the overall duty cycle is reduced; however, metal deposition rates can be very high, particularly if multiple wires are used.

### 1.4 Number and distribution of welders

A comparison of the industrial economies of the world suggests that there might be of the order of 3 million workers worldwide who perform some welding. In the USA, more than 185 000 workers are employed as welders, brazers or thermal cutters, and it is estimated that up to 700 000 US workers carry out some welding during their work (National Institute for Occupational Safety and Health, 1988).

The balance of different welding processes is difficult to estimate, partly because manufacturers do not publish figures of sales of welding equipment and materials. Such figures are available for Sweden in 1974 (Ulfvarson, 1981), and these are summarized in Table 1. Approximately 22% of Swedish welders were reported to be stainless-steel welders. This is a higher proportion than in countries of the European Economic Community, as the average for France, the Federal Republic of Germany, Spain and the UK was about 10% prior to 1979; and the proportion is even lower in less developed countries (Stern, 1980a).

In western Europe, MIG welding has a greater market share than in the USA because it usually allows greater productivity than MMA welding, since fewer welders are needed to lay the same amount of weld metal. This affects estimates not only

**Table 1. Distribution of Swedish welders by process and material in 1974[a]**

| Process[b] | Material | | | | |
|---|---|---|---|---|---|
| | Total | Mild-steel | Stainless-steel | Aluminium | Other |
| MMA | 25 585 | 16 854 | 5 896 | 1 496 | 1 339 |
| MIG + MAG | 9 143 | 6 232 | 1 594 | 1 141 | 176 |
| TIG | 4 216 | 1 547 | 1 529 | 913 | 233 |
| Gas | 3 823 | 2 762 | 479 | 325 | 257 |
| Submerged arc | 783 | 540 | 210 | 32 | 1 |
| Total | 43 550 | 27 935 | 9 708 | 3 907 | 2 006 |

[a]From Ulfvarson (1981)

[b]MMA, manual metal arc; MIG, metal inert gas; TIG, tungsten inert gas

of total numbers of welders but also of the relative importance of different welding processes. Sales of MMA electrodes in the major economies represent about 46% by weight of the total for all consumables. In terms of weld metal sales, i.e. excluding the weight of flux, MMA represents about 41% of the total. Assuming weld metal deposition rates of 3 kg/h for MMA and 7 kg/h for MIG welding, MMA must represent about two-thirds of welding in terms of arcing time. Furthermore, as the duty cycle for MMA might be only about half that for semi-automatic processes, MMA welding might represent about 80% of welders' payroll time (Jefferson, 1988).

Many types of metal are welded, including stainless-steel, high chromium armour plate, aluminium, copper and nickel; however, the large majority of welding is on mild and low alloy steels. Stainless-steel represents only about 4-5% of MMA electrode sales and about 3% of MAG and TIG wire sales in western Europe. Similarly, about 2-3% of MAG and TIG wire sales are aluminium.

## 2. Welding Fumes and Gases

### 2.1 Introduction

Welders are exposed to a variety of airborne contaminants arising from the welding process and other operations in the work place. In the literature, the term 'welding fume' is applied variously to some or all of the emissions from welding. In this monograph, the term is applied only to the particulate emissions intrinsic to the various welding processes, to distinguish these from gaseous emissions. Incidental particulate emissions, for example, from the pyrolysis of paint on metal being welded, are excluded from this definition.

The chemical composition and physical properties of welding fumes and gases and details of occupational exposures of welders in the work place have been reviewed (American Welding Society, 1973; Ulfvarson, 1981; Tinkler, 1983; Stern, R.M. *et al.*, 1986; National Institute for Occupational Safety and Health, 1988). The aerosol contains contributions from a number of sources: (*a*) vaporization of the wire, rod or metallic/alloying coatings; (*b*) decomposition and vaporization of the flux materials; (*c*) spatter from the arc region and weld pool and fumes therefrom; and (*d*) evaporation from the molten weld metal.

The consumable is the major source of fume, the workpiece making only a minor contribution unless it bears a surface coating.

The elemental composition of a welding aerosol reflects the composition of the consumable used, while the relative abundance of the elements in the aerosol is a function of the physics and chemistry of the arc and geometry of the weld: low-melting-point metals are relatively enriched in the fume (Mn by a factor of 2-6, Cu and Pb by a factor of 3-5), while the more refractory metals are depleted by factors of e.g., 0.07-0.5 for Fe, 0.2-0.7 for Cr and 0.03-0.4 for Ni (when present) (see e.g., Malmqvist *et al.* 1986).

Potential occupational exposure to fumes from a given consumable can be estimated by combining information on the relative elemental abundance of the aerosol, as determined from a chemical analysis of welding fumes produced in the laboratory under controlled conditions, with the total aerosol concentration expected on the basis of work-place measurements. Actual elemental exposures can be determined on the basis of fume samples collected at the work place by stationary samplers placed on the shop floor or by personal samplers placed in the breathing zone. Detailed descriptions of standard sampling methods have been proposed by a number of sources (e.g., American Welding Society, 1973; British Standards Institution, 1986), and the general characteristics of welding fumes have been studied under controlled conditions (e.g., American Welding Society, 1973; Evans *et al.*, 1979; Mayer & Salsi, 1980). Although a welder usually works for long periods with a single type of consumable, changing conditions may result in variations in the chemical composition of the fume with time over a working shift. In addition, the presence of other process applications in the vicinity contributes to the chemical composition of the background: under certain conditions, e.g., TIG (see below), the background may contribute significantly to the fume collected in the breathing zone, although typically the background fume concentration as measured with stationary samplers is about one-tenth that found in the breathing zone (Ulfvarson, 1981). Hence, the presence of specific elements determined by chemical analysis of samples obtained in the work place may not be corroborated by laboratory measurements of nominally the same welding process.

Each consumable produces a unique fume in terms of elemental composition (see, e.g., Mayer & Salsi, 1980), particle size distribution and identifiable stoichiometric compounds (see, e.g., Fasiska *et al.*, 1983). Since there are thousands of different consumables, the only way to review data on composition and exposure derived from laboratory and work-place measurements is by use of tables of ranges of elemental concentration for very general classes of processes, applications and consumables. This technique has the disadvantage that one cannot determine from the tables the actual composition of a specific welding fume; on the other hand, since welders use many consumables during a working week, their actual exposure is properly reflected in the logarithm of the median values so obtained.

Not only particulate matter but also a wide range of gaseous pollutants is produced by welding, either through decomposition of compounds in the flux coating or core of the consumable or through oxidation, dissociation or other chemical reactions in the air mixed into the arc or surrounding the arc region.

Estimates of exposure to potentially toxic gases (ozone, carbon monoxide, nitrogen oxides) based on production rates measured in the laboratory may be unreliable because of the influence of local ventilation and work-place design on the actual concentrations found in the welders' breathing zone. Determination of occupational exposures to gases must be based on work-place measurements.

## 2.2 Chemical composition and physical properties of welding fumes

### (*a*) *Elemental composition*

Fasiska *et al.* (1983) identified 38 individual types of covered electrodes (MMA/steel) and 20 classes of MIG/Al fume, the fumes from which contain one or more elements in high abundance. The detailed chemical composition of a number of classes of welding fume are summarized in Table 2. The range (when available) of elemental distributions is given, together with an indication of the analytical method used. Fumes for chemical analysis are typically produced in a 'fume box', standards for which have been reviewed recently (Moreton, 1986).

A description of work-place exposures and the chemistry of welding fumes can be considerably simplified by recognizing that each couplet of process technology-application represents a source of a broad class of welding fume that is similar in constituents if not in concentration. Three major process technologies (MMA, MIG/MAG, TIG) applied to two classes of metal (mild steel (MS) and stainless steel (SS)), plus a few additional couplets (e.g., MIG/Al), however, account for perhaps 80% of all exposures in welding (Stern, 1983). In addition, MIG/Ni and MMA/Ni processes, with wire or electrodes (i.e., consumables) containing high levels of nickel, are used on cast iron and low-alloy steel. MIG/MAG processes produce fume with components from the metal/alloy wire alone, while fume from flux-producing

**Table 2. Average or range (%) of elemental distribution of welding fumes by type**

| Element | Manual metal arc fume | | Metal inert gas fume | | Method[a] | Reference |
|---|---|---|---|---|---|---|
| | Mild steel | Stainless steel | Mild steel | Stainless steel | | |
| Si | 2.7–8.1 | 2.9–5.6 | 1.6–3.3 | 0.9 | XRF | Mayer & Salsi (1980) |
| | – | 10 | – | 1.7 | XRF | Moreton *et al.* (1986) |
| F | 7–14 | 16–24 | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| | – | 14.9 | – | – | XRF | Moreton *et al.* (1986) |
| | 0.6–17 | 7–11.5 | 0.05–14 | – | XRF | Mayer & Salsi (1980) |
| Cl | ND–0.54 | ND–0.34 | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| K | 9–19 | 18–22 | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| | – | 19.9 | – | < 0.1 | XRF | Moreton *et al.* (1986) |
| | 5.1–15 | 8.7–15.4 | 0.11–5.7 | – | XRF | Mayer & Salsi (1980) |
| Ca | 0.62–2.6 | 1.3–10 | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| | – | 0.4 | – | < 0.2 | XRF | Moreton *et al.*(1986) |
| | 0.09–10.8 | 3.8–6.8 | 0.01–13.6 | – | XRF | Mayer & Salsi (1980) |
| Ti | ND–0.54 | 0.62–2.3 | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| | – | 2.1 | – | 0.1 | XRF | Moreton *et al.* (1986) |
| | 0.6–2.4 | 7.7–12.7 | 0.006–2.8 | – | XRF | Mayer & Salsi (1980) |
| Cr | ND–0.07 | 3.0–3.4 | 0.07 | 10–12 | PIXE | Malmqvist *et al.* (1986) |
| | – | 5.0 | – | 13.4 | XRF | Moreton *et al.* (1986) |
| | 0.11–0.7 | 6.5–9.2 | 0.2–0.6 | – | XRF | Mayer & Salsi (1980) |
| Mn | 2.8–5.9 | 2.4–14 | 7.3 | 4.8–5.3 | PIXE | Malmqvist *et al.* (1986) |
| | – | 5.0 | – | 12.6 | XRF | Moreton *et al.* (1986) |
| | 2.7–5.6 | 4.3–5.0 | 3.9–7.0 | – | XRF | Mayer & Salsi (1980) |
| Fe | 11–32 | 3.3–3.7 | 45 | 28–31 | PIXE | Malmqvist *et al.* (1986) |
| | – | 5.1 | – | 33.3 | XRF | Moreton *et al.* (1986) |
| | 14.4–31.8 | 6.0–15.9 | 33–55 | – | XRF | Mayer & Salsi (1980) |
| Ni | ND | 0.22–0.44 | ND | 4.5–4.8 | PIXE | Malmqvist *et al.* (1986) |
| | – | 0.4 | – | 4.9 | XRF | Moreton *et al.* (1986) |
| | 0.01–0.32 | 0.48–2.9 | 0.01–0.06 | – | XRF | Mayer & Salsi (1980) |
| Cu | ND–0.08 | ND–0.01 | 0.26 | 0.06–0.09 | PIXE | Malmqvist *et al.* (1986) |
| | – | < 0.1 | – | 0.6 | XRF | Moreton *et al.* (1986) |
| | 0.04–0.24 | 0.09–0.14 | 0.01–0.18 | – | XRF | Mayer & Salsi (1980) |
| Zn | 0.04–0.29 | 0.11–0.25 | 0.04 | 0.17–0.18 | PIXE | Malmqvist *et al.* (1986) |
| | 0.04–0.07 | 0.007–0.10 | 0.08–0.40 | – | XRF | Mayer & Salsi (1980) |

**Table 2 (contd)**

| Element | Manual metal arc fume | | Metal inert gas fume | | Method[a] | Reference |
|---|---|---|---|---|---|---|
| | Mild steel | Stainless steel | Mild steel | Stainless steel | | |
| As | ND–0.06 | ND | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| | 0.005–0.05 | 0.003–0.01 | 0.009–0.12 | – | XRF | Mayer & Salsi (1980) |
| Rb | ND | ND–0.02 | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| Zr | ND–0.54 | ND | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| Mo | ND | ND–0.09 | ND | 0.92–0.95 | PIXE | Malmqvist *et al.* (1986) |
| | – | < 0.02 | – | 0.6 | XRF | Moreton *et al.* (1986) |
| | 0.005–0.3 | 0.2–1.4 | 0.1–0.2 | – | XRF | Mayer & Salsi (1980) |
| Pb | < 0.07 | ND–0.04 | ND | ND | PIXE | Malmqvist *et al.* (1986) |
| | 0.03–0.28 | 0.08–0.55 | 0.05–0.22 | – | XRF | Mayer & Salsi (1980) |

[a]XRF, X-ray fluorescent spectrometry; PIXE, proton-induced X-ray spectrometry; –, no data; ND, not detected

processes (flux-cored electrode welding, MMA) contains significant contributions from the vaporization and decomposition of the flux-forming components of the filler or coating. For simplicity, the following list indicates the elements that occur in more than trace (i.e., 1%) quantities in the respective fumes of general-purpose electrodes:

| | |
|---|---|
| MIG/Al | Al |
| MIG/Ni | Ni, Fe |
| MIG-MAG/MS | Fe, Mn, Si |
| MIG-MAG/SS | Fe, Mn, Cr, Ni |
| MIG/MS | Fe, Mn, Si, K |
| MMA/Ni | Ni, Fe, Ba |
| MMA/MS | Fe, Mn, Ca, K, Si, F, Ti |
| MMA/SS | Fe, Mn, Ca, Si, F, K, Ti, Cr, Ni |

In addition to the elements listed above and in Table 2, many other trace elements (e.g., Ag, Ga, Nb, Se, Sn, Sr) have been identified in special-purpose welding fumes (Pedersen *et al.*, 1987).

### (*b*) *Oxidation state of chromium*

Considerable attention has been given to the oxidation state of chromium in welding fumes. (See Pedersen *et al.*, 1987, for a recent review.) The only soluble species of chromium in welding fumes is Cr[VI]. (For a discussion of the definition of solubility for Cr[VI] compounds, see p. 55 of the monograph on chromium, and the General Remarks, pp. 42-43). Table 3 gives information on the solubility and oxidation state of chromium in MMA/SS, MIG/SS and TIG/SS welding fumes. For all practical purposes, the (long-term) insoluble Cr[VI] content of SS welding fumes is less than 0.5% and is more typically of the order of 0.2-0.3%, and is thus negligible from the point of view of exposure. The high Cr[VI] content of MMA fumes is attributed to the presence of alkaline metals in the flux coating; hence, flux cord electrode fume resembles MMA fume with regard to chromium chemistry due to the presence of the flux forming materials in the core, although the technique resembles MIG. Numerous attempts have been made to alter the Cr[VI] content of MMA/SS fume; in a recent approach, potassium was replaced by sodium in a modified electrode (Kobayashi & Tsutsumi, 1986), resulting in a significant reduction in the relative Cr[VI] content (see below).

The concentration of Cr[VI] and the Cr[VI]/Cr (total) ratio in MIG(MAG)/SS welding fumes has been the subject of considerable discussion. Stern *et al.* (1984) showed that collection of MIG/SS fume in an impinger can result in fixation of 30% and more of the total Cr as Cr[VI] (compared to a maximum of 3% in membrane-collected fumes). The Cr[VI]:Cr(total) is heavily dependent on welding parameters (current, voltage, arc length) and time after welding (Thomsen & Stern, 1979; Stern, 1983). Maximal concentrations of Cr[VI] occur after about 10 s and then fall by about a factor of 3 within 3 min (Hewitt & Madden, 1986).

Occupational exposure to Cr[VI] also occurs in stainless-steel processes other than welding. Sawatari and Serita (1986) showed that the fumes from plasma spraying contain 27% Cr[VI]. Flame spraying, electric arc spraying and plasma spraying of additives containing mixtures of Fe, Cr and Ni produced fumes with approximately 6-8% Cr, of which 22-69% was Cr[VI] (Malmqvist *et al.*, 1981).

A problem with respect to chromium speciation has been lack of standardized collection and analytical methods. Reduction of fume during dry membrane collection and reduction or oxidation of fume during analysis could lead to under- or over-reporting of Cr[VI] concentrations (Pedersen *et al.*, 1987).

(*c*) *Crystalline materials*

Chemical analysis of welding fume is usually based on methods which allow determination only of the elemental content. Frequently, composition is given in terms of the putative oxide (e.g., $Fe_2O_3$, $Fe_3O_4$, $CrO_3$) although such assignment of compound is not justified without additional crystallographic evidence. Recently, a number of authors have begun to investigate the presence of crystallographic compounds in a range of welding fumes.

