III. CHARACTERISTICS OF WELDING PROCESSES

A. Identification of Processes

More than 80 different types of welding and allied processes are in commercial use, including brazing and thermal cutting (Figure III-1). The most commonly used processes are briefly discussed in this section. Definitions for types of welding processes appear in the Glossary. Appendix D lists industries that employ welders, brazers, and cutters, along with their respective standard industrial classification (SIC) codes.

1. Arc Welding

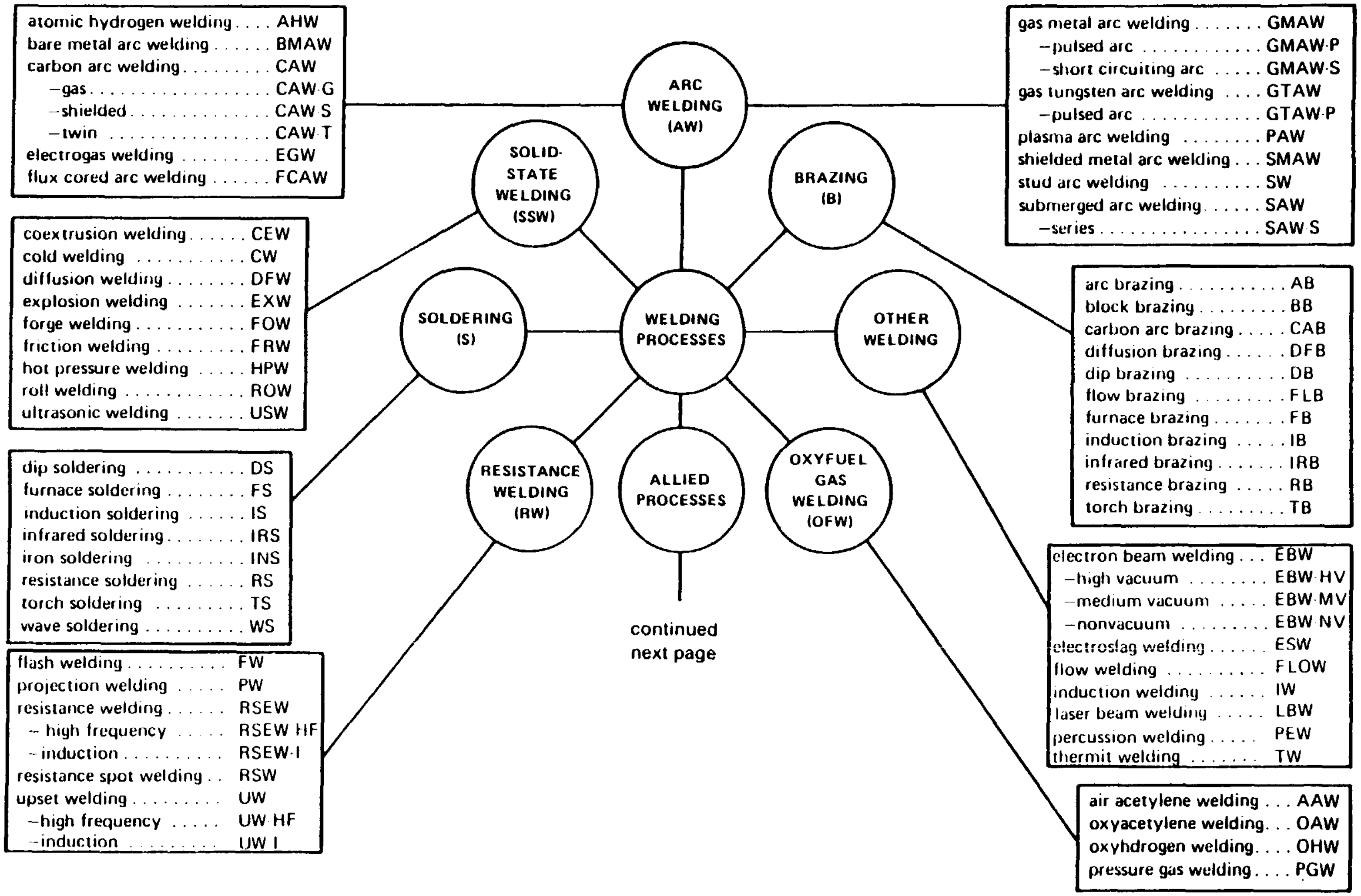
In arc welding, heat is created as electricity flows across a gap between the tip of the welding electrode and the metal. Arc welding is the most frequently used process. It encompasses numerous variations, depending on the types of electrodes, fluxes, shielding gases, and other equipment that may be used. The arc welding process involves the melting of an electrode by an electric current to form a molten puddle in the base metal. Because of the generated heat, the base metal also becomes molten at the joining surfaces, which bond upon cooling.

Electrodes are manufactured as bare wire or as wire lightly to heavily coated with flux material. Bare wire electrodes are the least expensive, but they are difficult to maintain, and they produce an inferior weld. Also, a coating of copper on filler materials may be used in place of a flux to prevent oxidation of the material before use. Flux material generally consists of asbestos, feldspar, fluorine compounds, mica, steatite (a form of talc), titanium dioxide, calcium carbonate, magnesium carbonate, or various aluminas. The flux prevents or removes oxides or other undesirable substances from the weld. Inert shielding gases such as helium, argon, or carbon dioxide are used in some variations of arc welding. These variations of arc welding are often referred to as shielded metal arc, metal inert gas, and plasma arc welding. The inert gas prevents oxygen and active chemicals in the atmosphere from reacting with the hot metal [AWS 1976].

2. Oxyfuel Gas Welding

Oxyfuel gas welding is the process by which heat from burning gases is used to melt the base metal without the use of welding rods; however, rods are used when extra metal is needed as a filler to obtain a complete bond. The composition of these consumable rods is very similar to that of the base metals. Some are coated with flux, the composition of which depends on the application.

