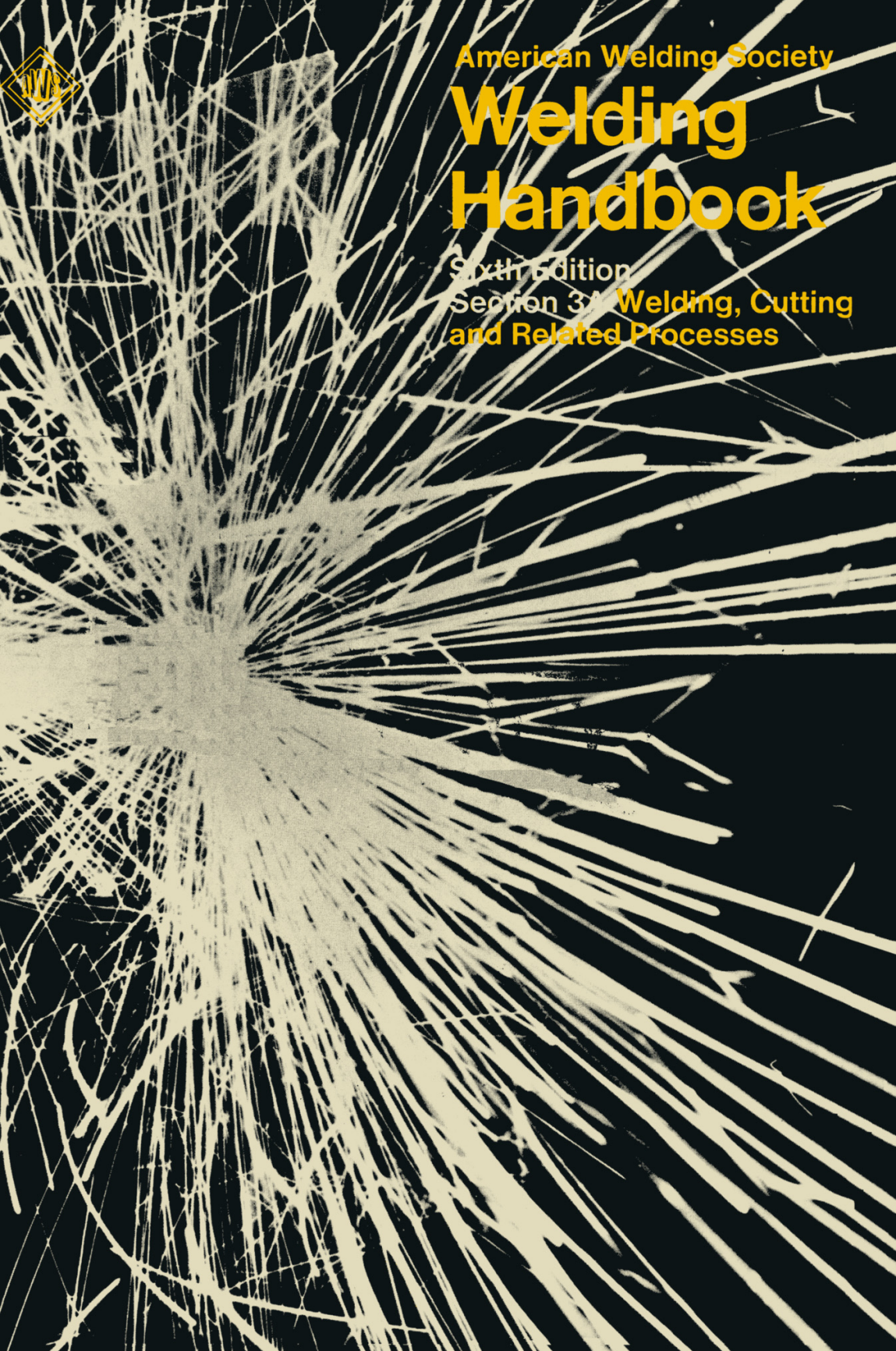

American Welding Society
Welding Handbook
Sixth Edition
Section 3A Welding, Cutting and Related Processes