Fasiska *et al.* (1983) found $Fe_3O_4$, $(Fe, Mn)_3O_4$, KF-$CaF_2$, $CaF_2$, $MnFe_2O_4$, $(Fe,Cu)Fe_2O_4$, $K_2CrO_4$, $K_2FeO_6$, NaF, $K_2FeO_4$, $K_2(Cr,Fe)O_4$, $(Fe,Ni)Fe_2O_4$ and

**Table 3. Distribution (%) of chromium by oxidation state and solubility and of nickel as a function of type of welding fume**

| Type of fume[a] | Cr (total) | Cr[VI] | | | Cr[VI]: Cr (total) | Cr[VI] soluble: Cr (total) | Ni (total) | Reference |
|---|---|---|---|---|---|---|---|---|
| | | Total | Soluble | Insoluble | | | | |
| MMA/SS | 2.9–4.4 | – | 1.5–3.2 | < 0.5–0.92 | – | 0.50–0.73 | 0.22–0.44 | Malmqvist *et al.* (1986) |
| MMA/SS | 5.0 | 4.1 | 3.8 | 0.3 | 0.82 | – | 0.4 | Moreton *et al.* (1986) |
| MMA/SS | 3.0–5.3 | 1.8–3.9 | – | – | 0.36–1.0 | – | 0.3–1.3 | Eichhorn & Oldenburg (1986) |
| MMA/SS | 4.9–7.3[c] | – | 4.4–5.4 | 0.4–1.8 | – | 0.74–0.91 | 0.03–0.6[d] | Kobayashi & Tsutsumi (1986) |
| (modified)[b] | 11.4 | – | 0.66 | 11.2 | – | 0.056 | 0.9 | |
| MMA/SS | 2.4–6.4 | – | 2.2–4.3 | 0.03–0.42 | – | 0.7–0.9 | 0.38–1.9 | Stern (1980b) |
| MMA/Ni[e] | 0.02 | – | – | – | – | – | 1.4 | Stern (1980b) |
| MIG/SS | 12 | – | 0.23 | < 2 | – | 0.019 | 4.5 | Malmqvist *et al.* (1986) |
| MIG/SS | 13.4 | – | 0.2 | < 0.1 | – | 0.015 | 4.9 | Moreton *et al.* (1986) |
| MIG/SS | 4.1–15.6 | 0.02–2.9 | – | 0.01–0.42 | 0.005–0.19[f] | – | 3.5–6.7 | Stern (1980b) |
| FCW/SS | 5.1 | 2.7 | 2.5 | 0.2 | 0.53 | – | 1.3 | Moreton *et al.* (1986) |
| MIG/Ni | 0.04 | – | < 0.004 | 0.04 | – | – | 53–60 | Stern (1980b) |

[a]MMA, manual metal arc; SS, stainless steel; MIG, metal inert gas; FCW, flux-cored electrode
[b]Covering comprises modified lime–titania
[c]Total $Cr_2O_3$
[d]Total NiO
[e][Ba = 40%; 6% water-soluble]
[f][Impinger collection]

$PbCrO_4$ in a wide range of MMA fumes; and Kobayashi and Tsutsumi (1986) found the following compounds in different MMA welding fumes:

| | |
|---|---|
| Non-lime MMA/MS | $Fe_3O_4$, $MnFe_2O_4$, $Fe_2O_3$ |
| Lime-type MMA/MS | $K_2CO_3$, $Fe_3O_4$, $MnFe_2O_4$, NaF, $CaF_2$, $KCaF_3$, KCl (and MgO and $Na_2CO_3$ in a modified type) |
| MMA/SS | $K_2CrO_4$, $Fe_3O_4$. NaF, $CaF_2$, $Na_2CrO_4$ (and LiF in a modified type) |

Combined X-ray diffraction analysis and Mössbauer spectroscopy showed that Fe in welding fume occurs as α-Fe (metallic) as well as in an iron oxide spinel ($Fe_3O_4$) with some degree of impurities and imperfection. MIG/MS and MIG/SS welding fumes contained approximately 7% α-Fe and 12% γ-Fe, respectively (Stern *et al.*, 1987). Although welding fumes contain considerable amounts of silicium in oxidized form, the presence of crystalline silica has not been reported; only amorphous silica is observed (Mayer & Salsi, 1980), presumably because the physical/chemical conditions for the formation of crystalline silica are not met during welding (Fasiska *et al.*, 1983; Kobayashi & Tsutsumi, 1986; Stern *et al.*, 1987). Previously asbestos and currently clays are used to provide elemental Al, Mg and Si; however, these originally crystalline materials are decomposed in the high temperature of the arc, and corresponding crystalline substances do not appear in the fumes.

(*d*) *Physical properties*

The most important physical characteristic of welding fumes is their particulate size distribution, as this property determines the degree to which fumes are respirable and how they are deposited within the respiratory tract. Aerodynamic mass median diameters of welding fumes have been determined with cascade impactors; typical values are as follows: MMA fumes: 0.35-0.6 μm for total fume (Malmqvist *et al.* 1986); 0.23-0.52 μm aerodynamic diameter (Eichhorn & Oldenberg, 1986); 0.2 μm for metallic parts (Mn, Fe) and 2.0 μm for slag components (Ca) (Stern, 1982); MIG fumes: < 0.2 μm (Stern, 1980b) and 0.11-0.23 μm aerodynamic diameter (Eichhorn & Oldenburg, 1986). Stern *et al.* (1984) and Malmqvist *et al.* (1986) showed by means of electron spectroscopy for chemical analysis and transmission electron microscopy that the outer layers of the amorphous matrix of MMA/SS fume particles are soluble in water and contain only Cr[VI]. With most digestion procedures, there is almost always an insoluble residue consisting of refractory cores from MIG/SS fume (Pedersen *et al.*, 1987). Transmission electrom microscopy showed that the particles of MIG fumes can be very crystalline and tend to form long chains, clusters and rafts, most of which, however, break up in solution (Stern, 1979; Grekula *et al.*, 1986; Farrants *et al.*, 1988). For MMA fumes, the situation is complex, since there are several sources of the aerosol. Slag particles make up a separate aerosol with a relatively large median diameter, and a certain fraction consists of particles similar to those found in MIG fumes. A third class of particles consist of an amorphous matrix containing droplets of metal-rich material, which in turn can contain a large number of crystalline precipitates, mostly of an impure, imperfect iron oxide (magnetic) spinel (Stern *et al.*, 1984).

Studies using energy dispersive analysis of X-rays in the electron microscope (Stern, 1979; Minni *et al.*, 1984; Grekula *et al.*, 1986; Gustafsson *et al.* 1986) show that individual particles, especially of MMA fume, can have widely varying chemistry; the particles of MIG fumes may be somewhat more homogeneous, the average particle chemistry resembling that of the fume.

Studies of the chemistry of fumes collected in liquid-filled impingers indicate that the elemental distribution varies as a function of particle size (Stern *et al.*, 1984).

## 2.3 Occupational exposures of welders

Exposures of welders that have been evaluated for carcinogenicity in previous IARC Monographs are listed in Table 4.

### (*a*) *Exposures to welding fumes*

Occupational exposures in the welding industry have been measured for decades. Ambient concentrations of welding fumes are determined by the rates of formation of fume during the process and the extent of ventilation. Steady-state concentrations of fumes in work-room/work-space air are determined by the ratio of fume formation rate (in mg/s) to the ventilation rate ($m^3$/s). In small, confined spaces with poor ventilation, the concentration increases with time: a single welder working with a process producing 10 mg/s of fume in a ship double-bottom section or container with a volume of 10 $m^3$ will be exposed to an environment containing 60 mg/$m^3$ fume after 1 min of arcing time. Typical 4-mm diameter electrodes produce 0.5-4 g total fume and have a burning time of 30-45 s. In most contemporary shops in industrialized countries, ventilation rates are designed to maintain the background level well below 5-10 mg/$m^3$; present levels usually average 2-4 mg/$m^3$ and have been decreasing by a factor of two per decade since the 1940s, as can be seen from a comparison of recent data with measurements of working place concentrations in the 1960s (e.g., Caccuri & Fournier, 1969).

In order to compare fume production from different welding techniques, two entities can be defined — total fume emission rate, E (g/min), and the relative fume formation index, R, which is the total mass of emitted fume standardized to the mass of the deposited consumable (excluding slag) in mg/g (Malmqvist *et al.*, 1986).

**Table 4. Occupational exposures of welders, other than to nickel and chromium compounds (evaluated elsewhere in this volume) that were evaluated for carcinogenicity in *IARC Monographs* Volumes 1–48**

| Agent | Degree of evidence for carcinogenicity[a] | | Overall evaluation[a] | Occurrence |
|---|---|---|---|---|
| | Human | Animal | | |
| Lead and lead compounds | | | | Welding fumes from special-purpose electrodes |
| Inorganic | I | S | 2B | |
| Arsenic and arsenic compounds | S | L | 1* | Impurity in some mild stainless-steel welding fumes |
| Asbestos | S | S | 1 | Insulation material, e.g., in shipyards |
| Toluene | I | I | 3 | Welding fumes from painted steel |
| Xylene | I | I | 3 | Welding fumes from painted steel |
| Phenol | I | I | 3 | Welding fumes from painted steel |
| Benzene | S | S | 1 | Welding fumes from painted steel |
| 1,4-Dioxane | I | S | 2B | Welding fumes from painted steel |
| Formaldehyde | L | S | 2A | Welding fumes from painted steel |
| Acetaldehyde | I | S | 2B | Welding fumes from painted steel |
| Acrolein | I | I | 3 | Welding fumes from painted steel |
| Methyl methacrylate | ND | I | 3 | Welding fumes from painted steel |

[a]S, sufficient evidence; L, limited evidence; I, inadequate evidence, ND, no adequate data. For definitions of the overall evaluations, see Preamble, pp. 36-37.

*This evaluation applies to the group of chemicals as a whole and not necessarily to all individual chemicals within the group.

For a particular welding technique and typical welding parameters, the rate of fume formation does not vary by more than a factor of 3 from the average. In MMA, the amount of fume produced per electrode is independent of the current but roughly proportional to the length of the arc, and hence welding voltage. Poor welding technique can result in twice the fume production per rod. The burn time of an electrode is inversely proportional to the current, so welding at twice the current produces twice the fume formation rate (see Stern, 1977; Malmqvist *et al.*, 1986). Under most open and shipyard conditions, exposure is determined by the relationship between the position of the welder's face mask and the rising plume; typically, the mask effectively reduces exposure by a factor of 3-6 (American Welding Society, 1973).

One way of describing welders' exposures is to present data in terms of cumulative distribution curves for various welding processes. Stern (1980a) generalized the data for Swedish and Danish workplaces (Ulfvarson *et al.*, 1978a,b,c; Ulfvarson, 1979, 1981) and found that the median reported 8-h TWA total dust concentration in the breathing zone was 10 mg/m³ for MIG/Al; that for MMA and MIG processes was 1.5-10 mg/m³. Within the 10-90% range, the distribution curves are parallel: the 90% limit is typically four times greater than the 50% value. Ulfvarson (1986) reviewed many of the general principles that relate to fume concentrations and pointed out that actual fume formation rates are quite similar in different welding processes (with the exception of TIG) and that most of the variation comes from differences in arcing time, which can be as low as 20% for certain MMA operations requiring considerable work-piece preparation, and close to 85% for certain MIG operations. Rutile electrodes emit higher fume concentrations than do basic electrodes, and, with the exception of ozone formation during MIG welding, working postures do not affect fume emissions from mild steel. General ventilation affects exposure considerably: low ventilation rates in the winter lead to a strong seasonal variation (by a factor of 2-3) in Scandinavian work places. Local exhaust, on average, reduces fume concentrations by only 58% in MMA welding and 35% in MIG welding, and by much less if not used properly (close to the arc) or if poorly maintained (Ulfvarson, 1986).

An indication of the range of exposures to total particles was provided by Ulfvarson (1981): the 50% and 90% exposures (in mg/m³) were: TIG/Al, 1 and 4; MIG/Al, 9 and 43; MMA/SS, 4 and 10; TIG/SS, 2 and 6; MMA/Ni, 2 and 10; MMA/MS, 10 and 28; MIG(MAG)/MS, 7 and 18; and MIG/SS, 2 and 5. Most of the results of studies in factories and shipyards are in agreement with the upper limits, as can be seen in Tables 5 and 6. Table 5 also shows total chromium, hexavalent chromium and nickel concentrations in various stainless-steel welding processes. The concentration of hexavalent chromium (mostly water-soluble) ranged from 25 to 1550 μg/m³ in MMA/SS, from $<1$ μg/m³ to $<20$ μg/m³ in MIG/SS and was $\leq 1$–$<6$ μg/m³ in TIG/SS. The nickel levels were 10 to 970 μg/m³, 30 to $<570$ μg/m³ and 10 to $<70$ μg/m³, respectively. Higher levels of chromium and nickel occur during special process applications and during welding in confined spaces. The levels of other air contaminants are summarized in Tables 5-7 for mild-steel and stainless-steel welding.

(*b*) *Biological monitoring of exposure* (see also pp. 484-485)

(i) *Chromium*

Both blood and urine levels of chromium are found to be elevated in stainless-steel welders compared to control populations (Gylseth *et al.*, 1977; Tola *et al.*, 1977; Kalliomäki *et al.*, 1981; Rahkonen *et al.*, 1983; Sjögren *et al.*, 1983a; Welinder *et al.*, 1983; Littorin *et al.*, 1984; Cavalleri & Minoia, 1985; Gustavsson & Welinder, 1986; Schaller *et al.*, 1986). Typical levels of chromium in biological fluids of stainless-steel welders are presented in Table 8.

**Table 5. Occupational exposures within the stainless-steel welding industry by process and application (average and/or range)**

| Reference (country) | Process[a] | Total fume (mg/m³) | Total Cr (µg/m³) | Cr[VI] (µg/m³ or % of total Cr) | Ni (µg/m³) | Cu (µg/m³) |
|---|---|---|---|---|---|---|
| Åkesson & Skerfving (1985) (Sweden) | MMA/SS | – | 101 (26–220) | – | 440 (70–970) | – |
| van der Wal (1985) (Netherlands) | MMA/SS | 2–40 | 30–1600 | 25–1550 | 10–210 | – |
| | MIG/SS | 1.5–3 | 60 | < 1 | 30 | – |
| | TIG/SS[b] | 0.8–4.2 | 10–55 | < 1 | 10–40 | – |
| | Background | 0.5–1.2 | – | – | – | – |
| | TIG/Monel | 1.3–5 | – | – | 330 | 215 |
| | MMA,TIG/Cu-Ni-Fe | 0.6–5.5 | – | – | 20–120 | 40–320 |
| Froats & Mason (1986)[b] (Canada) | MIG/SS (1st plant) | 0.3–2.25 | – | 0.1–0.6 | – | – |
| | MIG/SS (2nd plant) | 0.67–8.32 | 8–37 | 1–3.4 | – | – |
| | SS grinders | 1.6–21.6 | 17–108 | 1–3 | – | – |
| Coenen *et al.* (1985, 1986) (German Democratic Republic) | MMA/SS[b] | 90%, < 13.4 | 90%, < 350 | 90%, < 400 | 90%, < 240 | – |
| | Small MMA/SS | – | 90%, < 210 | 90%, < 30 | 90%, < 70 | – |
| | Large MMA/SS | – | 90%, < 1200 | 90%, < 980 | 90%, < 570 | – |
| | Background | 90%, < 8 | 90%, < 170 | 90%, < 60 | 90%, < 220 | – |
| | TIG/SS[b] | 90%, < 5.4 | 90%, < 40 | 90%, < 6 | 90%, < 70 | – |
| | Background | 90%, < 1 | 90%, < 40 | 90%, < 2 | 90%, < 26 | – |
| | MIG/SS[b] | 90%, < 12.8 | 90%, < 190 | 90%, < 20 | 90%, < 160 | – |
| | Background | 90%, < 3.5 | 90%, < 80 | 90%, < 10 | 90%, < 80 | – |
| | MAG/SS[b] | 90%, < 41 | 90%, < 340 | 90%, < 30 | 90%, < 190 | – |
| | Background | 90%, < 14.4 | 90%, < 30 | 90%, < 3 | 90%, < 20 | – |
| Ulfvarson *et al.* (1978b) (Sweden) | MMA/SS | 75%, < 6.3 | 75%, 400 | 98% | 75%, < 40 | – |
| | Background | 75%, < 4 | 75%, < 50 | 11.5% | 75%, < 22 | – |
| | MIG/SS | 75% < 2.65 | 75%, < 94 | – | – | – |
| | Background | 75%, < 2 | 75%, < 50 | – | – | – |
| van der Wal (1986)[b] (Netherlands) | PC/SS | 1.0–7.5 | 30–440 | < 1–40 | < 10–260 | – |
| | PW/SS | 0.2–1.1 | 20–30 | < 1 | 1–20 | – |

[a]MMA, manual metal arc; SS, stainless-steel; MIG, metal inert gas; TIG, tungsten inert gas; AlB, aluminium bronze; PC, plasma cutting; PW, plasma welding