MASTER CHART OF WELDING AND ALLIED PROCESSES



atomic hydrogen welding	AHW
bare metal arc welding	BMAW
carbon arc welding	CAW
–gas	CAW-G
–shielded	CAW-S
–twin	CAW-T
electrogas welding	EGW
flux cored arc welding	FCAW

coextrusion welding	CEW
cold welding	CW
diffusion welding	DFW
explosion welding	EXW
forge welding	FOW
friction welding	FRW
hot pressure welding	HPW
roll welding	ROW
ultrasonic welding	USW

dip soldering	DS
furnace soldering	FS
induction soldering	IS
infrared soldering	IRS
iron soldering	INS
resistance soldering	RS
torch soldering	TS
wave soldering	WS

flash welding	FW
projection welding	PW
resistance welding	RSEW
– high frequency	RSEW-HF
– induction	RSEW-I
resistance spot welding	RSW
upset welding	UW
–high frequency	UW-HF
–induction	UW-I

gas metal arc welding	GMAW
–pulsed arc	GMAW-P
–short circuiting arc	GMAW-S
gas tungsten arc welding	GTAW
–pulsed arc	GTAW-P
plasma arc welding	PAW
shielded metal arc welding	SMAW
stud arc welding	SW
submerged arc welding	SAW
–series	SAW-S

arc brazing	AB
block brazing	BB
carbon arc brazing	CAB
diffusion brazing	DFB
dip brazing	DB
flow brazing	FLB
furnace brazing	FB
induction brazing	IB
infrared brazing	IRB
resistance brazing	RB
torch brazing	TB

electron beam welding	EBW
–high vacuum	EBW-HV
–medium vacuum	EBW-MV
–nonvacuum	EBW-NV
electroslag welding	ESW
flow welding	FLOW
induction welding	IW
laser beam welding	LBW
percussion welding	PEW
thermit welding	TW

air acetylene welding	AAW
oxyacetylene welding	OAW
oxyhydrogen welding	OHW
pressure gas welding	PGW

continued next page

Figure III-1.--Welding and allied processes. (Copyright by the American Welding Society, 550 LeJeune Road, P.O. Box 351040, Miami, Florida 33135; reprinted with permission.)

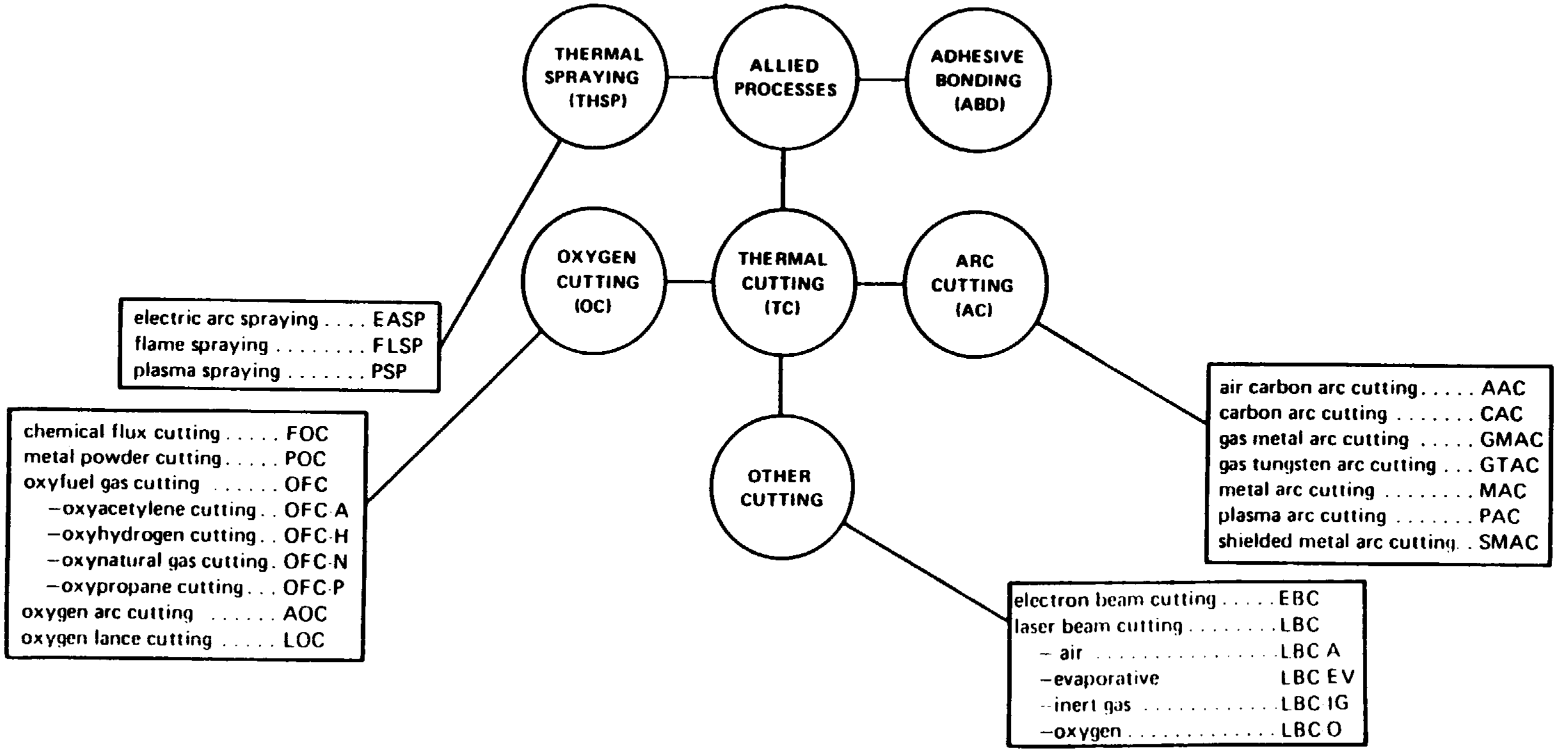


Figure III-1 (Continued).--Welding and allied processes. (Copyright by the American Welding Society, 550 LeJeune Road, P.O. Box 351040, Miami, Florida 33135; reprinted with permission.)