Welding Handbook

Sixth Edition

SECTION THREE

PART A

Welding, Cutting And Related Processes

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Welding Handbook

IN FIVE SECTIONS

1 Fundamentals of Welding
2 Welding Processes: Gas, Arc and Resistance
3 Special Welding Processes and Cutting
4 Metals and Their Weldability
5 Applications of Welding

Prepared under the direction of
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Preface

It is truly a reflection of the growth of our industry that this Sixth Edition of Volume 3, Welding, Cutting, and Related Processes, should be big. Since the last edition of this Volume was published five years ago, all the "old" welding processes have been refined, and "new" ones added to meet today's needs for more reliable and economical ways to join two or more parts together. The welding industry has never been so big as it is today.

Neither has Volume 3. The various Chapter Committees have completely reworked all 20 Chapters — and added significantly to the contents of each. This is a valuable contribution and we would not have it otherwise; however, the physical size of the book made it necessary for us to examine our own practices.

Because of the new information included in each of the 20 Chapters, it was necessary to editorially cull the material to bring it to producible size. Because the Chapter Committees had done such a fine job, the culling was limited to elimination of only illustrations and then only after much agonizing over each one. Despite all this, Volume 3 was still too large.

It was decided to split this Volume into Part A and Part B, each to include 10 Chapters. This is Part A, Chapters 40 to 50. Part B, Chapters 51 to 60, will follow, to complete the Sixth Edition of Volume 3, Welding, Cutting and Related Processes.

This course of action is the best way to bring AWS members and subscribers *all* the information, as *accurate* as we can make it, and as *promptly* as we can get it to you.

STANLEY T. WALTER, *Editor*

A special appreciation is in order for Stan Walter. Stan died just before this Section went to the printer. Many of us remember him as a willing worker on the various AWS Committees over the years, and we miss him as an AWS staff member and friend.

EDWARD A. FENTON
Executive Director

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CHAPTER 41

GAS WELDING

FUNDAMENTALS OF PROCESS

DEFINITIONS AND GENERAL DESCRIPTION

Gas welding is a group of welding processes wherein coalescence is produced by heating with a gas flame or flames with or without the application of pressure, and with or without the use of filler metal. Gas welding is an inclusive term used to describe any welding operation that makes use of a fuel gas combined with oxygen, or in rare instances, air as a heating medium.

In gas welding, the fuel gas and oxygen are mixed in the proper proportions in a mixing chamber which is generally a part of the welding tip assembly. The torch is designed to give the welder complete control of the welding flame. The gas welding torch can be used to supply the heat for other allied operations such as heating of parts for welding, bending or straightening members, flame hardening, flame annealing, flame descaling and surfacing.

Gas welding involves the melting of the base metal and the filler metal, if used, by means of the flame produced at the tip of the welding torch. The molten metal from the plate edges and the filler metal, if used, intermix in a common molten pool and upon cooling coalesce to form one continuous piece.

The gas flame is also used for braze welding, which differs from gas welding in that the melting temperature of the filler metal used in braze welding is below that of the base metal. This allows the braze welding operation to be performed at a temperature below that at which the base metal would melt, but at or above the melting temperature of the filler material. Braze welding differs from brazing, in that the joint design for braze welding is similar or identical to that used in gas welding, and capillary action is not a factor in the formation of a bond.

Acetylene is usually used as the fuel gas in gas welding because the oxy-acetylene flame provides the highest flame temperature of all the commonly used fuel gases. With proper adjustment, the flame can also supply the proper atmosphere to provide a protective covering over the metal in the molten pool which is maintained during welding. A 1:1 mixture of oxygen to acetylene provides flame temperatures up to 5600°F (3092°C), approximately twice the melting temperature of steel, and produces the high localized heating necessary for welding.

Hydrocarbon fuel gases such as propane, butane, natural gas and various mixtures employing these gases as well as others, are not suitable for welding ferrous materials because of either their low flame temperature or the excessive oxidizing characteristics of the flame. These fuel gases can be used to weld some of the nonferrous metals but find greatest application in brazing and soldering. Oxyacetylene welding is by far the most widely used of the gas welding methods.