[b]Breathing zone

**Table 6. Occupational exposures of welders during various processes and applications in the mild-steel and non-ferrous industry**

| Reference (country) | Process[a] | Total fume ($mg/m^3$) | CO (ppm) | $NO_2$ or $NO_x$ ($mg/m^3$) | F ($mg/m^3$) | Cu ($mg/m^3$) | Mn ($mg/m^3$) |
|---|---|---|---|---|---|---|---|
| Casciani *et al.*[c] (1986) (Italy) | MMA/MS: | | | | | | |
| | No exhaust | 8.8–90.6 | 1–47 | 0–6.5[d] | | | |
| | Average | 32.0 | 6.0 | 1.09 | 0.83 | | |
| | With exhaust | 1.3–7.9 | | | | | |
| | Average | 4.34 | | | | | |
| Ulfvarson *et al.* (1978c) (Sweden) | MMA/MS | 1.3–53 | < 5–10 | < 0.5–2.5 | | 0.007–0.094 | 0.089–0.77 |
| | Average | 7.7 | | | | 0.016 | 0.26 |
| | MAG, MIG, TIG/MS | 1.3–52 | < 5–150 | < 0.5–0.5 | | 0.008–0.14 | 0.066–1.8 |
| | Average | 7.0 | 3 | | | 0.027 | 0.30 |
| van der Wal (1985) (Netherlands) | MMA/MS[c] | 1.3–13.2 | | 0.09[b] | | | |
| | Average | 5.3 | | | | | |
| | Background | 0.6–3.1 | | | | | |
| | MIG-MAG/MS[c] | 0.9–12.9 | | 0.09 | | | |
| | Average | 4.4 | | | | | |
| | Background | 0.4–6.7 | | | | | |

[a]MMA, manual metal arc; MS, mild steel; FCW, flux-cored electrode; MAG, metal active gas; MIG, metal inert gas
[b]$NO_2$
[c]Breathing zone
[d]$NO_x$

**Table 7. Concentrations of gaseous pollutants in welding fume**

| Reference (country) | Process[a] | CO | $O_3$ | $NO_2$ | $NO_x$ | NO | $Ni(CO)_4$ |
|---|---|---|---|---|---|---|---|
| Sipek & Smårs (1986) (Sweden) | TIG/SS | | 0.97 ppm | 0.21 ppm | | 0.005 ppm | |
| | TIG/SS | | 0.31 ppm | 2.0 ppm | | 0.44 ppm | |
| Hallne & Hallberg (1982) (Sweden) | MMA/Ni | 15–100 ppm | | 0.1–0.2 ppm | | 0.6–2.6 ppm | 0.02 ppm |
| Wiseman & Chapman (1986) (Canada) | TIG/Ni | | | | | | ≤0.00011 ppm |
| | MIG/Ni | | | | | | < 0.0001 ppm |
| | MIG/SS | | | | | | < 0.0001 ppm |
| | TIG/SS | | | | | | < 0.0001 ppm |
| van der Wal (1985) (Netherlands) | | | | (breathing zone) | | (background) | |
| | MMA/MS | | | | | | |
| | MIG-MAG/MS | | < 5 μg/m³ | ND–0.4 mg/m³ | | ND–0.7 mg/m³ | |
| | TIG/SS | | < 5 μg/m³ | ND–0.3 mg/m³ | | ND–0.7 mg/m³ | |
| | MIG/SS | | < 5 μg/m³ | ND–0.8 mg/m³ | | ND–1.1 mg/m³ | |
| | MIG/Al bronze | | ≤100 μg/m³ | ND–1.7 mg/m³ | | ND–0.6 mg/m³ | |
| | MIG/Al | | > 1000 μg/m³ | ND–0.1 mg/m³ | | ND–0.1 mg/m³ | |
| van der Wal (1986) (Netherlands) (breathing zone) | PC/SS | | | < 0.01–2 mg/m³ | | | |
| | PW/SS | | | 0.03–0.2 mg/m³ | | | |
| Ulfvarson (1981) (Sweden) | | | (50%,90%) | | (50%,90%) | | |
| | TIG/Al | | ≤0.02, 0.08 ppm | | ≤1, 7.6 ppm | | |
| | MIG/Al | | ≤0.08, 0.43 ppm | | ≤0.5, 3.2 ppm | | |
| | MMA/MS | | | | ≤0.2, 1.1 ppm | | |
| | MMA/SS | | < 0.01 ppm | | ≤0.5, 3.0 ppm | | |
| | MIG-MAG/SS | | ≤0.02, 0.2 ppm | | ≤0.5, 2.0 ppm | | |
| | MIG-MAG/MS | | ≤0.03, 0.08 ppm | | ≤0.5 ppm | | |

[a]TIG, tungsten inert gas; SS, stainless-steel; MMA, manual metal arc; MIG, metal inert gas; MAG, metal active gas; PC, plasma cutting; PW, plasma welding

**Table 8. Concentrations of chromium in biological fluids from stainless-steel welders**

| Reference (population)[a] | Concentration of chromium | | |
|---|---|---|---|
| | In urine | In serum (plasma) | In erythrocytes |
| Verschoor *et al.* (1988)[b] | | | |
| MMA/SS welders | 3 (1–62) μg/g creatinine | 0.2 (0.04–2.9) μg/l | - |
| SS Boilermakers | 1 (0.3–1.5) μg/g creatinine | 0.2 (0.07–0.7) μg/l | - |
| Controls | 0.4 (0.1–2.0) μg/g creatinine | 0.2 (0.01–0.9) μg/l | - |
| Angerer *et al.* (1987)[b] | | | |
| MMA-MIG/SS welders | 33 (5.4–229) μg/l | 9 (2.2–69) μg/l | 0.3 (< 0.6–39) μg/l |
| Gustavsson & Welinder (1986)[c] | | | |
| MMA/SS welders | 15.6–61.1 μmol/mol creatinine | 52–190 nmol/l | 27–188 nmol/l |
| After summer vacation | 2–11.3 μmol/mol creatinine | < 13–58 nmol/l | < 20–65 nmol/l |
| Schaller *et al.* (1986)[d] | | | |
| MMA + TIG + MIG/SS welders | 8.3 (0.4–67.4) μg/g creatinine | 2.5 (0.4–7.8) μg/l | - |
| Zschiesche *et al.* (1987)[e] | | | |
| MMA/SS welders | 6.7 (2.2–34.8) μg/g creatinine<br>11.6 (2.4–42) μg/l | | |
| MAG-MIG/SS welders | 4.9 (3.2–10.9) μg/g creatinine<br>6.3 (3.4–21.9) μg/l | | |
| TIG/SS welders | 2.7 (2.3–4.5) μg/g creatinine<br>4.5 (4.1–8.6) μg/l | | |
| Controls | 1.4 (0.8–2.4) μg/g creatinine<br>1.6 (0.8–3.4) μg/l | | |
| Emmerling *et al.* (1987)[e] | | | |
| MMA/SS welders | 28 (8.1–54) μg/l | 10.7 (5.3–20.8) μg/l | 3.6 (1.3–12.5) μg/l |
| MIG-MAG/SS welders | 14.8 (4.9–30.7) μg/l | 5.7 (2.7–13.3) μg/l | 0.6 (0.4–1.4) μg/l |
| TIG welders | 8.7 (4.7–14.5) μg/l | 5.5 (3.0–8.1) μg/l | 1.5 (0.6–3.4) μg/l |

[a]MMA, manual metal arc; SS, stainless-steel; MIG, metal inert gas; TIG, tungsten inert gas; MAG, metal active gas
[b]Geometric mean, range
[c]Range
[d]Median, 90% range
[e]Median, 68% range

(ii) *Nickel*

Consistent results have been difficult to obtain with regard to the levels of nickel in blood and urine of persons exposed during welding, although levels are elevated when compared to unexposed individuals (Table 9).

**Table 9. Concentrations of nickel in work-room air and in the urine of stainless-steel welders**

| Reference (population)[a] | Concentration of nickel | | |
|---|---|---|---|
| | In air (μg/m³) | In plasma (μg/l) | In urine[a] (mean ± SD or range) |
| Åkkeson & Skerfving (1985)[b] | 440 | | |
| MMA/SS welders Monday morning before work | | | 12 (4.2–34) μg/l; 8.8 (3.1–14.1) μg/g creatinine |
| MMA/SS welders Thursday p.m. | | | 18 (8.1–38 μg/l); 12.4 (4.1–50.4) μg/g creatinine |
| Zschiesche *et al.* (1987)[c] | | | |
| MMA/SS welders post-shift | 19 | | 7.5 (2.5–15) μg/l; 4.5 (2.5–12) μg/g creatinine |
| MIG/SS welders | 66 | | 11.2 (4.1–28) μg/l; 8.1 (3.5–21.4) μg/g creatinine |
| Controls | – | | 2.3 (1.2–5.1) μg/g creatinine; 1.8 (1.1–5.0) μg/g creatinine |
| Angerer & Lehnert (1990)[d] | | | |
| MMA/SS welders | 72 ± 82 (< 50–260) | 4.3 ± 3.9 (< 1.8–18.1) | 13.2 ± 26.5 (0.6–164.7) μg/l |
| MIG/SS welders | 100 ± 82 (< 50–320) | 3.9 ± 4.2 (< 1.8–14.6) | 26.8 ± 53.6 (1.2–209.4) μg/l |
| MMA/SS and MIG/SS welders | – | 5.6 ± 4.1 (< 1.8–19.6) | 20.3 ± 18.3 (0.1–85.2) μg/l |
| Controls | – | < 1.8 | 0.9 ± 1.4 (< 0.1–13.3) μg/l |

[a]MMA, manual metal arc; SS, stainless-steel; MIG, metal inert gas; TIG, tungsten inert gas
[b]Median and range; welding of high-nickel alloy (75% Ni)
[c]Median and 68% range
[d]Mean ± SD (range)

(iii) *Manganese*

Most ferrous welding fumes contain manganese, and the range of manganese concentrations in blood and urine of exposed welders is considerably higher than the range in unexposed individuals, although there is considerable overlap (Järvisalo *et al.*, 1983; Zschiesche *et al.*, 1986). Cutters of manganese steel had elevated plasma levels of Mn (up to 28 nmol/l) compared to baseline levels (11 nmol/l) (Knight *et al.*, 1985).

(iv) *Fluoride*

Increased urinary fluoride excretion levels were detected in arc welders using basic electrodes; the fluoride levels correlated with the total dust exposures (Sjögren *et al.*, 1984; see Table 6).

(v) *Lead*

High blood lead concentrations may occur after thermal cutting or welding of lead oxide-coated steel (Rieke, 1969). Increased concentrations of lead in blood were seen in welders in a ship repair yard (Grandjean & Kon, 1981).

(vi) *Aluminium*

Welders utilizing the MIG/Al technique had elevated blood and urinary levels of aluminium (Sjögren *et al.*, 1983b). After exposure to air concentrations of 1.1 (0.2-5.3) mg/m$^3$ aluminium, the urinary aluminium level was 82 (6-564) µg/l (54 (6-322) µg/g creatine); after an exposure-free period, the concentration had decreased to 29 (3-434) µg/l among welders with more than ten years' exposure (Sjögren *et al.*, 1988).

(vii) *Barium*

Barium is found as a constituent in the coating of electrodes with a high nickel content for use on cast iron, and fumes from MMA/Ni welding can contain up to 40% barium (Stern, 1980b). Oldenburg (1988) found that up to 60% of barium in welding fumes was water-soluble. The concentration of barium in poorly ventilated spaces was about 20 mg/m$^3$ (Zschiesche *et al.*, 1989); increased exposure to barium resulted in higher urinary excretion of barium (Dare *et al.*, 1984).

(*c*) *Exposures to welding gases*

Welding processes produce not only particulate matter but also some gaseous pollutants. The high temperature of the arc and the presence of large surface areas of metal at temperatures above 600°C lead to the production of various oxides of nitrogen from the atmosphere. Decomposition of carbonates present in MMA electrode coatings and flux cores produces a protective shield of active carbon dioxide; this gas is also used in MIG/MAG welding as a shield component. Carbon monoxide is also produced, and in some cases has been used as an experimental shield gas component, together with either argon or helium (American Welding Society, 1973, 1979). It has been postulated that the presence of carbon monoxide in the vicinity of welding in which nickel is present, either in the work piece or in the consumable, could result in the formation of nickel carbonyl, which is extremely toxic (see pp. 387-388). Measurements with an instrument with a detection limit of 0.0001 ppm, however, indicated that nickel carbonyl is produced only occasionally in amounts that just exceed the detection threshold (Wiseman & Chapman, 1986).

Occupational exposures to gases have been described for the US industry by the American Welding Society (1973) and for the Swedish industry by Ulfvarson (1981). The results of the latter (see Table 7) reveal that most exposures to ozone arise during MIG and TIG welding of aluminium. Electric arc welding, and particularly MIG/SS, TIG/SS and MIG/Al welding, produce ozone by the ultra-violet decomposition of atmospheric oxygen; high concentrations are found mostly within 50 cm of the arc. The highest exposures to ozone are found in MIG welding of AlSi alloys: emission rates are 5-20 times those for MIG/SS. The presence of nitrogen monoxide, produced in large amounts by MMA welding, acts as a sink for ozone ($NO + O_3 = NO_2 + O_2$) so that little or no residual ozone is produced in this process (Sipek & Smårs, 1986).

Tables 6 and 7 provided an indication of the ranges of gases found with various processes and working conditions. A major problem in interpreting occupational measurements is that sometimes continuous recording instruments are used to sample concentrations behind the face shield, and sometimes grab samples are taken using sampling tubes placed in front of the shield.

(*d*) *Exposures to organic constituents of welding fumes*

Welding is frequently performed on mild-steel base plates coated with shop primer, and although welders are usually instructed to remove the primer from the welding zone, this is frequently not done. Welding on primed plate can significantly increase the total fume concentration, especially if a zinc-based primer has been used. Primers frequently contain organic binders based on alkyl, epoxy, phenolic or polyvinyl butyral. A significant amount of organic material occurs in the fumes originating from pyrolytic decomposition of the plastic. Benzo[*a*]pyrene is frequently found, its distribution being approximately log-normal: 50% of observed values lie below 10 ng/m$^3$, while 98% lie below 1000 ng/m$^3$ (Ulfvarson, 1981). Table 10 gives a summary of the concentrations of some of the organic substances identified in welding fume.

(*e*) *Other exposures*

Because welding can be performed under a wide variety of industrial settings, welders (or those engaged in welding) are potentially exposed to a great number of substances derived from the welding process itself or from other industrial activities being performed in the immediate vicinity (bystander effect). The range of incidental exposures during welding was reviewed by Zielhuis and Wanders (1986).

**Table 10. Organic substances found during welding of painted mild steel**

| Paint type | Organic compound identified | Mean concentration ($mg/m^3$) | Reference |
|---|---|---|---|
| Not reported | Aldehydes, ketones, methylbenzofurane, phenol, dioxane, 2,4-hexadienal, 2-hexanone, alcohols, naphthalene, cresol, pyridine, saturated and unsaturated aliphatic and aromatic hydrocarbons ($C_6$–$C_{14}$), etc. | | Bille *et al.* (1976) |
| Not reported | Toluene<br>Methylethylketone<br>Ethanol<br>Xylene<br>Benzene<br>Ethylbenzene<br>Isobutanol<br>*n*-Decane | 0.07<br>0.02<br>0.2<br>2.8<br>< 0.05<br>1.2<br>< 0.006<br>0.1 | Ulfvarson *et al.* (1978c) |
| Epoxy | Alkylated benzenes[a], aliphatic alcohols ($C_1$–$C_4$)[a], bisphenol A[a], phenol[a], aliphatic ketones ($C_3$–$C_5$), acetophenone, aliphatic aldehydes ($C_1$–$C_4$), aliphatic amines ($C_1$–$C_2$) | | Engström *et al.* (1988) |
| Ethyl silicate | Aliphatic alcohols ($C_1$–$C_4$)[a], butyraldehyde[a], butyric acid, aliphatic aldehydes ($C_6$–$C_9$), formaldehyde, acetaldehyde, acetic acid | | |
| Polyvinyl butyral | Aliphatic alcohols ($C_1$–$C_4$)[a], butyraldehyde[a], butyric acid[a], formaldehyde[a], acetaldehyde, acetic acid, phenol | | |
| Modified epoxy ester | Aliphatic aldehydes ($C_1$–$C_9$)[a], aliphatic acids ($C_5$–$C_9$)[a], methyl methacrylate[a], butyl methacrylate[a], phenol[a], bisphenol A[a], alkylated benzenes, aliphatic alcohols ($C_1$–$C_4$), phthalic anhydride, acrolein, aliphatic hydrocarbons ($C_6$–$C_7$) | | |
| Modified alkyd | Aliphatic aldehydes ($C_6$–$C_9$)[a], acrolein[a], phthalic anhydride[a], aliphatic acids ($C_5$–$C_9$)[a], alkylated benzenes, aliphatic alcohols ($C_1$–$C_4$), formaldehyde, benzaldehyde | | |

[a]Major compound

Ultra-violet radiation is produced during all electric arc welding. The ranking order for emission is MIG > MMA > TIG, with typical fluxes of the order of 22 $W/m^2$ for MIG (at 1 m from the arc) and 0.7-2.5 $W/m^2$ for MMA welding (American Welding Society, 1979; Moss & Murray, 1979). Infra-red radiation is also produced, and emissions in excess of 3500 $W/m^2$ were found in a number of allied processes

(Grozdenko & Kuzina, 1982). Extremely low frequency and radio frequency radiation are produced by the 50-60-Hz currents used in welding, the interruption of current by metal transfer in the arc, and by the radio frequency generators used for igniting MIG and TIG arcs. Typical magnetic flux densities near welding generators range from 2 to 200 μT (Stuchly & Lecuyer, 1989), and current pulses of up to 100 000 A have been found to produce magnetic flux densities of upward of 10 000 μT at distances of 0.2-1.0 m from cables of transformers (Stern, 1987).

Most welders prepare their own work piece by mechanical grinding. This produces an aerosol which, although it has a relatively large aerodynamic diameter, is frequently directed towards the face of the welder. Aerosols from stainless-steel grinding can contain appreciable amounts of metallic nickel and chromium (Koponen *et al.*, 1981).