3. Resistance Welding

Resistance welding is a process in which pieces of metal are pressed together and an electric current is passed through them. At the contact point, there is sufficient resistance to cause an increase in temperature and melting of the metal.

4. Brazing

Brazing is the process by which metals are heated and joined together by a molten filler metal at temperatures exceeding 450°C (840°F) [AWS 1980]. Soldering, which is not included in this document, is similar to brazing, but it uses filler metals that have melting points below 450°C. The filler metal used in brazing may be in the form of wire, foil, filings, slugs, powder, paste, or tape. Fluxes must be used unless the process is performed in a vacuum, since oxidation of the brazed area will weaken the bond. The most common ingredients of fluxes are borates (e.g., lithium, potassium, and sodium), fused borax, fluoroborates (e.g., potassium and sodium), fluorides (e.g., lithium, potassium, and sodium), chlorides (e.g., lithium, potassium, and sodium), acids (e.g., boric acid and calcined boric acid), alkalis (e.g., potassium hydroxide and sodium hydroxide), and water (either as water of hydration or as an addition for paste fluxes) [AWS 1963].

5. Thermal Cutting

Thermal cutting includes processes that cut the metal by melting. These processes are divided into two main groups: oxygen and arc cutting. Oxygen cutting is performed on plain carbon, manganese, and low-chromium-content steels. When the metal is heated and exposed to oxygen, it oxidizes and melts. Flame cutting uses a fuel gas (or a combination of gases) such as acetylene, hydrogen, natural gas, or propane that burns and produces sufficient heat to vaporize and separate the metal. Arc cutting is used with nonferrous metals, stainless steels, or steels with a high chromium or tungsten content [AWS 1980].

B. Potential for Exposure

Welding, brazing, and thermal cutting processes generate exposures to many chemical and physical agents. Chemical and physical agents produced by these processes are described in the following sections, which identify the source, mechanism of production, disposition, and exposure concentrations found in many occupational environments. The potential exists for other confounding exposures (e.g., asbestos and heat) in the work environment of welders and needs to be assessed for each welding process.

1. Fumes and Other Particulates

A fume is generated by volatilization of melted substances with subsequent condensation of solid particles from the gaseous state [Dinman 1978]. For the processes discussed in this document, temperatures may range from about 450°C (840°F) for brazing [AWS 1980] to well above 15,000°C (27,000°F) for plasma arc cutting [Grimm and

Kusnetz 1962; Siekierzynska and Paluch 1972]. The single largest source of fumes is the filler metal being used [Jones 1967; Heile and Hill 1975].

Fumes may also originate from the base metal [Jones 1967], from coatings applied to the base metal [Pegues 1960; Oliver and Molyneux 1975], and from the flux or electrode coating [Thrysin et al. 1952]. Fume particles typically have a diameter of less than 1 micrometer (μm) [Hewitt and Hicks 1973; Heile and Hill 1975; Akselsson et al. 1976].

Fumes are not the only sources of airborne particulates. Fluxes and filler metals used in powdered form (e.g., in submerged arc welding and furnace brazing) may enter the air as fugitive dusts. Mineral and metal dusts may also be produced when material is pulverized during the cleaning of welds and brazes by surface brushing or grinding [Moreton et al. 1975]. Historically, the potential has also existed for asbestos exposure during welding processes. These exposures often occurred as a result of using materials that contained asbestos, disturbing asbestos insulation while welding, or working near other operations that used asbestos.

Steel and Sanderson [1966] investigated the composition of welding fumes to determine the extent of impurities that may be present in fluxes. Flux that is formulated into a coating for stick electrodes may generate shielding gas, produce slag, alloy with rods, or act as binders. In one of their experiments, these investigators conducted shielded metal arc welding on mild steel in a test chamber using 12 different commercial electrodes. Air samples were collected at a distance from the source of exposure that corresponded to the breathing zone of a welder standing upright. On several occasions, fume concentrations exceeded NIOSH RELs for lead and vanadium pentoxide. Chromium(VI), copper, and manganese were also detected.

The chemical composition of the airborne fumes generally reflects the elemental composition of the base and filler metals and the flux, but the fume components may have different chemical forms. Thus concentrations of the various fume components may vary for each job and process and are best determined on a case-by-case basis.

a. Alkali Metals and Alkaline Earths

The airborne concentrations of calcium, magnesium, potassium, and sodium are significantly greater in the emissions from lime (low-hydrogen) electrodes than in those from nonlime electrodes [Morita and Tanigaki 1977; Kimura et al. 1974]. Although concentrations vary greatly within the two classes, low-hydrogen electrodes generally produce higher concentrations of calcium, magnesium, potassium, and sodium in their fumes.

b. Aluminum

Aluminum is generally found in small quantities in the fumes from all types of electrodes, both low-hydrogen and non-low-hydrogen.