GASES

Many processes are involved in gas welding and many fuel gases are employed. The commercial fuel gases have one common property: they all require oxygen to support combustion. A fuel gas, when burned with oxygen, must have: (1) high flame temperature, (2) high rate of flame propagation, (3) adequate heat content and (4) minimum chemical reaction of the flame with base and filler metals in order to be used for welding operations.

Acetylene and hydrogen are the only fuel gases commercially available that possess all the desired properties. Other gases, such as propane and natural gas, have sufficiently high flame temperatures but exhibit low flame propagation

rates. These other gas flames are excessively oxidizing at oxy-fuel gas ratios high enough to produce usable heat transfer rates. Flame-holding devices, such as counterbores on the tips, are necessary for stable operation and good heat transfer even at the higher oxy-fuel gas ratios. These gases, however, can be used for brazing, soldering and similar operations where the demands upon the flame characteristics and heat transfer rates are not excessive.

Tables 41.1, 2 and 3, as well as Fig. 41.1, detail some of the properties of commercial gases. These data may be used to determine cost, availability and btu content. Care should be taken when a fuel gas is selected from such data, since properties not listed may be involved.

The temperature of the flame is evaluated by either the Fahrenheit or Centigrade scale. The heat quantity is measured in British thermal units (btu) or kilogram calories (kg-cal). These units may be converted from one to the other by use of the following relationship: 1 kg-cal = 3.968 btu.

ACETYLENE

The fuel gas most widely used in gas welding in acetylene. A compound of carbon and hydrogen (C_2H_2), the gas contains 92.3% carbon and 7.7% hydrogen by weight. It is colorless, lighter than air and has a sweet, easily distinguishable odor similar in many respects to that of garlic. Acetylene contained in cylinders has a slightly different odor from that of pure generated acetylene. This difference is due to the acetone vapor contained in the cylinder.

Table 41.1— Ignition temperatures and limits of flammability of various fuel gases

Name of Gas	Ignition Temperature at Atmospheric Pressure, ° F		Limits of Flammability in Percentage by Volume at Atmospheric Pressure and Room Temperature			
			In Air		In Oxygen	
	In Oxygen	In Air	Lower	Upper	Lower	Upper
Acetylene	781–824	763–824	2.5	80.0	2.8	93.0
Methane	1033–1292	1202–1382	5.0	15.0	5.4	59.2
Ethane	968–1166	968–1166	3.2	12.4	4.1	50.5
Propane	914–1058	960–1100	2.4	9.5	..	..
Butane	1130	920–1070	1.9	8.4	..	..
Hydrogen	1076–1094	1076–1094	4.0	74.2	4.7	93.9

Acetylene is a highly combustible compound that liberates heat upon decomposition. Acetylene contains a higher percentage of carbon than any of the numerous other hydrocarbons. This combination gives the oxyacetylene mixture the hottest flame of any of the commercially used gases.

At temperatures above 1435°F (780°C) or at pressures above 30 psig, acetylene gas is unstable and an explosive decomposition may result even without the presence of oxygen. This characteristic has been taken into consideration in the preparation of a code of safe practices for the use of acetylene gas. It has become an accepted safe practice never to use acetylene at pressures exceeding 15 psig in generators, pipelines and hose.