Asbestos may be encountered by welders in shipbuilding and construction, either from the spraying of asbestos coatings (as a fireproofing measure) or during repair and removal of insulation from pipes, ducts and bulkheads (Sheers & Coles, 1980; Stern, 1980a; Newhouse *et al.*, 1985). Asbestos gloves and heat-protective cloth have been traditionally used by welders.

Sand blasting, as used extensively in the past for surface preparation, can contribute to exposure to free silica, although such exposures have not been studied systematically; glass beads are usually now used.

(*f*) *Regulatory status and guidelines*

Occupational exposure limits for airborne chromium and nickel in various forms are given in the respective monographs. The occupational exposure limit (time-weighted average) in the USA for welding fume (total particulate) is 5 mg/m$^3$ (American Conference of Governmental Industrial Hygienists, 1988).

## 2.4 Chemical analysis of welding fumes and gases

Within recent years, standard practices have been developed for monitoring exposures in order to comply with occupational exposure limits for elements, compounds and nuisance dusts. Most measurements are made using personal monitoring systems with a small battery-driven pump at a flow of about 1 l/min connected to a cassette containing a membrane filter, which is mounted on the lapel or behind the face mask of welders for one or two periods of 3 h. Values are derived for time-weighted average concentrations of total fumes by weighing the filter before and after exposure; elemental concentrations are determined by chemical analysis of the filters (see American Welding Society, 1973; British Standards Institution, 1986). Attempts have also been made to make time-resolved analyses of exposures using special techniques (Barfoot *et al.*, 1981).

A wide range of methods has been used to analyse welding fumes. Proton-induced X-ray emission fluorescence energy analysis has been used for total analysis of the elements (Malmqvist *et al.*, 1986; Pedersen *et al.*, 1987). This is an inexpensive method for providing information on all elements heavier than phosphorus, but one disadvantage is that special calibration methods are necessary which are not always accurate, and no detailed comparison has been reported between the results of this method and wet chemical methods. Special methods can be used to determine specific elements: Malmqvist *et al.* (1986) used a nuclear reaction to determine fluorine and electron spectroscopy to determine the relative distribution of Cr[VI] to total Cr on particle surfaces. The diphenyl carbazide technique, sometimes as adapted by Thomsen and Stern (1979), has been used widely to determine the Cr[VI] content of soluble fractions (Abell & Carlberg, 1984; National Institute for Occupational Safety and Health, 1985). Energy dispersive X-ray analysis has been used to identify the elemental content of individual particles under the electron microscope (Grekula *et al.*, 1986), and X-ray diffraction methods have been used to identify crystalline species. X-Ray photoelectron spectroscopy and Auger electron spectroscopy have been used to identify chemical species on the surface of particles and, together with argon sputtering, to analyse deeper within the particles (Minni, 1986).

In only a few cases have systematic comparisons been made of the results of various techniques on the same fume samples. Oláh and Tölgyessy (1985) showed that the results of X-ray fluorescence and neutron activation methods with regard to MMA fume composition agreed to within 5%.

It is becoming common practice to collect two filters for analysis of SS fumes — one for speciation of chromium and analysis of nickel and the other for total elemental analysis. Gas fibre filters without organic binders or polyvinylchloride filters are recommended (e.g., van der Wal, 1985; Pedersen *et al.*, 1987) to avoid reduction of Cr[VI], which can be as much as 95% if cellulose acetate filters are used. Typical procedures for the analysis of SS fumes are as follows. One part of the filter is leached with distilled water or 1% sodium carbonate at room temperature for 30 min to extract the soluble fraction. Soluble Cr[VI] in the leachate (filtered through a 0.45-μM Duropore membrane) is then determined by the diphenyl carbazide method (or by atomic absorption spectrometry). A second part of the filter is leached with 3% sodium carbonate and 2% sodium hydroxide in water (heated with a cover glass and avoiding formation of white fumes), and total Cr[VI] content is determined by the diphenyl carbazide method in the leachate. A third part of the filter is leached with nitric and hydrochloric acids for 1 h at 175°C and analysed by atomic absorption spectrometry to determine other elements and total chromium. A fourth part of the filter is fused with sodium carbonate for determination of total chromium in the melt solution (van der Wal, 1985).

Digestion of MIG/SS fumes in phosphoric acid:sulfuric acid (3:1) avoids the formation of insoluble residues, which can be as much as 20% of total fume mass for certain types, prior to analysis by atomic absorption spectroscopy for total metallic content (Pedersen *et al.*, 1987).

# 3. Biological Data Relevant to the Evaluation of Carcinogenic Risk to Humans

## 3.1 Carcinogenicity studies in animals

(*a*) *Intratracheal instillation*

*Hamster*: Groups of 35 male Syrian golden hamsters, six weeks of age, received weekly intratracheal instillations of either (i) 2.0 mg of the particulate fraction of MIG/SS fume (containing 0.4% chromium and 2.4% nickel) in 0.2 ml saline; (ii) 0.5 mg or 2 mg of MMA/SS fume (containing 5% chromium and 0.4% nickel) in 0.2 ml saline; (iii) 0.2 ml saline alone; or (iv) 0.1 mg calcium chromate in 0.2 ml saline (see also the monograph on chromium, p. 123). The group receiving 2.0 mg MMA/SS fume had an acute toxic reaction to treatment, and, from week 26 onwards, the dose was given monthly. Following the 56 weeks of treatment, all animals were maintained for a further 44 weeks, at which time the study was terminated [survival figures were not given]. At 12 months, a single anaplastic tumour of the lung, probably a carcinoma, according to the authors, was found in the group that received 0.5 mg MMA/SS; and, at termination of the study, a single mixed epidermoid/adenocarcinoma of the lung was found in the group given 2 mg MMA/SS fume. No lung tumour was reported in the saline control, MIG/SS fume or calcium chromate-treated groups (Reuzel *et al.*, 1986).

(*b*) *Intrabronchial implantation*

*Rat*: Groups of 51 male and 49 female Sprague-Dawley rats, weighing 140-330 g (males) and 115-195 g (females), received surgical implants of five 1-mm stainless-steel mesh pellets into the left bronchus. The pellets were loaded with either (i) 7.0 mg of the particulate fraction of shielded metal arc welding fume (comparable to MMA/SS fume) containing 3.6% total chromium, of which 0.7% was of low solubility, with a particle size of 0.3-0.6 μm as mass median aerodynamic diameter and suspended in cholesterol (50:50 by weight); (ii) 6.7 mg of a thermal spray fume (a mixture of chromic oxide[III] and [VI], containing a total of 56% chromium, of which 40% was of low solubility, produced by blowing an air-jet containing chromic oxide through a flame) suspended in cholesterol (50:50 by weight); or (iii) cholesterol alone (about 5.0 mg). A further three rats received intrabronchial pellets loaded with 40% benzo[*a*]pyrene (4.9-5.65 mg) in cholesterol as a positive control group. The experiment was terminated at 34 months; about 50% of animals were still alive at two years. No lung tumour was seen in the cholesterol control group, while all three benzo[*a*]pyrene-treated treated rats developed squamous-cell carcinomas or carcinomas *in situ* around the site of pellet implantation. A single, microscopic, subpleural squamous-cell carcinoma was found in the right lung of a rat given shielded metal arc welding fume, but the authors considered this to be unrelated to treatment (Berg *et al.*, 1987)

### 3.2 Other relevant data in experimental systems

#### (*a*) *Absorption, distribution, excretion and metabolism*

##### (i) *Mild-steel welding*

Male Wistar rats were exposed by inhalation to 43 mg/m³ (particle size, 0.12 μm mass median average diameter) MMA/MS welding fumes for 1 h per work day for up to four weeks; a saturation level of 550 μg/g dry lung of the welding fumes was observed. Clearance of the welding fume particles from the lung followed a two-phase exponential equation; most of the accumulated particles were excreted within a half-time of six days and the remainder with a half-time of 35 days. The two major components of the mild steel — iron and manganese — had similar pattern of saturable lung retention, but manganese was cleared much faster initially (the first half-time was 0.5 day). Some of the inhaled manganese was apparently soluble and was quickly absorbed from the lung, whereas the absorption of exogenous iron was slower and was obscured by a simultaneous occurrence of endogenous iron in lung tissue. Under the same exposure conditions, alveolar retention of the mild-steel welding fumes was much lower and its clearance much faster than the corresponding parameters for stainless-steel (Kalliomäki *et al.*, 1983a,b).

Male Sprague-Dawley rats were exposed for 46 min by inhalation to MMA/MS welding fumes (1178 mg/m³; particles, 0.13 μm mass median average diameter) containing $< 0.1\%$ chromium and cobalt. The immediate retention of the fume particles totalled 1.5 mg/lung, and the elemental composition of the fumes retained was slightly different from that of the original airborne fumes, indicating some selective retention/clearance. Iron was cleared from the lungs substantially more slowly than chromium or cobalt, and pulmonary retention of iron was represented as a three-phase exponential curve with half-times of 0.2 (50% of the deposit), 1.6 (32%) and 34 (18%) days (Lam *et al.*, 1979).

##### (ii) *Stainless-steel welding*

Dunkin-Hartley guinea-pigs were exposed by inhalation for 256 min to MIG/SS welding fumes (990 mg/m³; particle size, 0.064 μm median diameter as determined by electron microscopy). The initial fractional deposit of the fume was 17%; the proportions of iron, cobalt, nickel and chromium retained in the lung were different from those in airborne fumes. During 80 days after exposure, the metals were cleared from the lungs at different rates: chromium > nickel > cobalt > iron, according to individual three-phase kinetic curves, with half-times ranging from 0.4-0.6 days for the first phase to 72-151 days for the third phase, depending on the metal. Iron, chromium and cobalt were eliminated mostly with faeces (maximal at days 2-3 after exposure) (Lam *et al.*, 1979).

Wistar rats were exposed to MMA/SS welding fumes (43 mg/m$^3$; 0.3 μm mass median diameter determined by electron microscopy) for 2 h per day for up to five days. The concentrations of chromium, nickel and exogenous iron in the lungs correlated well with the cumulative exposure time. No saturation trend was found for any of the metals. The average pulmonary concentration of chromium after the maximal exposure of 10 h was 39 ppm (mg/kg), that of nickel was 5.7 ppm (mg/kg) and that of exogenous iron, 132 ppm (mg/kg). The level of chromium was also elevated in the blood, kidneys, liver and spleen, while those of nickel and iron did not increase significantly in these tissues (Kalliomäki *et al.*, 1982a).

Male Wistar rats were exposed to 43 mg/m$^3$ MMA/SS welding fumes for 1 h per work day for up to four weeks. Median particle size of the fume was 0.3-0.6 μm mass median average diameter as determined by electron microscopy. A linear relationship was observed between the duration of exposure and the concentration of exogenous iron, chromium and nickel in the lung. A simplified single exponential lung clearance model gave the following half-times: exogenous iron, 50 days; chromium, 40 days; and nickel, 20 days. The concentration of chromium in the blood was significantly elevated only during exposure, and it decreased rapidly after termination of exposure; concentrations of exogenous iron and nickel were near the detection limits (Kalliomäki *et al.*, 1983c). Use of the MIG/SS welding technique instead of the MMA/SS technique under comparable exposure conditions did not substantially change the pulmonary retention patterns of the welding fumes, but it markedly changed the clearance patterns, especially for chromium. After exposure to MMA welding fume, chromium, manganese and nickel were cleared at half-times of 40, 40 and 30 days, respectively; with the MIG fumes, the half-time for chromium was 240 days, while the clearance of manganese and nickel obeyed the double-exponential model with half-times of two and 125 days for manganese and three and 85 days for nickel (Kalliomäki *et al.*, 1983d, 1984).

Welding fumes collected from the MMA/SS and MIG/SS assemblies were suspended in normal saline (1% suspension) and instilled intratracheally into male Wistar rats at a dose of 0.2 ml/rat, and the fate of the metals contained in the fumes was followed for up to 106 days. After exposure to the MMA/SS fumes, iron, chromium and nickel were cleared with half-times of 73, 53 and 49 days, respectively; but with MIG/SS fume, practically none of the metal was cleared within two months. The disposition of chromium in the MMA/SS fume closely resembled that of intratracheally instilled soluble chromates, whereas the very slow lung clearance of chromium from the MIG/SS fumes was still slower than that of water-insoluble chromates or Cr[III] salts. Thus, the clearance of chromium strongly depends on the physicochemical form of chromium in the welding fume (Kalliomäki *et al.*, 1986).

The dissolution of MMA/SS and MIG/SS welding fumes was studied in the lungs of male Wistar rats following one to four weeks' exposure by inhalation to 50 mg/m³ for 1 h per day. Two particle populations with different behaviours were found in the lungs of rats exposed to the MMA/SS fumes. The particles of the principal population (0.1-0.25 μm mass median average diameter as determined by electron microscopy) dissolved in both alveolar macrophages and type-1 epithelial cells in about two months; quickly and slowly dissolving forms of chromium, manganese and iron were detected in these particles. The particles of the minor population (0.005-0.1 μm determined as above) showed no signs of dissolution during the three-month observation period; they were found to contain very stable mixed spinels. Inhalation of the MIG/SS fumes resulted in lung deposition of only one particle population, which was very similar to the minor population in the MMA/SS fumes; no dissolution of these particles was observed within three months (Anttila, 1986).

(*b*) *Toxic effects*

(i) *Mild-steel welding*

Deposition of MMA/MS welding fumes in the lungs of male CFE rats following single exposures by inhalation or by intratracheal injection resulted in the development of reticulin fibres in the particle-laden macrophage aggregates, with only sparse collagen fibre formation, which did not increase markedly up to 450 days (Hicks *et al.*, 1983). The particles caused alveolar epithelial thickening with proliferation of granular pneumocytes and exudation of lamellar material. Foam cells appeared in alveoli. Formation of nodular aggregates of particle-laden macrophages and giant cells was observed as a delayed effect 80-300 days after exposure (Hicks *et al.*, 1984). Similar nonspecific pulmonary changes were seen in the lungs of Sprague-Dawley rats exposed to MMA/MS welding fumes (mass median diameter, 0.62 μm) as a single exposure to 1000 mg/m³ for 1 h or to 400 mg/m³ for 30 min per day on six days per week during two weeks (Uemitsu *et al.*, 1984).

In MRC hooded rats, single intratracheal instillations (0.5-5 mg/rat) of either 'basic' (18% $SiO_2$, 30% F, 23% Fe, 6% Mn) or 'rutile' (41% $SiO_2$, 2% Ti, 39% Fe, 3% Mn) MMA/MS welding particles, suspended in saline increased the ribonuclease and protease activity of lavaged cells by one week after administration (White *et al.*, 1981).

Cultured alveolar macrophages from the lavaged lungs of male Brown-Norway rats were exposed for one day to total dust or to the water-insoluble fraction of fume particles [size unspecified] from MMA/MS and MIG/MS welding (15, 25 or 50 μg/ml). Both dusts were toxic to the cells in a concentration-related manner; MMA/MS dust was more toxic than that of the MIG/MS. The toxicity of the MMA/MS and MIG/MS particles was not related to the water-soluble components (Pasanen *et al.*, 1986).

In rat peritoneal macrophages *in vitro*, none of three welding fumes derived from MS showed fibrogenic potential; pure magnetite dust was also inactive (Stern & Pigott, 1983; Stern *et al.*, 1983).

When alveolar macrophages from bovine lungs were exposed *in vitro* to MMA/MS welding particles (both 'basic' and 'rutile'; up to 40 μg/ml) for 17 h, dose-related detachment of cells, morphological changes and a decrease in viability were seen. Toxicity was reduced significantly by supplementation of the cell culture with 10% calf serum, but not by bovine serum albumin. Release of lactic dehydrogenase, but not of *N*-acetyl-β-glucosaminidase, was also observed. The 'basic' fumes were slightly more active than the 'rutile' fumes (White *et al.*, 1983).

(ii) *Stainless-steel welding*

Two days after a single exposure of male Sprague-Dawley rats to MMA/SS welding fumes (1000 mg/m$^3$ for 1 h or 400 mg/m$^3$ for 30 min per day, six days per week during two weeks; mass median diameter, 0.8 μm), hyperplasia of mucous cells was seen in the bronchial epithelium which tended to increase with time (maximal at day 7). No other significant pathological effect was observed (Uemitsu *et al.*, 1984).

In the study of White *et al.* (1981; see above), MMA/SS welding particles (containing 16% $SiO_2$, 13% F, 2% Fe, 3% Mn, 2% Cu and 2.5% Cr (nearly all in a water-soluble Cr[VI] form)) suspended in saline also increased the ribonuclease and protease activity of lavaged cells from MRC hooded rats.

Male Sprague-Dawley rats received a single intratracheal instillation of the soluble or insoluble fraction of MMA/SS welding fume particles containing 3.5% chromium (nearly all soluble Cr[VI]) or potassium dichromate at doses equivalent to those found in the fume particles. One week after instillation, most of the toxicity of the welding particles could be related to the content of soluble Cr[VI], although the insoluble particles also produced some changes at the alveolar surface (White *et al.*, 1982).