Morita and Tanigaki [1977] reported a range of 0.21% to 1.44% aluminum (as Al_2O_3), and Kimura et al. [1974] noted a range of 0.1% to 0.8% in the fumes for all electrodes tested.

c. Beryllium

Bobrishchev-Pushkin [1972] evaluated the composition of fumes produced by the electron beam welding of beryllium bronze. The welding was done in a vacuum chamber that was flushed with air before opening. The purged air was filtered, and the collected fumes were analyzed for beryllium. As in most electron beam welding, two pieces of base metal (2% beryllium content) were joined without the use of a filler metal. Samples of the purged air contained detectable amounts of beryllium in only 5 of the 44 samples. However, periodic cleaning by dry scrubbing of the vacuum chamber walls caused redispersion of fumes that contained beryllium concentrations of 130 to 150 $\mu g/m^3$ in the chamber and 4 $\mu g/m^3$ in the breathing zones of welders working outside the chamber.

d. Cadmium

Cadmium concentrations in the breathing zone have been reported to be 10 to 250 $\mu g/m^3$ during shipboard brazing with a silver- and cadmium-based filler metal [Oliver and Molyneux 1974]. Cadmium-bearing alloys are used in more than 50% of all brazed joints [Timmins et al. 1977].

e. Chromium

Both the chromium concentration and its oxidative state vary within the fumes depending on the welding or cutting process and the base metal. Virtamo [1975] compared fume composition in shielded metal arc welding, gas tungsten arc welding, gas metal arc welding, and plasma arc cutting. These operations were performed on high-alloy, nickel-chromium stainless steel to determine the relative amounts of nickel, chromium(VI), and total chromium evolved in the fumes. Analysis of breathing zone samples indicated the following:

- Shielded metal arc welding produced the highest water-soluble chromium(VI) fume concentrations--as high as 720 $\mu g/m^3$.
- Gas tungsten arc welding produced chromium(VI) concentrations below the 10-$\mu g/m^3$ detection limit in 8 of 10 samples (the highest concentration found was 45 $\mu g/m^3$).
- No chromium(VI) was detected during plasma arc cutting or gas metal arc welding.

While surveying Swedish worksites, Ulfvarson [1981b] found higher chromium concentrations with shielded metal arc welding than with gas metal arc welding on stainless steel. The median breathing zone concentration of chromium [almost all soluble chromium(VI)] was

150 $\mu g/m^3$ at 86 worksites where shielded metal arc welding was performed. For gas metal arc welding, the median breathing zone concentration of chromium (mostly insoluble) was about 20 $\mu g/m^3$ at 41 worksites.

At a large maintenance shop, Arnold [1983] assessed the exposures of three groups of welders. The first group performed gas tungsten arc and gas metal arc welding. Their breathing zone samples all contained <6 $\mu g/m^3$ of chromium(VI). Group II performed shielded metal arc welding and had breathing zone concentrations of chromium(VI) that averaged 14 $\mu g/m^3$, with a high of 90 $\mu g/m^3$. Group III used a variety of welding methods--mostly shielded metal arc welding (including flux cored arc and gas metal arc welding). Within this group, the average chromium(VI) concentration was 64 $\mu g/m^3$, with a high of 329 $\mu g/m^3$.

Both Lautner et al. [1978] and Ulfvarson [1981b] found that shielded metal arc welding produced the highest percentage of chromium(VI) in the fumes. When electron spectroscopy was used for chemical analysis (ESCA), gas metal arc and gas tungsten arc welding of stainless steel produced only traces of chromium(VI) (concentrations too small to be quantified). Shielded metal arc welding generated 73% of the total chromium in the fumes as chromium(VI) (mean net mass = 1,016 μg chromium(VI)/filter).

f. Fluorides

The inclusion of fluorspar in low-hydrogen (lime) electrodes produces significant amounts of fluoride compounds in welding fumes. In a study conducted by Kimura et al. [1974], welding fumes contained 11% to 18% fluoride. Another study [Persinger et al. 1973] reports that the fumes contained 14% to 23% fluoride when low-hydrogen electrodes were used for shielded metal arc welding on mild and high-tensile steel. Tebbens and Drinker [1941] found that high-alloy electrodes containing 1 to 5 mg fluoride per electrode generated fumes that contained 9% to 26% fluoride compounds. This high percentage was partly due to the low melting points of the fluoride compounds. Only negligible amounts of hydrogen fluoride were detected in the welding emissions.

g. Iron

Iron is the main constituent of the fume when welding is performed on non-alloy steel. Dreesen et al. [1947] studied arc welders in steel ship construction and reported welding fumes with iron concentrations above 20 mg/m^3. Ulfvarson [1981b] collected breathing zone samples for welders performing shielded metal arc and gas metal arc welding. The geometric mean concentration for iron was 14 mg/m^3 during the welding of unpainted non-alloy steel and 30 mg/m^3 during the welding of painted non-alloy steel. Akbarkhanzadeh [1979] surveyed British worksites (mostly shipyards) where shielded metal arc welding was being performed on mild steel. The mean concentration of iron (ferric oxide) from 209 breathing zone samples was 2 mg/m^3. The iron concentration increased linearly with increasing arc current (correlation coefficient = 0.323, $p<0.001$). Kleinfeld et al. [1969] sampled welders while they performed oxyfuel cutting and shielded metal arc welding; they found concentrations of iron oxide ranging from 0.65 to 1.7 mg/m^3 inside the welders' face shields and from 1.6 to 12 mg/m^3 outside the face shield.

h. Lead

Because zinc may contain lead as an impurity, significant amounts of lead can be generated when welding zinc-primed steel or steel that has been hot-dipped in zinc. Pegues [1960] determined lead concentrations from air samples collected in the breathing zone of workers performing oxyacetylene cutting and arc welding on zinc-coated steel. Welding was performed in a confined space without ventilation on steel that was protected by hot-dip galvanization and on steel that was painted with zinc silicate. During arc welding, breathing zone concentrations of lead ranged from 0.9 to 15.2 mg/m^3 with the zinc-silicate-coated steel, and from 0.4 to 0.7 mg/m^3 with the galvanized steel. During oxyacetylene welding, lead concentrations ranged from 1.2 to 3.5 mg/m^3 with the zinc-silicate-coated steel, and from 0.2 to 0.7 mg/m^3 with the galvanized steel.

i. Manganese

Akbarkhanzadeh [1979] collected breathing zone samples from welders performing shielded metal arc welding of mild steel coated with an unspecified primer and found average manganese fume concentrations of 0.14 mg/m^3. By comparison, breathing zone samples from welders performing shielded metal arc and gas metal arc welding had average manganese concentrations of 3.1 mg/m^3 during welding on primed mild steel and 1.4 mg/m^3 during welding on unprimed mild steel [Ulfvarson 1981].