MIG/SS welding fume deposited in the lungs of male CFE rats had similar effects to those of MMA/MS fume, reported above (Hicks *et al.*, 1983, 1984). MIG/SS particles injected intradermally or given by topical application to Dunkin-Hartley guinea-pigs had moderate sensitizing properties, which were stronger than those of MMA/MS particles but weaker than those of chromates (Hicks *et al.*, 1979). After intramuscular injection to CFE rats and Dunkin-Hartley guinea-pigs, the MIG/SS and MMA/MS materials were much less toxic and irritant than the MMA/SS material. The differences in fibrogenic properties were less pronounced, but MMA/SS still had the greatest effect (Hicks *et al.*, 1987).

The toxic effects of MMA/SS fume in baby hamster kidney and Syrian hamster embryo cells were more pronounced than that of MIG/SS fume. The effect of MMA/SS fume corresponded to the content of soluble chromates (potassium dichromate), while that of MIG/SS fume was greater, implying phagocytosis of less soluble chromium particles. Freshly produced welding fume appeared to be more active than stored samples (Hansen & Stern, 1985).

Cultured alveolar macrophages from the lavaged lungs of male Brown-Norway rats were exposed for one day to the total dust or to the water-insoluble fraction of fume particles [size unspecified] from MMA/SS and MIG/SS (15, 25 or 50 μg/ml). Both dusts were toxic in a concentration-related manner, but the MMA/SS dust was more toxic than that of MIG/SS. MMA/SS particles, but not MIG/SS particles, were less toxic after prewashing. The effects of MMA/SS on cell viability were similar to those observed after exposure of cells to potassium chromate at equivalent concentrations (Pasanen *et al.*, 1986).

In rat peritoneal macrophages *in vitro*, MMA/SS had distinct fibrogenic potential (Stern & Pigott, 1983; Stern *et al.*, 1983).

When alveolar macrophages from bovine lungs were exposed *in vitro* to MMA/SS welding particles, chromium[III] chloride or potassium dichromate (at up to 30 nmol (1.6 μg) chromium/ml) for 17 h, dose-related detachment of cells, morphological changes and a decrease in viability were seen. Within the concentration range tested, the MMA/SS fume particles were more toxic than potassium dichromate, while Cr[III] had no effect on cell viability. Toxicity was reduced significantly by supplementation of the cell culture with 10% calf serum, but not by bovine serum albumin. Release of lactic dehydrogenase, but not of *N*-acetyl-β-glucosaminidase, was also observed (White *et al.*, 1983).

The cytotoxic effects of two MIG/SS and one MMA/SS welding fumes were tested at concentrations of 5-200 μg/ml in normal human embryonic pulmonary epithelium cells (L132) in culture. At equal concentrations, the two MIG/SS fumes had comparable cytotoxicity which was somewhat greater for the fume containing more nickel (60% *versus* 4% nickel). The MMA/SS fume was much more toxic, probably because it contained high proportions of soluble Cr[VI], fluorine and potassium; a comparable effect was obtained with an equivalent concentration of sodium chromate. The particles were phagocytized by the cells. Changes in cell morphology were also observed (Hildebrand *et al.*, 1986).

(*c*) *Effects on reproduction and prenatal toxicity*

No data were available to the Working Group.

(*d*) *Genetic and related effects*

The Working Group noted that the evaluation of genetic effects of welding fumes is complicated not only by many variations in welding techniques but also by variations in collection and storage methods prior to testing. In the studies reported, several different methods of sample collection and application were used. Particulate fractions were collected on filters and then suspended in water (Hedenstedt *et al.*, 1977; Knudsen, 1980; Hansen & Stern, 1985; Baker *et al.*, 1986), in dimethyl sulfoxide (Maxild *et al.*, 1978), in culture media (Koshi, 1979; Niebuhr *et al.*, 1980; de Raat & Bakker, 1988) or in phosphate buffer (Biggart *et al.*, 1987). In one study, particulate and volatile fractions were separated and the latter passed into a chamber containing bacteria on petri dishes (Biggart & Rinehart, 1987). Studies for genetic and related effects of welding fumes are summarized in Appendix 1 to this volume.

(i) *Mild-steel welding*

MMA and MIG welding fumes did not inhibit growth of either *Escherichia coli* W3110 *pol*A$^+$ or the repair-deficient *E. coli* P3478 *pol*A$^-$ strain (Hedenstedt *et al.*, 1977).

MS welding fumes were not mutagenic to *Salmonella typhimurium* TA97, TA98, TA100 or TA102 (Hedenstedt *et al.*, 1977; Maxild *et al.*, 1978; Etienne *et al.*, 1986). The gaseous phase from MMA/MS welding induced mutation in *S. typhimurium* TA1535 but not in TA1538, while the particulate fraction (in phosphate buffer) induced mutation in TA1538 but not in TA1535 (Biggart & Rinehart, 1987; Biggart *et al.*, 1987).

MMA/MS and MIG/MS did not increase the incidence of chromosomal aberrations in Chinese hamster ovary cells at doses up to 32 μg/ml (MMA) or 1000 μg/ml (MIG) (Etienne *et al.*, 1986) and did not induce morphological transformation of Syrian baby hamster kidney cells at doses up to 600 μg/ml (MMA) or 600 μg/ml (MIG) (Hansen & Stern, 1985). [See General Remarks for concern about this assay.] Relatively high doses of MMA/MS (50-300 μg/ml), but not of MIG/MS (250-1000 μg/ml), fumes increased the frequency of sister chromatid exchange in Chinese hamster ovary cells (Etienne *et al.*, 1986; de Raat & Bakker, 1988).

Neither MMA/MS (at 64-217 mg/m$^3$ for 6 h per day, five days per week for two weeks) nor MIG/MS (at 144 mg/m$^3$ for 6 h per day, five days per week for two weeks) fumes increased the frequency of sister chromatid exchange in peripheral blood lymphocytes or of chromosomal aberrations in either peripheral blood lymphocytes or bone-marrow cells of rats after exposure by inhalation (Etienne *et al.*, 1986).

(ii) *Mild-steel and cast-iron welding with nickel-rich electrodes*

With MMA welding fumes from cast iron employing a nickel-rich (95% Ni) electrode, no mutagenicity was detected in four strains of *S. typhimurium* (TA97, TA98, TA100 and TA102) at up to 20 mg/plate; no *hprt* locus mutation and no induction of chromosomal aberrations, but an increased frequency of sister chromatid exchange, were observed in Chinese hamster ovary cells (Etienne *et al.*, 1986). In another study, an increased frequency of sister chromatid exchange was seen in an unspecified cell line [probably human peripheral lymphocytes] exposed to 100-500 μg/ml MIG/MS welding fume from a 95%-nickel electrode (Niebuhr *et al.*, 1980). The same type of fume caused anchorage-independent growth of baby hamster kidney fibroblasts at 100-400 μg/ml (Hansen & Stern, 1984). [See General Remarks for concerns about this assay.]

MMA welding fumes from cast iron employing a nickel-rich (95% Ni) electrode did not increase the frequency of sister chromatid exchange in peripheral blood lymphocytes or of chromosomal aberrations in either peripheral blood lymphocytes or bone–marrow cells of rats after exposure by inhalation to 57 $mg/m^3$ for 6 h per day, five days per week for two weeks (Etienne *et al.*, 1986).

(iii) *Stainless-steel welding*

Growth of the repair-deficient *E. coli* P347S *pol*A$^-$ mutant was selectively inhibited, as compared to *E. coli* W3110 *pol*A$^+$, by MMA/SS but not by MIG/SS fumes, demonstrating that MMA/SS has a greater DNA damaging potential (Hedenstedt *et al.*, 1977).

Both MMA/SS and MIG/SS fumes were mutagenic to *S. typhimurium* TA97, TA98, TA100 and TA102 (Hedenstedt *et al.*, 1977; Maxild *et al.*, 1978; Etienne *et al.*, 1986). The mutagenicity of some but not all fume samples was diminished by addition of an exogenous metabolic system from rat livers.

It was reported that MMA/SS fumes did not enhance unscheduled DNA synthesis in human cells (Reuzel *et al.*, 1986) [details not given]. MMA/SS fumes induced a significant response at the *hprt* locus (6-thioguanine resistance) at 10 μg/ml in one experiment of three in the Chinese hamster V79 cell line (Hedenstedt *et al.*, 1977). [The Working Group considered the overall effect to be negative.] Responses at the *hprt* locus varied according to the way in which fume was generated (Etienne *et al.*, 1986).

Sister chromatid exchange was induced by MMA/SS and MIG/SS fumes in Chinese hamster ovary cells (Etienne *et al.*, 1986; de Raat & Bakker, 1988) and Don hamster cells (Koshi, 1979; Baker *et al.*, 1986); these fumes also induced chromosomal aberrations in Don (Koshi, 1979) and Chinese hamster ovary (Etienne *et al.*, 1986) cell lines, and mitotic delay was found after treatment of hamster Don cells with the water-soluble and -insoluble fractions of MMA/SS fumes (Baker *et al.*, 1986).

MMA/SS (50 μg/ml) and MIG/SS (400-800 μg/ml) welding fumes induced anchorage-independent growth of Chinese baby hamster kidney cells, and 5 μg/ml MMA/SS and 18 μg/ml MIG/SS fumes caused morphological transformation of Syrian hamster embryo cells (Hansen & Stern, 1985).

MMA/SS fumes were mutagenic *in vivo* following intraperitoneal injection of 100 mg/kg bw over days 8, 9 and 10 of gestation, as observed in the mouse fur spot test (Knudsen, 1980); however, no increase in the frequency of either sister chromatid exchange in peripheral blood lymphocytes or of chromosomal aberrations in either peripheral blood lymphocytes or bone-marrow cells of rats was found after inhalation of MMA/SS fumes (60-100 mg/m$^3$ for 6 h per day, five days per week for two weeks) or MIG/SS fumes (124-172 mg/m$^3$ for 6 h per day, five days per week for two weeks) (Etienne *et al.*, 1986).

[The greater genotoxic activity *in vitro* of MMA/SS fumes as compared with MIG/SS welding fumes generally corresponds to their higher content of Cr[VI]. In the absence of chromium, the presence of nickel is sufficient to account for the observed activity *in vitro*.]

### 3.3 Other relevant data in humans

#### (*a*) *Absorption, distribution, excretion and metabolism*

In human lungs on autopsy, welding-fume particles seemed to be preferentially retained in central regions, mainly behind but also in front of the hilus (Kalliomäki *et al.*, 1979). Characteristic stainless-steel particles could be identified by electron probe analysis in lung tissue from two deceased arc welders (Stettler *et al.*, 1977). Analysis by energy-dispersive X-ray technique of lung tissue from one welder revealed intracellular particles containing both iron and silicon (Guidotti *et al.*, 1978), while tissue samples from ten other welders revealed large amounts of iron in fibrotic septa, but no increase in the content of silicon (Funahashi *et al.*, 1988). Lung tissue from two SS welders contained up to 500 times more nickel and 60 times more chromium than in controls, but the high nickel levels may have been due in part to exposures at a nickel refinery (Raithel *et al.*, 1988).

Urinary chromium excretion after work in active welders using MMA/SS or MIG/SS correlated with concentrations of soluble chromium compounds in the air during the work day (Tola *et al.*, 1977; Sjögren *et al.*, 1983a; Welinder *et al.*, 1983; Mutti *et al.*, 1984; see Table 8). Concentrations of chromium in urine and plasma obtained from 103 MMA/SS and MIG/SS welders at the end of the shift were strongly correlated; chromium concentrations in erythrocytes, though much lower, correlated better with plasma levels than with urinary chromium concentrations

(Angerer *et al.*, 1987). In ten MMA/SS welders, airborne chromium exposures correlated poorly with chromium concentrations in whole blood and plasma, but correlated significantly with increases occurring in blood and plasma concentrations during the shift (Rahkonen *et al.*, 1983). In welders using exclusively gas-shielded welding techniques, chromium concentrations in urine and blood were barely increased above background levels (Angerer *et al.*, 1987).

In welders with a long exposure history, urinary chromium excretion remained high during three exposure-free weeks, possibly due to slow excretion of previously retained chromium (Mutti *et al.*, 1979). Accumulation of chromium is suggested by the observation that urine and plasma chromium concentrations may not return to background levels in MMA/SS welders over a weekend (Schaller *et al.*, 1986). Increased excretion of chromium was also seen in nine retired welders (average, four years since cessation of exposure) who had done mainly MMA/SS but also some MIG and TIG welding (Welinder *et al.*, 1983). Good correlations were found in ten MMA/SS welders between chromium levels in body fluids and the retention rate for magnetic dust, as estimated by magnetopneumography (Rahkonen *et al.*, 1983).

Increased urinary nickel excretion was seen in MMA/SS welders but not in TIG welders, perhaps due to differences in the solubility of the airborne nickel compounds (Kalliomäki *et al.*, 1981). Urinary nickel excretion of ten MMA/SS welders correlated significantly with airborne exposures (Rahkonen *et al.*, 1983). Increased nickel concentrations were also seen in plasma and urine of shipyard (Grandjean *et al.*, 1980) and other welders (Bernacki *et al.*, 1978).

Increased concentrations of aluminium (Sjögren *et al.*, 1985), barium (Dare *et al.*, 1984), fluoride (Sjögren *et al.*, 1984), lead (Grandjean & Kon, 1981) and manganese (Järvisalo *et al.*, 1983) have been measured in samples of blood and urine from some groups of welders (see section 2.3).

(*b*) *Toxic effects*

Adverse health effects of exposures during welding have been reviewed by Zober (1981a,b), Stern *et al.* (1983) and the National Institute for Occupational Safety and Health (1988).

Sensitivity to chromate resulted in contact dermatitis in five welders exposed to chromate-containing welding fumes (Fregert & Övrum, 1963). Cutaneous exposure to sparks and radiation may cause burns and other damage to the skin (Roquet-Doffiny *et al.*, 1977), and localized cutaneous erythema and small cutaneous scars are frequent in welders. The ultra-violet radiation from welding operations can cause acute keratoconjunctivitis in the absence of eye protection, but such episodes normally cause no apparent lasting clinical abnormality or decrease in visual acuity (Emmett *et al.*, 1981).

Metal fume fever is a nonspecific, acute illness characterized by fever, muscle pain and leukocytosis; it is fairly common among welders. For example, 23/59 ship repair welders had experienced metal fume fever during the previous year, and 4/59 had suffered more than six incidents of the illness during that time (Grandjean & Kon, 1981). In another study, 31% of 530 welders aged 20-59 had experienced metal fume fever at least once (Ross, 1974). This condition may rarely be associated with angioedema and urticaria (Farrell, 1987). Several cases of asthmatic reactions due to components of welding fume have been recorded (Keskinen *et al.*, 1980; Bjørnerem *et al.*, 1983). Acute inhalation of metal fumes containing cadmium or ozone may result in chemical pneumonitis and pulmonary oedema (Beton *et al.*, 1966; Anthony *et al.*, 1978).

Welders who had used electrodes with a high chromium content for many years showed signs of erosion of the nasal septum (Jindrichova, 1978). Chronic inflammation was observed in upper airway epithelium of welders (Werner, 1977).

Several groups of welders, in particular nonsmokers, experienced more frequent chronic rhinitis, cough, phlegm, dyspnoea, wheezing and chronic bronchitis than expected (Barhad *et al.*, 1975; Antti-Poika *et al.*, 1977; Akbarkhanzadeh, 1980; Kalliomäki *et al.*, 1982b; Keimig *et al.*, 1983; Schneider, 1983; Mur *et al.*, 1985; Cotes *et al.*, 1989). Indicators of pulmonary function, such as vital capacity and forced expired volume in 1 s, showed decrements related to welding exposures (Peters *et al.*, 1973; Barhad *et al.*, 1975; Akbarkhanzadeh, 1980; Kalliomäki *et al.*, 1982b; Cotes *et al.*, 1989). Small airway disease may be the first sign of pulmonary abnormalities in shipyard welders, as reflected by increased closing volume and closing capacity (Oxhoj *et al.*, 1979) and decreased terminal flow volumes (Kilburn *et al.*, 1985; Cotes *et al.*, 1989). One study showed a significant correlation in welders between respiratory symptoms and thoracic magnetic dust content (Näslund & Högstedt, 1982), while no such relationship was detected in another study (Stern *et a*l., 1988). (The methods used to detect magnetic dust have been reviewed (Lippmann, 1986), and there is evidence that magnetic properties are unstable in lung over long periods (Stern *et al.*, 1987).) Further, some studies indicated a minimal or no difference in prevalence rates of respiratory symptoms and pulmonary function in welders compared to control groups (Fogh *et al.*, 1969; Hayden *et al.*, 1984; McMillan & Pethybridge, 1984). Forced ventilatory capacity was decreased to similar degrees in shipyard welders, pipe-coverers and pipe-fitters, suggesting that past asbestos exposure in some groups of welders may affect pulmonary function (Peters *et al.*, 1973). [The Working Group noted that possible selection bias among long-term welders, interaction with smoking, questionable validity of control groups and poor characterization of the exposures decreased the value of some studies.]