The percentage of manganese in welding fumes was reported to be relatively independent of the type of electrode [Kimura et al. 1974; Morita and Tanigaki 1977]. In a study of 61 brands of electrodes of different composition [Morita and Tanigaki 1977], the level of manganese oxide (MnO) in the fume ranged from 2.5% to 9.5%. In a similar study of 25 brands of electrodes, Kimura et al. [1974] observed fumes containing 3.3% to 11.2% manganese as MnO. Fumes from ilmenite electrodes tended to have higher concentrations of manganese compared with those generated from lime electrodes.

j. Nickel

Virtamo [1975] assessed the nickel content of fumes generated from shielded metal arc welding, gas metal arc welding, and plasma arc cutting of stainless steel. Shielded metal arc welding produced nickel concentrations that ranged from trace amounts to 160 μg/m^3; gas metal arc welding produced concentrations as high as 60 μg/m^3; and plasma arc cutting produced concentrations up to 470 μg/m^3. When Ulfvarson et al. [1981] surveyed welders who were performing shielded metal arc and gas metal arc welding of stainless steel, a median breathing zone concentration of approximately 25 μg nickel/m^3 was determined for shielded metal arc and approximately 5 μg nickel/m^3 for gas metal arc welding. Bernacki et al. [1978] reported an average airborne concentration of 6 μg nickel/m^3 (with a high of 46 μg nickel/m^3) from welding nickel-alloyed steel. Wilson et al. [1981] examined various maintenance welding operations at a chemical plant and found that the highest nickel concentrations were produced when welding was conducted on stainless steel inside distillation towers. Airborne concentrations of nickel from 22 of 23 samples exceeded the NIOSH REL of 15 μg/m^3. The mean concentration of nickel was 3.65 μg/m^3, with a high of 17.6 μg/m^3.

k. Silica

Silica in welding fumes originates from the coating on the electrode, which varies in quantity depending on the type of electrode used. Twenty-six brands of ilmenite and lime titania electrodes produced fumes containing 18% to 22% silicon as silicon dioxide (SiO_2); two brands of iron powder/iron oxide electrodes produced fumes containing 8% and 12% SiO_2; and 10 brands of lime electrodes produced fumes containing 4% to 11% SiO_2 [Kimura et al. 1974].

In a study of 61 brands of electrodes, Morita and Tanigaki [1977] observed that the mean silica contents of fumes were as follows: (1) 33% for 7 high-titania and iron powder/iron oxide electrodes, (2) 22% for 26 brands of ilmenite and lime titania electrodes, (3) 12% for 1 high-cellulose electrode produced, and (4) 6% for 27 low-hydrogen electrodes.

Tebbens and Drinker [1941] observed the presence of silica in fumes generated from the shielded metal arc welding of mild steel. Silica and silicates are commonly used ingredients in fluxes on mild-steel-covered electrodes. When two such electrodes were tested, one generated fumes containing 15% crystalline silica plus a high silicate content; fumes from the other contained no crystalline silica but were high in silicates. The two electrodes generated comparable amounts of silicon (18% to 22% of the total fume), which was present as soluble silicates or amorphous silica. X-ray diffraction was used to confirm the absence of crystalline silica.

l. Titanium

In two studies [Morita and Tanigaki 1977], ilmenite, lime titania, and high-titania electrodes generated similar percentages of titanium in fumes. In the first study, 30 of these types of electrodes produced a range of 0.6% to 2.3% titanium as titanium dioxide (TiO_2). When 30 different brands of iron oxide/iron powder and low-hydrogen electrodes were tested in that same study, a range of 0.1% to 0.4% TiO_2 was found in the fume. The second study [Kimura et al. 1974] examined 25 brands of electrodes. Thirteen brands of ilmenite, lime titania, and titania electrodes produced a range of 0.6% to 5.5% TiO_2 in the fume; the remaining 12 iron powder/iron oxide and lime electrodes generated fumes containing 0.2% to 0.9% TiO_2.

m. Zinc

In a study of oxypropane flame cutting and shielded metal arc welding in a shipyard [Bell 1976], fumes containing zinc were generated from the protective coating on the metal. Breathing zone concentrations ranged from no detectable zinc to 8.6 mg/m^3. Shielded metal arc welding of metal plate treated with zinc powder and zinc chromate primers produced fumes containing up to 74 mg zinc/m^3 when ventilation was poor. A report on fumes from welding and flame cutting processes in the shipbuilding and ship-repairing industry [IIW 1970] showed breathing zone zinc concentrations as high as 44 mg/m^3. Ulfvarson [1981b] collected breathing zone samples from welders who were gas metal arc welding on mild steel that was either untreated or coated with a zinc tetraoxychromate/iron oxide primer. Samples collected during the welding of untreated steel had a mean zinc concentration of 0.11 mg/m^3, and those collected during the welding of primer-coated steel had a mean zinc concentration of 0.43 mg/m^3. Dreesen et al. [1947] reported zinc concentrations in area samples that exceeded 12 mg/m^3 (15 mg/m^3 expressed as zinc oxide) in welding fumes produced from arc welding on steel during ship repair. Pegues [1960] (see subsection 1,h, Lead, of this chapter) analyzed fume samples collected from workers performing oxyacetylene cutting and arc welding on zinc-coated steel in a confined space without ventilation. Steel that had two types of zinc-coatings (e.g., zinc silicate and galvanized steel) were evaluated to determine the generation of zinc in the fumes. The zinc-silicate-coated steel produced a mean zinc concentration of 19.81 mg/m^3 during electric arc welding and 12.28 mg/m^3 during oxyacetylene cutting. Electric arc welding of galvanized steel produced a mean zinc concentration of 6.63 mg/m^3. No exposures to zinc were detected during oxyacetylene cutting.