Early reports suggested that inhalation of welding fumes may cause siderosis, a benign pneumoconiosis (Doig & McLaughlin, 1936; Enzer & Sander, 1938); small, rounded opacities (Attfield & Ross, 1978) and nonspecific reticulomicronodulation (Mur *et al.*, 1989) were seen on X-ray examination. Some authors have reported no fibrosis or related pulmonary function changes (Harding *et al.*, 1958; Morgan & Kerr, 1963) and it has been shown that the radiographic changes may be reversible (Doig & McLaughlin, 1948; Garnuszewski & Dobrzynski, 1967; Kujawska & Marek, 1979). In other cases, analysis of histology and of pulmonary function abnormalities have indicated pulmonary fibrosis of varying degrees in welders (Charr, 1953, 1956; Angervall *et al.*, 1960; Stanescu *et al.*, 1967; Slepicka *et al.*, 1970; Brun *et al.*, 1972; Irmscher *et al.*, 1975; Patel *et al.*, 1977). Although considerable accumulation of iron oxide dust was documented in these studies, the demonstration of asbestosis in shipyard welders (Selikoff *et al.*, 1980; McMillan, 1983; Kilburn *et al.*, 1985) would suggest that factors other than iron oxide, such as silica (Friede & Rachow, 1961; Meyer *et al.*, 1967; Fabre *et al.*, 1976), could contribute to the pathogenesis of pulmonary fibrosis.

The number of days lost due to sickness attributed to respiratory disease was 2.3 times higher in welders at a petrochemical plant than among other workers not exposed to welding fumes (Fawer *et al.*, 1982). In one study, absence of welders due to sickness appeared to be related primarily to smoking (McMillan, 1981).

A slight increase in serum creatinine level was seen in SS welders, which was unrelated to urinary chromium excretion; no sign of tubular damage was detected (Verschoor *et al.*, 1988), in agreement with the results of a previous study (Littorin *et al.*, 1984). No increased risk for chronic kidney disease was seen in welders (Hagberg *et al.*, 1986).

(*c*) *Effects on reproduction and prenatal toxicity*

At a fertility clinic, poor sperm quality was seen more often among male SS and other metal welders than expected, and women employed as SS welders had delayed conception (Rachootin & Olsen, 1983). Among patients examined for sperm quality at other fertility clinics, welders had a significantly increased risk of reduced sperm quality (Haneke, 1973; Mortensen, 1988).

In a study using census data over a four-year period, female welders showed a slightly greater spontaneous abortion rate than other industrial workers and other employed women, but the increase was not statistically significant; no increase was seen for the wives of welders (Hemminki & Lindbohm, 1986).

(*d*) *Genetic and related effects*

The studies described below are summarized in Appendix 1 to this volume.

Husgafvel-Pursiainen *et al.* (1982) studied the frequency of sister chromatid exchange and chromosomal aberrations in a group of 23 male MMA/SS welders and in 22 males from the office of a printing company. The groups were healthy and were controlled for smoking and previous exposure to clastogenic agents; none of the subjects had had a recent viral infection, vaccination or diagnostic radiation. The age difference between the welders (mean, 45 years) and the controls (mean, 37 years) was considered not to be relevant. All of the welders worked in poorly ventilated areas, had been exposed for at least four years, with a mean of 21 ± 10 (SD) years, and had had little or no exposure to other agents in their occupational history. Sampling of six workers was repeated 1.5 years later. Exposure was mainly to alkaline chromates (calcium chromate and potassium dichromate), with airborne Cr[VI] levels of 0.03-4 mg/m$^3$, and to nickel (as poorly water-soluble alloy in iron oxide fume particles), estimated to be four to eight times lower than to chromium. Urinary levels in exposed workers were 0.2-1.55 μmol/l (10-80 μg/l) chromium and 0.05-0.15 μmol/l (3-9 μg/l) nickel. No effect of exposure was observed over control values for sister chromatid exchange (9.7 ± 0.3 cell) or chromatid and chromosome-type aberrations (1.8%); no change was observed during the 1.5-year observation period. [The Working Group noted the high frequency of sister chromatid exchange in controls.] An increased frequency of sister chromatid exchange ($p <$ 0.01) was observed in smokers in both exposed and unexposed groups.

No increase in the frequency of cytogenetic damage was observed in a well controlled, pair-matched (for sex, age, smoking habits, socioeconomic class, living area, drug and alcohol consumption) study of 24 MMA/SS workers from six industries (Littorin *et al.*, 1983). None of the controls had had any exposure to SS fumes or to known mutagenic or carcinogenic agents. Workers had been exposed for seven to 41 years (mean, 19 years) to Cr[VI] and to lesser amounts of nickel and molybdenum. Exposures to chromium, calculated as time-weighted average exposures for one work day from personal air samplers, were 4-415 μg/m$^3$ total chromium (mean, 81 μg) and 5-321 μg/m$^3$ Cr[VI] (mean, 55 μg). Urinary chromium levels were 5-155 μmol/mol creatinine (mean, 47 μmol/mol creatinine) for exposed workers *versus* < 0.4-7.0 μmol/mol creatinine (mean, 1.5 μmol/mol creatinine) for controls. No increase was observed in the total number of structural chromosomal aberrations (4.1% in welders, 4.4% in controls) nor in sister chromatid exchange frequency (11/cell in welders, 12/cell in controls) nor in the incidence of micronuclei (0.78% in welders, 0.79% in controls). No effect of smoking was observed, except for some types of chromosomal aberration (structural rearrangements). [The Working Group noted the high background frequencies of sister chromatid exchange and aberrations and that samples were shipped with 16-h lags to the analysing laboratory.]

In a larger study, Koshi *et al.* (1984) observed increased frequencies of both sister chromatid exchange and chromosomal aberrations in workers engaged in both MMA/SS and MIG/SS welding, with exposures to chromium, nickel, manganese and iron. Sampling was done three times over three years, with 17 workers sampled in the first survey and 44 in each of the subsequent surveys. Workers were exposed for five to 20 years (mean, 12.1 years). Air sampling using personal dust samplers showed a large variation (4-174 mg dust/m$^3$) in individual exposure. Urinary chromium levels were 3-59 μg/l (mean, 9.8 ± 9.2) for exposed workers and 3-6 μg/l (mean, 4.1 ± 1.2) for controls, who were six and seven office workers for the first and second surveys, respectively, and 20 workers in a nonchemical research station for the third. The groups were controlled for smoking, alcohol and coffee intake, and previous exposure to diagnostic radiation or clastogenic drug intake. The three surveys, which gave significantly uniform results, showed an increase in sister chromatid exchange frequency ($p < 0.01$) from 8.11 ± 1.08 in controls (n = 33) to 8.80 ± 1.61 in exposed workers (n = 105). Smoking enhanced the frequency of sister chromatid exchange in the exposed workers ($p < 0.01$) and in controls; however, the difference was not statistically significant. The frequency of aberrant metaphases increased from 3.2 in controls to 4.7 ($p < 0.01$) in exposed workers. Increased frequencies of chromatid gaps (from 2.1% to 3.5%), chromosome gaps (from 0.23% to 0.3%) and chromatid breaks (from 0.2% to 0.3%) were observed ($p < 0.01$ or $p < 0.05$).

## 3.4 Case reports and epidemiological studies of carcinogenicity to humans

### (*a*) *Case reports and descriptive epidemiology*

#### (i) *Case reports*

The most frequent cancer reported in welders has been of the respiratory system (Gobbato *et al.*, 1980; Sheers & Coles, 1980; Bergmann, 1982), but skin cancer has also been reported (Roquet-Doffiny *et al.*, 1977).

#### (ii) *Mortality and morbidity statistics*

Guralnick (1963), using vital statistics, reported on mortality among welders and flame cutters in the USA aged 20-64 in 1950. The standardized mortality ratio (SMR) for all neoplasms was 91 (182 deaths [95% confidence interval (CI), 78-105]), and that for lung, trachea and bronchial cancer was 92 (34 deaths [95% CI, 64-129]). No excess mortality was reported for cancers at other sites.

Logan (1982) analysed cancer mortality by occupation using the statistics of the UK Office of Population Censuses and Surveys. For welders, the SMR for all neoplasms was 57 in 1931 and 126 in 1971; the SMR for lung cancer was 118 in 1951 and 151 in 1971. The Registrar General (Office of Population Censuses and Surveys, 1986) reported mortality by occupation for 1979-80 and 1982-83 in the UK; the SMR for lung cancer was 146 for welders (men aged 20-64).

An excess risk for lung cancer among welders and flame cutters was reported by Milham (1983) in a proportionate mortality analysis for Washington State, USA, for 1950-79, which confirmed his previous results for 1950-71 (Milham, 1976). In 1950-71, increased mortality was found for all neoplasms (257 deaths; proportionate mortality ratio [PMR], 104 [95% CI, 92-118]), for bronchus and lung cancer (67 deaths; PMR, 137 [95% CI, 106-174]) and for urinary bladder cancer (12 deaths; PMR, 162 [95% CI, 89-300]).

Petersen and Milham (1980), using the same method, analysed mortality in the state of California, USA, for 1959-61; no excess of lung cancer was seen among welders and flame cutters.

Menck and Henderson (1976) reviewed all deaths from cancer of the trachea, bronchus and lung occurring in 1968-70 among white males aged 20-64 and all newly diagnosed lung cancer cases registered by the Los Angeles County Cancer Surveillance Program, USA, for 1972-73, in relation to the occupation and industries reported on death certificates or in hospital records. For welders, they found a SMR of 137 based on 21 deaths and 27 newly diagnosed cases [95% CI, 101-182].

Decouflé *et al.* (1977) analysed the information on occupation contained in hospital files of cancer patients at the Roswell Park Memorial Institute in New York, USA, and compared it to that of noncancer patients. Based on 11 cases, the relative risk (RR) for lung cancer associated with occupation as a welder and flame cutter was 0.85 (0.67 when adjusted for smoking). From the same study, Houten *et al.* (1977) reported a nonsignificant RR of 2.5 for stomach cancer for welders and flame cutters, based on three cases.

Gottlieb (1980) analysed the lung cancer deaths occurring in Louisiana, USA, in 1960-75 among employees in the petroleum industry. Using a case-control approach, lung cancer deaths were compared to an equal number of deaths from non-neoplastic diseases. Eight of the cases and two of the controls had been welders [odds ratio, 3.5; nonsignificant].

Morton and Treyve (1982) determined all cases of lung and pleural neoplasms admitted to all 20 hospitals in three Oregon counties during 1968-72. Comparisons were made with information on occupation according to the 1970 US census. The incidence among the occupational category of 'welders, burners, etc.', was 125.8 per $10^5$ as compared with 70.8 per $10^5$ in the male population (comparative incidence, 178).

Death certificates for lung cancer cases from Alameda County, CA, USA, between 1958 and 1962 were analysed in relation to usual occupation by Milne *et al.* (1983), using a case-control approach. Lung cancer deaths were compared to all other cancer deaths occurring in persons over 18 years of age. The odds ratio for welders was 1.2 (nonsignificant), based on five cases and 16 controls.

Mortality among metal workers in British Columbia, Canada, during the period 1950-78 was analysed by Gallagher and Threlfall (1983) from death certificates using a proportionate mortality approach. The PMR for lung cancer (74 deaths; PMR, 145; 95% CI, 115-183) and for Hodgkin's disease (nine deaths; PMR, 242; 95% CI, 110-460) was significantly increased in welders. The PMR for all neoplasms in this group was 114 (207 deaths; 95% CI, 99-132).

Information on occupation contained in death certificates from the state of Massachusetts, USA, between 1971 and 1973 was analysed by Dubrow and Wegman (1984). A statistically significant association was reported between welding and prostatic cancer (standardized mortality odds ratio, 256; 14 deaths).

(*b*) *Cohort studies*

Dunn *et al.* (1960) and Dunn and Weir (1965, 1968) assembled a group of workers employed in 14 occupations in California, USA, and followed them up for mortality. Information was collected from union files and from a self-administered questionnaire reporting a full occupational history and smoking habits for members of the cohort in 1954-57; expected figures were based on age- and smoking-specific rates for the whole cohort. In the latest extension of the follow-up, until 1962, the SMR for lung cancer among 10 234 welders and burners was 105 (49 cases [95% CI, 78-139]). [The Working Group noted that three of the 14 groups used to calculate expected numbers had been exposed to asbestos, and the follow-up of cases was incomplete.]

An industrial population from facilities in Midland, MI, USA, was followed up for mortality by Ott *et al.* (1976). The cohort was constituted of all 8171 male employees between the ages of 18 and 64 on the 1954 employees census list and was followed up through 1973. There were 1214 deaths; 861 employees (10.5%) who remained untraced were assumed to be alive. Expected figures were computed on the basis of the US white male population mortality rates. The overall SMR for welders and lead burners was 98, based on 37 deaths [95% CI, 69-135], and the SMR for all malignant neoplasms was 162, based on 12 deaths [95% CI, 84-283]. No excess was found for cancer at any particular site.

Puntoni *et al.* (1979) followed up subjects who were shipyard workers in Genoa, Italy, employed or retired in 1960, 1970 and 1975 or dismissed or retired during 1960-75. Expected numbers were computed on the basis of mortality among the male population of Genoa. Among oxyacetylene (autogenous) welders, 66 deaths were observed, giving a significantly increased overall mortality (158); four deaths from lung cancer were reported, giving a RR estimate of 125 [95% CI, 34-320]. Overall mortality among electric arc welders was not increased; three deaths from lung cancer were observed, giving a RR estimate of 160 [95% CI, 33-466]. The authors noted that the group was potentially exposed to asbestos.

All white male welders employed in 1943-73 at the Oak Ridge, TN, USA, nuclear facilities were included in a study conducted by Polednak (1981). A total of 1059 subjects were followed up until 1974 and were subdivided in two subgroups: the first (536) was constituted of welders at a facility where nickel-alloy pipes were welded; the second (523) included welders working with mild steel, aluminium and stainless-steel. Data on smoking habits were available from about 1955. US national mortality rates were used for computing expected figures. Mortality from all causes and from all cancers was slightly lower than expected in both subgroups. There was an excess of deaths from lung cancer (17 cases; SMR, 150; 95% CI, 87-240), and the excess was slightly higher in the group of other welders (ten deaths; SMR, 175; 95% CI, 84-322) than in the nickel-alloy welders (seven deaths; SMR, 124; 95% CI, 50-255).

Beaumont and Weiss (1980, 1981) followed up for mortality a cohort of 3247 welders from local 104 of the International Brotherhood of Boilermakers, Iron Ship Builders, Blacksmiths, Forgers and Helpers in Seattle, WA, USA. Subjects were included if they had had at least three years of union membership and at least one of these years between January 1950 and December 1973. Vital status was ascertained as of 1 January 1977. Fifty deaths from lung cancer were observed *versus* 37.95 expected on the basis of US national mortality rates (SMR, 132 [95% CI, 98-174]). For deaths that occurred 20 years or more after first employment, the SMR was 174 (39 cases [95% CI, 124-238]). A re-analysis of the same data by Steenland *et al.* (1986), using an internal comparison group of members of the local union who were not welders and applying two types of regression analyses, yielded similar results.

McMillan and Pethybridge (1983) investigated the mortality of a cohort of welders, boilermakers, shipwrights, painters, electrical fitters and joiners employed for at least six months between 1955 and 1974 at HM Dockyard Devonport, UK, with follow up through 1975. The proportionate mortality of welders was compared to that of the other occupational groups. The PMR for lung cancer was 104 [95% CI, 34-243] based on five deaths. Three deaths from mesothelioma were also reported among the welders. [The Working Group noted that painters were included in the cohort and that there was potential exposure to asbestos.]

Lung cancer mortality in a cohort of foundry workers was investigated by Fletcher and Ades (1984). The cohort consisted of all men hired between 1946 and 1965 in nine steel foundries in the UK and employed for at least one year. The 10 250 members of the cohort were followed up until the end of 1978 and assigned to 25 occupational categories according to information from personnel officers. Lung cancer mortality for the subcohort of welders in the fettling shop was higher than expected on the basis of mortality rates for England and Wales (eight cases; SMR, 146; 95% CI, 62-288); however, for nonwelders in the fettling shop, the SMR was [177] (58 cases).

The mortality of welders and other craftsmen employed at a shipyard in Newcastle, UK, was investigated by Newhouse *et al.* (1985). All employees hired between 1940 and 1968 were included in the study, making a total of 3489 workers, of whom 1027 were welders; these were followed up until the end of 1982. The SMRs for welders compared with the general population of England and Wales were 147 for all causes and 191 for lung cancer. However, when the Newcastle conurbation was taken as a reference, the overall SMR was 114 (195 cases; 90% CI, 100-127), and the SMR for lung cancer was 113 (26 cases; 90% CI, 80-157). In addition, one death from mesothelioma was reported for welders, indicating possible exposure to asbestos.

Becker *et al.* (1985) followed up a cohort of 1221 stainless-steel welders first exposed before 1970 who had undergone the compulsory technical examination for welders in the Federal Republic of Germany. A population of 1694 turners was followed up as a comparison cohort. Smoking histories, as reported by workplace foremen, were similar for the two groups. The overall mortality of the cohort of welders was significantly lower than that of the general population (SMR, 66; based on 77 deaths [95% CI, 52-82]). The SMR for cancer of the trachea, bronchus and lung was 95 (six cases [95% CI, 35-207]) in comparison with the general population. In comparison with turners and assuming a ten-year latency, the welders had an age-adjusted rate ratio for all cancers of 2.4 (95% CI, 1.1-5.1) and a ratio for trachea, bronchus and lung cancer of 1.7 (95% CI, 0.7-4.0). In addition, two deaths from pleural mesothelioma were reported. [The Working Group could not exclude selection bias in the assembly of the cohort; the two deaths from mesothelioma among welders suggest that they were exposed to asbestos.]