2. Specific Gases

A number of toxic gases such as carbon monoxide, oxides of nitrogen, ozone, and various photochemical and pyrolytic decomposition products of halogenated hydrocarbons are present or produced by chemical reactions during welding. Fuel gases that may be released (such as propane, acetylene, and hydrogen) are asphyxiants. These gases and oxygen may combust during use [Occupational Health (London) 1975]. The lower explosive limits (LELs) for some of these gases are quite low--for example, 2.3% for propane, 4.1% for hydrogen, and 2.5% for acetylene. Oxygen is hazardous at higher than normal concentrations because it increases the flammability of materials (e.g., clothes) [Jefferson 1970].

Shielding gases such as argon, nitrogen, helium, and carbon dioxide (CO_2) may also be present. Alone, these gases do not normally pose a hazard; however, in confined spaces they may displace the oxygen-containing air and give no warning of oxygen deficiency because they are odorless and colorless.

Many of the gases that may be encountered during various welding processes are listed below with information on their source of generation and reported concentrations.

a. Carbon Monoxide

Carbon monoxide CO exposures often result from the reduction of CO_2 used for shielding in gas metal arc welding. de Kretser et al. [1964] found CO concentrations often approaching 300 ppm when CO_2 exposures were measured at 1400 parts per million (ppm) during gas metal arc welding. Ulfvarson [1981b] found CO exposures to be sporadic and at low concentrations in many Swedish work sites except where gas metal arc welding was being done. At the latter sites, about 10% of the measurements had CO readings above 50 ppm, with peak readings of 150 ppm. Press and Florian [1983] found that for gas metal arc welding, CO concentrations increased as the percentage of carbon dioxide was increased in the shielding gas.

Erman et al. [1968] measured CO concentrations in poorly ventilated confined spaces during shipbuilding operations. Welding was done on steel with CO_2 gas metal arc welding. CO concentrations increased as the duration of welding increased. In a space of 4.9 m^3, CO concentrations exceeded 160 mg/m^3 (145 ppm) within 40 min. Ulfvarson et al. [1981a] assessed the generation of CO during flame cutting of primed steel. They found that in a laboratory setting, CO concentrations up to 35 ppm were generated when the ventilation was poor. Flame cutting of primed steel during ship repair and construction in confined spaces produced CO concentrations exceeding 100 ppm.

b. Oxides of Nitrogen

An arc or a very high-temperature flame may cause the oxygen and nitrogen in the air to combine and form oxides of nitrogen. One combustion product, nitrogen dioxide (NO_2), has been detected in shielded arc welding, oxyacetylene welding, arc gouging [Fay et al. 1957], gas metal arc welding [Erman et al. 1968], submerged arc welding, and oxyacetylene and oxypropane cutting [IIW 1970].

Tests performed with tungsten electrodes produced 0.3 to 0.5 ppm of nitrogen oxides with helium shielding and 2.5 to 3.0 ppm with argon shielding. The higher concentrations for both were obtained when the shield gas flow rate was doubled.

Ferry and Ginther [1953] found lower NO_2 concentrations for oxyacetylene welding, argon-shielded gas metal arc welding, and carbon arc gouging. The authors speculated that the increase in current for gas metal arc welding produced the higher NO_2 concentrations. Akbarkhanzadeh [1979], however, found no relationship between the current and the generation rates for nitrogen oxides when shielded metal arc welding was performed on mild steel. Ferry and Ginther [1953] observed that nitrogen dioxide concentrations were always greatest in the area of visible fume (within 0.15 m of the arc). At greater distances from the arc, the concentrations decreased in all directions except in the direction of the fume stream. The authors suggested that NO_2 is formed thermally and diffuses away from the arc. In a study [IIW 1980] that used oxyacetylene welding, flame size was an important factor in the generation of nitrogen oxides. Generation rates for nitrogen oxides were 10 times higher with an unrestricted flame length than with a 10-mm flame. In addition, increasing blowpipe size from 1 to 8 produced dramatic increases in nitrogen oxide concentrations. Ventilation that is adequate to control exposures to total fumes is sufficient to control nitrogen oxide exposures [Ferry and Ginther 1953; Akbarkhanzadeh 1979; IIW 1980].

Octavian and Nicolae [1968] observed that nitrogen oxides are formed at a distance from plasma arc cutting or argon-shielded arc welding, with maximum formation rates at 1.75 to 2.5 m and 4 m, respectively. Nitrogen oxide concentrations were determined by drawing air through a quartz tube at various distances from the welding operations and therefore measuring only those oxides formed by UV radiation.

Press [1976] found that for plasma arc cutting of aluminum alloys with an argon/hydrogen mixture, the highest measured concentrations were 2 ppm for NO_2 and 9 ppm for nitrous oxide (N_2O). Both concentrations were determined in the absence of ventilation. Siekierzynska and Paluch [1972] examined emission rates of nitrogen oxides for plasma arc cutting on various base metals that were 0.5 mm thick. Although N_2O concentrations were not given, generation rates were reported to be very similar for cutting mild steel (150 mg/sec), alloy steel (140 mg/sec), copper (70 mg/sec), brass (80 mg/sec), and aluminum (70 mg/sec). The NO_2 emission rates were 50 mg/sec for mild steel, 40 mg/sec for alloy steel, 45 mg/sec for copper, 50 mg/sec for brass, and 40 mg/sec for aluminum. Concentrations as high as 100 ppm have been reported [Maddock 1970; Mangold and Beckett 1971].

c. Ozone

In the presence of UV light, atmospheric oxygen can convert to ozone [Lunau 1967]. Among the various welding processes, gas metal arc and gas tungsten arc welding produce the highest ozone concentrations, especially when aluminum is used as a base metal [Lunau 1967; Press and Florian 1983; Ditschun and Sahoo 1983].