Englund *et al.* (1982) linked information from the Swedish Cancer Registry files for 1961-73 to the population census file of 1960. Welders were among the occupational groups for which the incidence of tumours of the nervous system was higher than in the general population, with a standardized incidence ratio (SIR) of 135 based on 50 cases [95% CI, 100-178].

Sjögren and Carstensen (1986) analysed the results of a linkage between the 1960 census file of male welders or gas cutters and the Swedish Cancer registry files between 1961 and 1979. Smoking data from a national survey were used to adjust incidence ratios, and the Swedish male national population was chosen as a reference. A 30% increase in the incidence of cancer of the trachea, bronchus and lung, based on 193 cases, was reported after adjustment for smoking; other sites at which excesses were observed were larynx (22 cases; RR, 1.3) and kidney (70 cases; 1.3). There was a nonsignificant increase in risk for mesothelioma (four cases; 1.5).

The possible associations between intracranial gliomas and occupation were examined by McLaughlin *et al.* (1987), linking information from the 1960 census and the Swedish cancer registry for 1961-79. Expected values were derived from national age- and sex-specific reference rates. An elevated SIR of 140 was found for welders and metal cutters, based on 46 cases [95% CI, 103-187].

Sjögren (1980) and Sjögren *et al.* (1987) studied and subsequently updated the mortality of a small cohort of 234 stainless-steel welders with high exposure to chromium in Sweden. Welders were included in the cohort only if representatives from the company stated that asbestos had not been used or had been used only occasionally and never such as to generate dust. In the extension of the study, a cohort of 208 railway track welders with low levels of exposure to chromium was also included in the design. Only welders with at least five years of employment between 1950 and 1965 were included in the study and followed up until the end of 1984. Expected deaths were calculated using national rates. Both groups were characterized by a low overall mortality (SMRs, 72 and 70, respectively). Mortality from cancer of the trachea, bronchus and lung was increased among welders with high chromium exposure (SMR, 249, based on five deaths; 95% CI, 80-581); the SMR was 33 (one death; 95% CI, 0-184) among welders with low exposure. According to Swedish measurements (Ulfvarson, 1979), stainless-steel welders are exposed on average to about 100 $\mu g/m^3$ Cr associated with use of coated electrodes. The level measured during railroad track (mild steel) welding was usually less than 10 $\mu g/m^3$ Cr (see Table 6).

A large cohort of shipyard and machine shop workers in Finland was followed up for cancer incidence by Tola *et al.* (1988). The cohort included a subset of 1689 welders who had welded mainly mild steel, with no exposure to hexavalent chromium. Only workers employed for at least one year between 1945 and 1960 were included in the study and followed up (99.7% complete) for cancer incidence from 1953 to 1981 through the Finnish Cancer Registry. Smoking habits were ascertained by a postal questionnaire sent to a one-third stratified sample of the members of the cohort or of the next-of-kin of decedents. The expected figures were based on the urban population in the same geographic area. The results did not indicate substantial differences with regard to smoking habits between the study population and the general population. Welders employed in shipyards had a SIR for lung cancer of 115 based on 27 deaths (95% CI, 76-167), and welders employed in machine shops had a SIR of 142 based on 14 deaths [95% CI, 77-237]. For neither of the groups was there an association with time since first exposure.

The International Agency for Research on Cancer has reported (IARC, 1989) the results of a large multicentre cohort study carried out on the working populations of welders employed in 135 companies located in eight European countries. The study included reanalyses of previous studies described above (Becker *et al.*, 1985; Sjögren *et al.*, 1987; Tola *et al.*, 1988) and newly assembled cohorts. The populations of the three previous studies constituted approximately one-third of the total cohort and contributed equally to the different subgroups of welders. A total of

11 092 welders were included in the analysis and followed through 1982-87, depending on the country. The completeness of follow-up was 97%. The SMR for deaths from all causes was 93, based on 1093 deaths (95% CI, 87-98). Mortality from all malignant neoplasms was increased (303 deaths; SMR, 113; 95% CI, 100-126), due mainly to a statistically significant excess of cancer of the trachea, bronchus and lung (116 deaths; SMR, 134; 95% CI, 110-160). Other sites for which excess deaths were seen were larynx (7 deaths; SMR, 148; 95% CI, 59-304), bladder (15 deaths; SMR, 191; 95% CI, 107-315), kidney (12 deaths; SMR, 139; 95% CI, 72-243) and lymphosarcoma (6 deaths; SMR, 171; 95% CI, 63-371). Subjects were assigned to one of three mutually exclusive groups: welding in shipyards, mild-steel welders and ever stainless-steel welders; the latter group also included those who had been predominantly stainless-steel welders. Lung cancer mortality was as follows: welders in shipyards (36 deaths; SMR, 126; 95% CI, 88-174); mild-steel welders (40 deaths, SMR, 178; 95% CI, 127-243); ever stainless-steel welders (39 deaths; SMR, 128; 95% CI, 91-175); and predominantly stainless-steel welders (20 deaths; SMR, 123; 95% CI, 75-190). Lung cancer mortality tended to increase with time since first exposure for mild-steel and stainless-steel welders; this pattern disappeared among mild-steel welders when broken down by duration of exposure and was most evident among predominantly stainless-steel welders, for whom a statistically significant trend was evident ($p < 0.05$): the distributions of observed:expected lung cancer deaths in the four groups of years since first exposure (0-9, 10-19, 20-29, >30) were 2:3.11, 5:5.67, 7:5.54 and 6:1.92, respectively. Five deaths from pleural mesothelioma were reported — one in the shipyard welders, two among mild-steel welders and two among stainless-steel welders (see Table 11). The results for cancer incidence followed the same pattern as those for cancer mortality.

Howe *et al.* (1983) examined the mortality of a cohort of 43 826 male pensioners of the Canadian National Railway company in 1965-77. During this period, 17 838 deaths occurred, and cause of death was ascertained for 94.4% by computerized record linkage to the Canadian national mortality data base. The only occupational information available was on that at the time of retirement. The 4629 individuals who had been exposed to welding fumes showed excess mortality from brain tumours (ten deaths; SMR, 318; 95% CI 153-586).

Stern (1987) pooled 1789 cases of lung cancer and 146 cases of leukaemia reported in epidemiological studies of different designs, most of which are reviewed here. Compared to the expected number of cases as derived from the reviewed publications, a risk ratio of 1.4 was found for respiratory cancer and 0.92 for leukaemia. The risk ratio for acute leukemia, based on 40 cases, was also 0.92.

The risks for lung cancer in the studies described above are summarized in Table 12.

**Table 11. Risks for death from respiratory cancer[a] and from pleural mesothelioma[b] by length of employment and follow-up among subcohorts of welders[c]**

| Study group | 0–19 years since first employment | | | | | | ≥20 years since first employment | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1–9 years' employment | | | ≥10 years' employment | | | 1–9 years' employment | | | ≥10 years' employment | | |
| | Lung cancer | | Meso-thelioma | Lung cancer | | Meso-thelioma | Lung cancer | | Meso-thelioma | Lung cancer | | Meso-thelioma |
| | Obs | SMR | Obs | Obs | SMR | Obs | Obs | SMR | Obs | Obs | SMR | Obs |
| Shipyard welders | 10 | 264 | | 1 | 69 | | 15 | 116 | 1 | 10 | 96 | |
| Mild-steel welders | 8 | 116 | 1 | 7 | 253 | | 10 | 254 | | 15 | 173 | 1 |
| Ever stainless-steel welders | 15 | 115 | | 2 | 67 | | 9 | 145 | | 13 | 157 | 1 |
| Predominantly stainless-steel welders[d] | 5 | 85 | | 2 | 69 | 1 | 2 | 161 | | 11 | 176 | |

[a]Cancers of trachea, bronchus and lung (ICD8, 162)
[b]Additional deaths due to pleural mesothelioma (ICD8, 163), which were not included in calculation of SMR
[c]From IARC (1989)
[d]Subset of ever stainless-steel welders group who were employed in companies with at least 70% of stainless-steel activity or had at least one occupational period of stainless-steel welding only

**Table 12. Lung cancer in welders (cohort studies)[a]**

| Reference (country) | No. of cases observed | SMR, PMR or SIR | 95% CI | Comments |
|---|---|---|---|---|
| Dunn & Weir (1968) (USA) | 49 | 105 | 78–139 | |
| Puntoni *et al.* (1979) (Italy) | 4 | 125 | 34–320 | Autogenous welders; two sets of |
| | | 212 | 58–542 | standard rates used (male population of Genoa and male staff of |
| | 3 | 160 | 33–466 | hospital) |
| | | 254 | 52–743 | Electrical welders; two sets of standard rates used |
| Polednak (1981) (USA) | 17 | 150 | 87–240 | All welders |
| | 7 | 124 | 50–255 | Welders exposed to nickel compounds |
| | 10 | 175 | 84–322 | Other welders |
| Beaumont & Weiss (1981) (USA) | 50 | 132 | 98–174 | |
| McMillan & Pethybridge (1983) (UK) | 5 | 104 | 34–243 | PMR for respiratory cancer (three mesotheliomas) |
| Fletcher & Ades (1984) (UK) | 8 | 146 | 62–288 | |
| Newhouse *et al.* (1985) (UK) | 26 | 113 | 80–157 | Shipyard welders; SMR, 191 when compared with general population of England and Wales (one mesothelioma) |
| Becker *et al.* (1985) (FRG) | 6 | 95 | 35–207 | Stainless-steel welders; expected number based on national mortality statistics |
| | 6 | 1.7 | 0.7–4.0 | Cohort of turners used as controls (two mesotheliomas) (rate ratio) |
| Sjögren & Carstensen (1986) (Sweden) | 193 | 142 | 123–163 | Unadjusted SMR (four mesotheliomas) |
| Sjögren *et al.* (1987) (Sweden) | 5 | 249 | 80–581 | Stainless-steel welders |
| Tola *et al.* (1988) (Finland) | 27 | 115 | 76–167 | Welders in shipyards (SIR) |
| | 14 | 142 | 77–237 | Welders in machine shops (SIR) |

[a]SMR, standardized mortality ratio; SIR, standardized incidence ratio; PMR, proportionate mortality ratio; CI, confidence interval

### (c) *Case-control studies*

Questions relating to employment as a welder or exposure to welding fumes are often included in case-control studies of cancer. In many of these studies, a long list of occupations/exposures is investigated, and any positive association found is likely to be reported; therefore, the possibility of a publication bias toward positive results must be taken into account when reviewing case-control studies.

#### (i) *Lung cancer*

Breslow *et al.* (1954) conducted a case-control study of 518 histologically confirmed lung cancer patients admitted to 11 hospitals in California, USA, in 1949-52, and randomly selected matched controls who were patients of the same age, sex and race admitted to the same hospitals for a condition other than cancer or a chest disease. Interviews for occupational and smoking histories were conducted by persons who were unaware of the case or control status of the interviewee. An elevated RR was seen for welders and sheet-metal workers doing welding, based on 14 cases and two controls [odds ratio, 7.2; 95% CI, 1.9-44.3; smoking-adjusted odds ratio, 7.7].

Blot *et al.* (1978) carried out a case-control investigation among male residents of a coastal area in Georgia, USA. A total of 458 newly diagnosed cases and deaths from lung cancer were compared to 553 controls collected from hospitals or from mortality registries, and matched by vital status, sex, age, race and county of residence. Persons with bladder cancer or chronic lung disease were excluded from among the controls. The results revealed an increased risk for all employment in shipyards but not for welders and burners (RR, 0.7, based on 11 cases and 20 controls).

A similar case-control study was conducted by Blot *et al.* (1980) in coastal Virginia, USA, including 336 deaths from lung cancer and 361 controls deceased from causes other than chronic respiratory diseases in 1976. Information on smoking habits and on occupation was collected by interviewing next-of-kin. Lung cancer risk was slightly elevated among workers in the shipbuilding industry, but an analysis of 11 exposed cases and nine exposed controls showed that welders and burners were not at increased risk [RR, 0.9; 95% CI, 0.4-2.3].

A case-control study of lung cancer among residents of Florence, Italy, by Buiatti *et al.* (1985) included all 376 histologically confirmed cases of primary lung cancer admitted to the main regional hospital in 1981-83. A group of 892 hospital controls of the same sex, age, period of admission and smoking habits was identified, and the ILO classification of occupation and a list of 16 known or suspected carcinogens were used for assessing occupational history. Men who had 'ever worked' in welding had an increased risk (adjusted for smoking), based on seven cases and five controls (odds ratio, 2.8; 95% CI, 0.9-8.5).

Silverstein *et al.* (1985) identified all deaths among members of the United Automobile Workers International Union ever employed at a metal stamping plant between 1966 and 1982 in Michigan, USA. Causes of death were obtained from death certificates, and information on employment from company lists. The data were analysed in a case-control fashion, with cancer deaths as cases and noncancer deaths as controls. Employment as a maintenance welder or millwright was considered to constitute exposure to coal-tar pitch volatiles and welding fumes, and all other occupations were considered to be unexposed. The RR for lung cancer was 13.2 (95% CI, 1.1-154.9), based on three cases. [The Working Group noted that millwrights may be engaged in gas cutting and not exposed to welding fumes in the usually accepted sense.]

Kjuus *et al.* (1986) conducted a case-control study in two industrialized areas of Norway and included 136 newly diagnosed male lung cancer cases and 136 controls identified through the medical files of the main hospital during 1979-83. Forty additional cases and 40 controls were included during the last two years of the study period from another hospital. Patients with obstructive lung disease were excluded from among the controls. Potential exposure to carcinogens was specifically investigated using the Nordic Classification of Occupations, and, for the last two years of the study period, subjects were asked about past exposure to 17 chemical agents and five specific work processes. For subjects already interviewed, exposures were inferred from the available occupational history. An increased risk was found for all welders (RR, 1.9; 95% CI, 0.9-3.7; 28 cases) and for the subset of stainless-steel welders (RR, 3.3; 95% CI, 1.2-9.3; 16 cases) after adjustment for smoking. Half of the cases exposed to stainless-steel welding had also been moderately or heavily exposed to asbestos; when this was taken into consideration in a logistic regression model, risk associated with stainless-steel welding was no longer statistically significant.

Gérin *et al.* (1986) presented preliminary results of a multicancer case-control study in hospitals in the Montréal, Canada, area. Lung cancer patients were used as cases and patients with cancers at 13 other sites as controls; a group of population subjects was also included in the control group. A detailed job-exposure matrix was constructed, and each subject was categorized after direct interview and evaluation of responses by experts in industrial hygiene. Welders were at increased risk for lung cancer (RR, 2.4; 95% CI, 1.0-5.4), based on 12 cases and 20 controls. For ten welders exposed to nickel, the RR was 3.3 (95% CI, 1.2-9.2).

Schoenberg *et al.* (1987) carried out a case-control investigation of lung cancer among white males in six areas of New Jersey, USA. Cases of cancer of the lung, trachea or bronchus were histologically confirmed and ascertained through hospital pathology records, the state cancer registry and death certificates in 1980-81. Controls were matched by age, race, area of residence and (for dead cases) date of death; subjects with respiratory disease were excluded. The study population comprised 763 cases and 900 controls. Information was obtained by personal interview either directly or from next-of-kin, and information on industry and job title was coded according to the 1970 census index system. Occupation as a welder or flame cutter was reported by 38 cases and 38 controls (smoking-adjusted RR, 1.2 [95% CI, 0.8-1.9]). Welders, burners, sheet-metal workers and boilermakers employed in shipyards had a significantly increased risk (RR, 3.5; 95% CI, 1.8-6.6); for those without reported exposure to asbestos, the RR was 2.5 (95% CI, 1.1-5.5).

A population-based case-control study was conducted by Lerchen *et al.* (1987) of 506 primary lung cancer cases reported to the New Mexico (USA) Tumor Registry between 1 January 1980 and 31 December 1982 and 771 controls who were interviewed about their occupational histories and smoking habits. The age-, ethnicity- and smoking-adjusted RR for welders in all industries was 3.2 (95% CI, 1.4-7.4), based on 19 cases and ten controls. When welders ever employed in shipyards were analysed separately, the RR was lower (2.2; 95% CI, 0.5-9.1), based on six cases and three controls, than for welders elsewhere than in shipyards (RR, 3.8; 95% CI, 1.4-10.7), based on 13 cases and seven controls.

Benhamou *et al.* (1988) conducted a case-control study in France of 1260 male lung cancer cases collected in 1976-80 and 2084 hospital controls matched by age, hospital of admission and interviewer. Cases and controls were classified as either nonsmokers or smokers. The RR for welders and flame cutters after adjusting for smoking was 1.4 (95% CI, 0.79-2.9), based on 18 exposed cases and 23 exposed controls.

A nested case-control analysis of deaths due to lung cancer among civilians employed at the Portsmouth Naval Shipyard, Maine, USA, between 1952 and 1977 was conducted by Rinsky *et al.* (1988); the cohort had previously been investigated by Najarian and Colton (1978) and Rinsky *et al.* (1981). Controls without cancer were matched on date of birth, year of first employment and duration of employment. Potential exposure to asbestos and to welding by-products was estimated from the job histories. The study population comprised 405 lung cancer deaths and 1215 controls from within the cohort of shipyard workers. The RR for subjects with probable exposure to welding by-products was 1.1 (95% CI, 0.8-1.7) based on 41 cases and 111 controls. When subjects with potential exposure were also included, the RR was 1.5 (95% CI, 1.2-1.8), based on 236 exposed cases and 597 controls.