In studies of argon-shielded arc welding of aluminum, Lunau [1967] found that after 3 to 5 min with a 200-ampere (A) current density, ozone concentrations averaged 5.1 ppm; with a 250-A current density, ozone was 7.5 ppm; and with a 300-A current, ozone was 8.4 ppm. All concentrations decreased over time because of strong thermal upcurrents formed from the heat during welding. Shironin and Dorosheva [1976] also found an increase in ozone concentrations with increasing current density. With continuous argon-shielded arc welding, breathing zone samples collected from welders indicated an average ozone concentration of 0.6 mg/m^3 when an 80-A current density was used. This concentration increased to 1.0 mg/m^3 at a 300-A current density; with pulsed arcing, the concentrations were 0.5 mg/m^3 for a 50% duty cycle and 0.7 mg/m^3 for a 75% duty cycle. When Ditschun and Sahoo [1983] assessed the generation of ozone during gas metal arc welding of copper-nickel and nickel-aluminum bronze alloys, ozone concentrations varied from 0.07 to 0.19 ppm.

Ferry and Ginther [1953] found that when argon-shielded gas tungsten arc welding was performed on a copper block, the breathing zone concentration of ozone was 0.1 ppm with a 55-A current and 0.5 to 0.6 ppm with a 110-A current. When a helium shield was used, the ozone concentration was 0.1 ppm with either current level.

The spatial distribution of ozone concentrations has been studied under various conditions [Fay et al. 1957; Frant 1963; Lunau 1967]. Ozone generation diminished as the distance from the arc increased [Lunau 1967]. In argon-shielded gas tungsten arc welding of aluminum, ozone concentrations were consistently higher than with argon-shielded gas metal arc welding. The author postulated that the high-energy (short-wavelength) UV rays resulting from gas tungsten arc welding caused more ozone formation.

Fay et al. [1957] also found that ozone concentrations were higher at 0.15 m from the arc in argon-shielded gas metal arc welding than at 0.60 m. However, the opposite was observed with argon-shielded gas tungsten arc welding, regardless of the metal welded or the current used. Frant [1963] also studied ozone concentrations in argon-shielded gas tungsten arc welding but found that the rate of ozone formation measured in a quartz tube was 10 times higher at 0.2 m than at 0.5 m from the arc.

Ferry and Ginther [1953] found that the shielding gas had a decided effect on ozone formation. Changing from argon to helium in gas tungsten arc welding caused ozone concentrations in the breathing zone to decrease from 0.5-0.6 ppm to 0.1 ppm regardless of the current level. Frant [1963] observed a similar reduction when using a CO_2 shield. In gas metal arc welding of steel, argon shielding produced 33 μg ozone/min, and carbon dioxide shielding produced 7 μg ozone/min when measured in a quartz tube placed 30 cm from the arc.

Several authors have shown that the type of base metal can affect the rate of ozone production. Frant [1963] found that ozone was produced at a concentration of 300 $\mu g/min$ during argon-shielded gas metal arc welding on aluminum, compared with only 33 $\mu g/min$

during argon-shielded gas metal arc welding on steel. Lunau [1967] showed large variations in ozone concentrations depending on the particular aluminum alloy being welded. Argon-shielded gas metal arc welding on pure aluminum produced 6.1 ppm ozone at 0.15 m from the arc; welding under the same conditions on a 5% magnesium alloy of aluminum produced only 2.3 ppm ozone; and welding on a 5% silicon alloy of aluminum produced 14.5 ppm ozone. Press and Florian [1983] observed that shielded metal arc welding of aluminum produced ozone concentrations 10 times higher than shielded metal arc welding of mild steel. In addition, much higher ozone concentrations occurred when a silicon alloy electrode was used for welding aluminum than when a magnesium alloy electrode was used.

d. Decomposition Products of Organics

Trichloroethylene and tetrachloroethylene are solvents commonly used to degrease metals. They may therefore be present on the surface of recently cleaned metal parts or in the atmosphere where welding processes are being performed. Ultraviolet radiation may react with the vapors of those solvents and produce a number of irritating and toxic gases as a result of photooxidation. Trichloroethylene may decompose into dichloroacetyl chloride, phosgene, hydrogen chloride, and chlorine [Rinzema 1971]. Tetrachloroethylene may yield trichloroacetyl chloride, phosgene [Andersson et al. 1975], hydrogen chloride, and chlorine [Rinzema 1971]. Methyl chloroform (1,1,1-trichloroethane) appears to undergo relatively little decomposition in the welding environment [Rinzema 1971].

Dahlberg and Myrin [1971] assessed 10 welding workshops and found that roughly five times as much dichloroacetyl chloride as phosgene was formed where welding was done in the presence of trichloroethylene vapor. There was almost a complete conversion of trichloroethylene vapor to phosgene (1.5 ppm) and dichloroacetyl chloride (10 ppm) at 30 cm from an argon-shielded aluminum welding arc located 4 m from a degreaser. In other workshop environments, Dahlberg and Myrin [1971] found 0.01 to 0.3 ppm of phosgene and 0.03 to 13 ppm of dichloroacetyl chloride.

Andersson et al. [1975] studied the formation of trichloroacetyl chloride and phosgene from tetrachloroethylene vapor during shielded metal arc and gas metal arc welding. These two hazardous products were formed in equal proportions. The authors recommended that welding be avoided in work environments contaminated with tetrachloroethylene.

A variety of other potentially toxic gases may be produced when the welding process inadvertently heats certain other materials. For instance, residual oil on steel may emit acrolein during welding [de Kretser et al. 1964].

3. Physical Agents

The potential exists for exposure to a variety of physical agents during the welding process. Workers may be subjected to excessive heat in the welding environment [NIOSH 1986], radiation emitted from the welding processes (including ionizing radiation and nonionizing radiation in the IR, visible, and UV ranges [Fannick and Corn 1969], noise, and electricity. The following types of exposures are representative of those that have been specifically documented in the work environments of welders.

a. Electromagnetic Radiation

Optical radiation may be produced by electric or plasma arcs. Radiation from a 50-A arc ranges from a wavelength of 200 to 800 nm [Marshall et al. 1977]. Levels produced from oxyfuel welding, torch brazing, and oxygen cutting are lower than levels produced by other welding methods [Moss and Murray 1979].