A population-based case-control study of lung cancer was conducted by Ronco *et al.* (1988) in two industrialized areas of northern Italy. All 126 deaths from lung cancer occurring among male residents in the area in 1976-80 and a random sample of 384 other deaths (excluding chronic lung conditions and smoking-related cancers) occurring in the same area during the same period were included in the study. Smoking habits and occupational information were collected from next-of-kin by interview (without knowledge of case or control status) using two lists of known and suspected occupational carcinogenic exposures. Subjects never employed in any of the occupations listed were considered to be unexposed. Logistic regression analysis adjusting for age, smoking and other occupational exposure gave a risk estimate of 2.9 (95% CI, 0.87-9.8) for welders, based on six cases.

The studies described above are summarized in Table 13.

**Table 13. Lung cancer in welders (case–control studies)[a]**

| Reference (country) | No. of cases exposed | RR | 95% CI | Comments |
|---|---|---|---|---|
| Breslow *et al.* (1954) (USA) | 14 | 7.2 | 1.9–44.3 | RR, 7.7 adjusted for smoking |
| Blot *et al.* (1978) (USA) | 11 | 0.7 | – | |
| Blot *et al.* (1980) (USA) | 11 | 0.9 | 0.4–2.3 | |
| Rinsky *et al.* (1988) (USA) | 41 | 1.1 | 0.8–1.7 | Probable welding exposure |
| | 236 | 1.5 | 1.2–1.8 | Potential welding exposure |
| Buiatti *et al.* (1985) (Italy) | 7 | 2.8 | 0.9–8.5 | Adjusted for smoking |
| Silverstein *et al.* (1985) (USA) | 3 | 13.2 | 1.1–154.9 | |
| Kjuus *et al.* (1986) (Norway) | 28 | 1.9 | 0.9–3.7 | All welders; adjusted for smoking |
| | 16 | 3.3 | 1.2–9.3 | Stainless-steel welders; adjusted for smoking |
| Gérin *et al.* (1986) (Canada) | 12 | 2.4 | 1.0–5.4 | All welders |
| | 10 | 3.3 | 1.2–9.2 | Welders exposed to nickel |
| Schoenberg *et al.* (1987) (USA) | 38 | 1.2 | 0.8–1.9 | Welders or flame cutters; adjusted for smoking |
| Lerchen *et al.* (1987) (USA) | 19 | 3.2 | 1.4–7.4 | All welders |
| | 6 | 2.2 | 0.5–9.1 | Welders employed in shipyards |
| | 13 | 3.8 | 1.4–10.7 | Welders not employed in shipyards |
| Benhamou *et al.* (1988) (France) | 18 | 1.4 | 0.79–2.9 | Adjusted for smoking |
| Ronco *et al.* (1988) (Italy) | 6 | 2.9 | 0.87–9.8 | Adjusted for smoking |

(ii) *Cancers of the urinary organs*

Howe *et al.* (1980) conducted a population-based case-control study of bladder cancer occurring in Canada in 1974-76 on a total of 632 case-control pairs matched by age, sex and neighbourhood of residence. Occupational histories were collected through direct interview, and two check lists of suspected occupations and substances carcinogenic for the bladder were used to obtain information on exposure. Exposure to welding fumes resulted in a RR of 2.8 (95% CI, 1.1-8.8) based on 17/6 discordant pairs (case ever worked, control never worked/case never worked, control ever worked as welder).

A case-control investigation of the lower urinary tract was conducted by Silverman *et al.* (1983) in the Detroit, USA, area. All histologically confirmed male cases, newly diagnosed from December 1977 to November 1978 in 60 of the 61 hospitals in the area, were included in the study. In total, 303 whites with bladder cancer and 296 population-based randomly selected white controls were included in the analysis. Information on occupation was collected by interview. The RR for the combined group of welders, flame cutters and solderers was 0.6 (95% CI, 0.3-1.0), based on 18 cases and 30 controls. Similar results were found when the analysis was limited to the same category within the motor vehicle manufacturing industry (RR, 0.6; 95% CI, 0.3-1.2; based on 12 cases and 22 controls).

Claude *et al.* (1988) carried out a hospital-based, matched case-control study of cancer of the lower urinary tract in northern Federal Republic of Germany. Cases were identified in the three main hospitals of the region between 1977 and 1985. The occupations of 531 male cases and their matched controls were ascertained. The RR for welders was 1.2 (95% CI, 0.52-2.8), based on 12/10 discordant pairs.

A population-based case-control investigation of bladder cancer was conducted in Canada between 1979 and 1982 by Risch *et al.* (1988). Of the 1251 eligible individuals, 835 (67%) cases were interviewed, with the consent of their physician, and 792 (53%) of the 1483 eligible controls agreed to be interviewed. The authors pointed out that this method might have affected the representativeness of cases and controls. When the data were analysed by the 26 occupations/industries specifically investigated through the questionnaire, employment in welding activities yielded a risk estimate of 1.1 (95% CI, 0.71-1.6).

The association of renal-cell carcinoma with various potential risk factors was studied by Asal *et al.* (1988) in a case-control study of 315 cases and 313 hospital and 336 population controls in the USA. Individuals were classified by occupation only if the period of exposure was one year or longer. The odds ratio for employment as a welder in comparison with population controls was 1.2 (95% CI, 0.7-2.2), based on 29 exposed cases. Results obtained using hospital controls were similar.

(iii) *Cancers at other sites*

A case-control study of *nasal cancer* was carried out in Denmark, Finland and Sweden by Hernberg *et al.* (1983a,b) with 287 cases identified through the national cancer registries between 1977 and 1980. A total of 167 cases (58%) were included in the study when deceased patients or nonrespondents were omitted. An equal number of controls were matched for country, sex and age at diagnosis, and both cases and controls were interviewed by telephone according to a standard protocol. The risk estimate for welding, flame-cutting and soldering was 2.8 (95% CI, 1.2-6.9) based on 17/6 discordant pairs. [See also the monographs on chromium and nickel, pp. 206 and 400-401.]

Following a report by the Danish Occupational Health Agency of a large number of cases of *laryngeal cancer* in welding workplaces, Olsen *et al.* (1984) conducted a case-control study to investigate the role of occupational exposure. All male laryngeal cancer patients newly diagnosed between 1980 and 1982 in the main five hospital departments in the country were included in the study, excluding the cases which prompted the study. For each case, four controls were selected from the same municipal person-registry in which the case was listed. The refusal rate was 4% among cases and 22% among controls, leaving 271 cases and 971 age- and sex-matched controls for the analysis. The RR related to welding, adjusted for age, alcohol and tobacco consumption, was 1.3 (95% CI, 0.9-2.0), based on 42 cases and 115 controls. The risk was highest for cancer located in the subglottic region (RR, 6.3; 95% CI, 1.8-21.6). Separate analysis for welders exposed to stainless-steel welding fumes gave a RR of 1.3 (95% CI, 0.7-2.7), based on 12 cases and 30 controls.

Stern, F.B. *et al.* (1986) carried out a case-control study of deaths due to *leukaemia* within a population of 24 545 male nuclear shipyard workers in Portsmouth, NH, USA, employed between 1952 and 1977 and who had died before 31 December 1980. Controls were selected from among other deaths, and four controls per case were matched by age, data of hire and length of employment; each control should not have died before the case. The entire occupational history of each individual was reconstructed using company files and other industrial sources. The risk estimate for ever having worked in welding was 2.3 (95% CI, 0.92-5.5) for all leukaemia and 3.8 (95% CI, 1.3-11.5) for myeloid leukaemia.

A case-control study of *chronic myeloid leukaemia* was carried out in Los Angeles County, CA, USA, by Preston-Martin and Peters (1988) between 1979 and 1985. Of the 229 eligible cases, 137 (60%) were interviewed by telephone; 130 pairs matched for age, sex and race were eventually included in the analysis. Employment as a welder yielded a crude RR of 19 [95% CI, 2.8-232.5], based on 19/1 discordant pairs.

Norell *et al.* (1986) conducted a case-control study of *pancreatic cancer* in the Stockholm-Uppsala region. Out of 120 eligible cases, 99 (83%) were included in the study. Both hospital- and population-derived controls were selected, with a response rate of 91% for the former and of 85% for the latter group. Information was collected through a self-administered questionnaire and further checked by telephone. The risk estimates for exposure to 'welding materials' were 1.7 (90% CI, 0.9-3.2), based on 13 cases and 27 hospital controls, and 2.0 (90% CI, 0.9-4.3), based on 11 population controls.

Olin *et al.* (1987) conducted a case-control study of *astrocytomas* in Sweden to investigate the possible etiological role of occupational exposures. Incident cases were identified from the two main hospitals in Stockholm and in Uppsala in 1980-81. Both hospital- and population-based controls of the same sex, age and date of diagnosis as the case were included in the study. Of the original 404 study subjects, 367 (91%) were included in the study, comprising 78 cases, 197 hospital controls and 92 population controls. Information was collected through self-administered questionnaire or filled in by the spouse. No increase in risk was reported for welding activities, with risk estimates of 0.6 (95% CI, 0.2-1.7), based on five cases and 15 hospital controls, and 0.2 (95% CI, 0.1-0.7), based on 19 population controls.

A case-control study of workers employed between 1943 and 1977 at two nuclear facilities in Oak Ridge, TN, USA, was conducted by Carpenter *et al.* (1988), in order to examine the possible association of primary *central nervous system cancers* (ICD8, 191, 192) with occupational exposure to chemicals. Job titles/departments were evaluated for potential exposure to 26 chemicals or chemical groups. Seventy-two white male and 17 white female cases were identified; four controls were selected for each case and matched on race, sex, nuclear facility where initially employed, year of birth and year of hire. The odds ratio for 33 cases ever exposed to welding fumes was 1.2 [95% CI, 0.6-2.4].

The hypothesis that childhood cases of *Wilms' tumour* might be related to parental perinatal exposures was tested by Kantor *et al.* (1979) by a case-control approach using the Connecticut (USA) Tumor Registry files for 1935-73. A total of 149 cancer-free controls were identified from health department files and matched to the 149 cases by age, sex and year of birth. Information on the occupation of the father was obtained exclusively from birth certificate files. Welder as the occupation of the father was mentioned on the birth certificates of three cases and no control (not significant).

A similar case-control study of *Wilms' tumour* was conducted by Wilkins and Sinks (1984), using the Columbus, OH, USA, Children's Hospital Tumor Registry files between 1950 and 1981. For each of 105 cases, two children were randomly selected from the Ohio birth certificate files and used as controls after matching for age, sex and race. For no case and for two controls the father's occupation at the time of birth was welder (not significant).

In a further case-control study (Bunin *et al.*, 1989), paternal occupational exposures of 88 cases of Wilms' tumour, obtained from a job-exposure matrix, were compared with those of an equal number of controls, obtained by random digital dialling and matched for date of birth. For a job cluster with exposure to aromatic and aliphatic hydrocarbons, metals and inorganic compounds, elevated crude odds ratios were seen for exposure before conception (5.3, 95% CI 1.5-28.6), during pregnancy (4.3, 95% CI, 1.2-23.7) and after pregnancy (3.3, 95% CI, 0.9-18.8). Within this cluster, the occupation of the father was welder for five cases but for only one control.

# 4. Summary of Data Reported and Evaluation

## 4.1 Exposure data

Welding has been an important industrial process since the early twentieth century and has become widespread since about 1940. A wide variety of welding techniques is used, although most welding is performed using electric arc processes — manual metal arc, metal inert gas and tungsten inert gas welding — all of which have been used for at least 40 years. Although most welding is on mild steel, about 5% is on stainless-steels; welding on stainless-steels can constitute more than 20% of welding in industrial economies. Welding of aluminium and other metals amounts to only a few per cent of the total.

The number of workers worldwide whose work involves some welding is estimated to be about three million.

Welders are exposed to a range of fumes and gases. Fume particles contain a wide variety of oxides and salts of metals and other compounds, which are produced mainly from electrodes, filler wire and flux materials. Fumes from the welding of stainless-steel and other alloys contain nickel compounds and chromium[VI] and [III]. Ozone is formed during most electric arc welding, and exposures can be high in comparison to the exposure limit, particularly during metal inert gas welding of aluminium. Oxides of nitrogen are found during manual metal arc welding and particularly during gas welding. Welders who weld painted mild steel can also be exposed to a range of organic compounds produced by pyrolysis. Welders, especially in shipyards, may also be exposed to asbestos dust.

## 4.2 Experimental carcinogenicity data

Particulates collected from stainless-steel welding fumes were tested by intratracheal instillation in hamsters and by intrabronchial implantation in rats. No treatment-related tumour was seen in rats, and single lung tumours were seen in groups of hamsters receiving manual metal arc stainless-steel welding fume. No study in which animals were exposed to welding fume by inhalation was available for evaluation.

## 4.3 Human carcinogenicity data

Two cohort studies of lung cancer mortality among persons in various occupations did not show significant increases in risk among welders. A total of three pleural mesotheliomas was reported from one of these studies. One large cohort study conducted in the UK showed an almost two-fold excess risk for lung cancer among shipyard welders, which was not confirmed when comparison was made with a local referent population. A moderately increased incidence of lung cancer was found in a large study of shipyard welders in Finland. Five studies conducted in the USA and Europe indicated an increased risk for lung cancer of about 30%.

A large European cohort study, including three cohorts reported previously, detected statistically significant increases in both the incidence of and mortality from lung cancer but demonstrated no consistent difference in cancer risk among stainless-steel welders as compared to mild-steel welders or to shipyard welders. In addition, five deaths were due to mesothelioma.

Of the 12 case-control studies on the association between lung cancer and exposure or employment as a welder, two detected no excess risk. Of the remaining ten, four showed a moderate excess, which was statistically significant in the largest study, conducted in the USA. The other six studies, of welders in various occupations, gave risk estimates exceeding a two-fold increase, which in four of the studies were statistically significant.

Four case-control studies conducted on bladder cancer — two in Canada, one in the USA and one in the Federal Republic of Germany — addressed the possible role of exposures during welding. Only one of the two from Canada reported a significantly increased risk.

Two case-control studies of leukaemia from the USA reported an elevated relative risk for myeloid leukaemia. No overall excess risk for either acute or all leukaemia was observed in a pooled analysis of data from several studies of welders.

Of the case-control studies of cancers at other sites, one on nasal cancer carried out in the Nordic countries, one on laryngeal cancer from Denmark and one on pancreatic cancer from Sweden reported elevated relative risks among welders.

## 4.4 Other relevant data

Welding fumes are retained in the lungs. Experimental studies have shown that sparingly soluble compounds may be released only slowly from the lungs. Elevated concentrations of chromium and nickel are seen in blood and urine, primarily in manual metal arc stainless-steel welders. Airway irritation and metal fume fever are the commonest acute effects of welding fumes. Studies of different groups of welders have documented an increased prevalence of pulmonary function abnormalities, in particular small airway disease, chronic bronchitis and slight abnormalities on chest X-rays, but only minimal indications of pulmonary fibrosis.

Reduced sperm quality has been reported in welders. Decreased fertility was seen in both male and female rats exposed to welding fumes; and the rate of fetal death was increased in pregnant female rats exposed to welding fumes.

One of three studies showed increased levels of sister chromatid exchange and chromosomal aberrations in peripheral blood lymphocytes of workers exposed during stainless-steel welding. The greater frequencies of sister chromatid exchanges were found in exposed workers who smoked.

In a single study, manual metal arc stainless-steel welding fumes injected intraperitoneally caused a mutagenic response in the mouse spot test. No increase in the frequency of sister chromatid exchange in peripheral blood lymphocytes or of chromosomal aberrations in lymphocytes or bone-marrow cells was observed in one study in rats after inhalation of stainless-steel or mild-steel welding fumes.

Both positive and negative results were obtained in tests for gene mutation in cultured mammalian cells exposed to stainless-steel welding fumes (manual metal arc). Stainless-steel welding fumes (manual metal arc and metal inert gas) induced transformation of mammalian cells *in vitro* in a single study. The frequencies of chromosomal aberrations and of sister chromatid exchange were increased in mammalian cells exposed *in vitro* to stainless-steel welding fumes (manual metal arc or metal inert gas). In a single study, mild-steel welding fumes (manual metal arc) increased the frequency of sister chromatid exchange but not of chromosomal aberrations in the same system. Fumes from the manual metal arc welding of mild steel or cast iron using a nickel electrode increased the frequency of sister chromatid exchange, but not of chromosomal aberrations, in mammalian cells *in vitro*.

Fumes from the manual metal arc or metal inert gas welding of stainless-steel and from manual metal arc welding of mild steel, but not the fumes from metal inert gas welding on mild steel or from mild steel welding on cast iron using a nickel electrode, were mutagenic to bacteria.

## 4.5 Evaluation[1]

There is *limited evidence* in humans for the carcinogenicity of welding fumes and gases.

There is *inadequate evidence* in experimental animals for the carcinogenicity of welding fumes.

### Overall evaluation

Welding fumes *are possibly carcinogenic to humans* (Group 2B).

[1]For definition of the italicized terms, see Preamble, pp. 33-37.

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