Sliney et al. [1981] conducted a study to determine the effectiveness of transparent welding curtains that were designed to block exposure to "blue light." The transparent curtains were most effective in blocking the wavelengths between 400 and 500 nm. These wavelengths are known to cause photochemical injury to the retina. The energy emitted from shielded metal arc welding was determined by van Someren and Rollason [1948] using a 4-gauge covered electrode operating at a 280-A current. The relative spectral distribution of emitted optical radiation was 5% in the UV range, 26% in the visible range, and 69% in the IR range.

Various factors can affect the radiation intensity from welding and cutting arcs [Dahlberg 1971; Lyon et al. 1976; Bartley et al. 1979; Bennett and Harlan 1980]. Increasing current flow causes a sharp increase in UV emissions. Gas metal arc welding of aluminum produces much greater UV intensity than gas tungsten arc welding. UV emissions increase by a factor of 10 when using magnesium instead of aluminum as an alloying material. The use of argon gas for shielding significantly increases the intensity of the optical radiation compared with carbon dioxide or helium as a shielding gas. As the amount of fume increases, the amount of radiation is reduced proportionately. When gas tungsten arc welding is performed on aluminum-magnesium alloys, the amount of UV emitted decreases as the arc length increases.

Tip size, flame type, and filler metal composition are other variables that affect the amount of UV, visible, and IR radiation produced by oxyfuel welding [Moss and Murray 1979]. Marshall et al. [1980] assessed the amount of optical radiation that was generated from carbon arc cutting. The results of those tests demonstrated that other physical agents such as sparks and noise present more serious hazards than optical radiation. The authors stated that the observed low level of optical radiation produced was probably due to the removal of particulate material from the air, which left no material to become luminescent.

IR radiation can be absorbed by a worker's clothing and skin [Moss et al. 1985] and can elevate the skin temperature and contribute to the body's heat load. Light-colored, loose clothing reduces the heating of the skin.

b. Electricity

Electrical shock from arc and resistance welding is a common hazard and can be sufficient to paralyze the respiratory system or to cause ventricular fibrillation and death. This risk is highest when equipment is in disrepair (e.g., worn insulation) or when electrical resistance through the welder is decreased (e.g., by sweat or standing in water) [Simonsen and Peterson 1977; Ostgaard 1981]. Even minor electrical shocks can cause serious secondary accidents (e.g., muscular reaction to the shock can cause a worker to fall).

c. Noise

Although high noise levels can occur during several types of welding processes (e.g., torch brazing and chipping), they are more often associated with plasma arcs than with any other [National Safety Council 1964]. The high noise levels with plasma arc occur from the passage of heated gas through the constricted throat of the nozzle at supersonic velocities. Noise levels have been measured in the 2,400 to 4,800-Hz range and often exceed 100 dBA. Low-velocity nozzles greatly reduce the noise emitted. The use of induction-coupled plasma jets also greatly reduces the level of noise [National Safety Council 1964]. Levels exceeding 90 dBA have been found in torch brazing operations [NIOSH 1978]. Cresswell [1971] described noise levels of only 70 to 80 dBA from torches using argon-hydrogen mixtures; however, nitrogen and nitrogen-hydrogen mixtures produced levels of 100 to 120 dBA. The same author also noted that cutting materials up to 50 mm thick did not usually pose a noise problem but that thicker materials produced more intense noise levels (levels not given) that required hearing protection.

d. Ionizing Radiation

X-rays are produced as secondary radiation by electron beam welding equipment. The configuration and operating principles of this equipment are similar to those of an X-ray tube [Taylor 1964]. The electrons are generated at the cathode, which is a heated tungsten filament. The electrons are accelerated toward a target by a difference in potential and are focused by using a magnetic field. X-rays are produced when high-speed electrons strike the workpiece, its metal base, or other materials. The intensity and energy of the X-rays are functions of the beam current, the accelerating voltage, and the atomic number of the material on which the beam impinges [Voltkova et al. 1969]. X-radiation may be produced in the electron beam gun itself, at the anode, or in the work chamber wherever the beam strikes a surface. The radiation may be produced any time that power is applied to the high-voltage portion of the equipment.

Radiation may be emitted from the welding equipment at vacuum ports, door flanges, or windows, or from motor shaft and power conduit openings [AWS 1978].

Nonconsumable thoriated tungsten electrodes are usually used in gas tungsten arc welding. The electrodes may contain 1% to 3% thorium oxide, which may potentially emit alpha radiation [Breslin and Harris 1952; Bergtholdt 1961]. Although the electrodes are considered nonconsumable, they are gradually used up. Breslin and Harris [1952] investigated the potential exposure to alpha radiation from thorium during various types of gas tungsten arc welding. Commercially available equipment was used to weld with a 2% thorium oxide electrode; welding operations were performed according to manufacturers' recommendations but without any ventilation. Personal air samples were collected in the operator's breathing zone at the lowest part of the welding helmet. General air samples were also taken at a distance of 1 ft (0.3 m) from the arc. Alpha activity was measured using alpha scintillation counters. No detectable alpha activity was found in the samples. The authors concluded that welding with thoriated tungsten electrodes poses no significant radiation hazard.

e. Radiofrequency Radiation

Radiofrequency (RF) radiation can be used in tungsten inert gas welding to start or continue an arc between the base metal and a nonconsumable tungsten electrode. The frequency of RF radiation in this application is reported to be less than or equal to 5 megahertz (MHz) with a power output of 20 to 30 kilowatts (kW). Since no one has measured the exposure of welders to electric or magnetic field radiation from this type of welding, potential exposure levels cannot be estimated [OSHA 1982].