Table 41.2— Constants of various fuel gases

Name of Gas	Chemical Formula	Specific Gravity, 60° F, Air = 1.000	Volume, Cu Ft per Lb, 60° F, 30 In. Hg	Weight, Lb per Cu Ft	Heat of Combustion Btu per Cu Ft, Dry, 30 In. Hg, 60° F		Cu Ft per Cu Ft of Fuel Gas Required for Combustion[a]		Cu Ft per Cu Ft of Fuel Gas Products of Combustion with Air[b]			Theoretical Flame Temp. with Air, ° F[f,g]	Heat of Formation Constant Pressure, Btu per Cu Ft
					Gross[c]	Net[d]	O_2[e]	Air	CO_2	H_2O	N_2		
Acetylene	C_2H_2	0.9056	14.45	0.0692	1483	1433	2.5	11.94	2.0	1.0	9.45	4770	−227.5
Methane	CH_4	0.5545	23.64	0.0423	1012	912	2.0	9.56	1.0	2.0	7.56	3750	103.1
Ethane	C_2H_6	1.0494	12.48	0.0801	1762	1612	3.5	16.75	2.0	3.0	13.23	3820	136.0
Propane	C_3H_8	1.5223	8.61	0.1162	2509	2309	5.0	23.89	3.0	4.0	18.90	3840	167.2
Butane	C_4H_{10}	2.0100	6.51	0.1535	3261	3010	6.5	31.06	4.0	5.0	24.51	3870	202.2
Hydrogen	H_2	0.0696	188.70	0.0053	325	275	0.5	2.39	..	1.0	1.89	4010	....

[a] The volumes are those required for theoretically complete combustion.
[b] The fuel gas products are calculated upon air with a composition of 79% N_2 and 21% O_2.
[c] The gross heat value is the value obtained by burning the gas in a Junker's calorimeter, which assumes that the products of combustion are added to the initial temperature and includes the heat of condensation of the water formed by the combustion.
[d] The net heat value differs from the gross value by the heat of vaporization of water and is calculated from the gross by subtracting the heat of vaporization of water at 60° F.
[e] A portion of these oxygen volumes may be obtained from the atmosphere to supplement oxygen from cylinders.
[f] The flame temperatures are not corrected for dissociation.
[g] With oxygen these temperatures are 5660° F for acetylene and 4820° F for hydrogen. Values for the other fuel gases not available.

Table 41.3—Combustion constants and composition of various manufactured and natural fuel gases

	Blast Furnace Gas	Blue Water Gas	Carburetted Water Gas*	Coal Gas*	Coke Oven Gas*	Oil Gas*	Producer Gas	Natural Gases						
								Follansbee, W. Va.	McKean Co., Pa.	Sandusky, Ohio	Pittsburgh, Pa.	Texarkana, Texas	Cleveland, Ohio	Oil City, Pa.
Methane, %	..	..	14.8	34.0	28.5	27.0	2.6	..	32.3	83.5	83.4	96.0	80.5	67.6
Ethane, %	..	..	..	..	..	..	..	31.8	67.0	12.5	15.8	..	18.2	31.3
Propane, %	..	..	..	..	..	..	..	67.7	..	..	..	..	..	..
Ethylene, %	..	..	12.8	6.6	2.9	2.7	0.4	..	..	..	..	..	..	..
Carbon monoxide, %	26.2	43.4	33.9	9.0	5.1	10.6	22.0	..	..	..	..	..	..	..
Carbon dioxide, %	13.0	3.5	1.5	1.1	1.4	2.8	5.7	..	..	0.2	..	0.8	..	..
Hydrogen, %	3.2	51.8	35.2	47.0	57.4	53.5	10.5	..	..	..	..	..	..	..
Nitrogen, %	57.6	1.3	1.8	2.3	4.2	3.4	58.8	0.5	0.7	3.8	0.8	3.2	1.3	1.1
Oxygen, %	..	..	..	..	0.5	..	..	..	..	..	..	..	..	..
Btu per cu ft, gross, 60° F, 30 in. Hg saturated H_2O	93	310	578	634	536	516	136	2220	1482	1047	1129	967	1131	1232
Btu per cu ft, net, 60° F, 30 in. Hg saturated H_2O	91.6	285	529	560	476	461	128	1970	1350	946	1021	873	1025	1120
Theoretical flame temperature, ° F†	2660	4167	4090	3910	3430	3970	3050	3835	3770	3740	3562	3580‡	3600‡	3620‡

* These gases also contain small amounts of benzene and oxygen.
† With the exception of those marked ‡, the flame temperatures are not corrected for dissociation and are based upon air with 21% oxygen and 79% nitrogen.

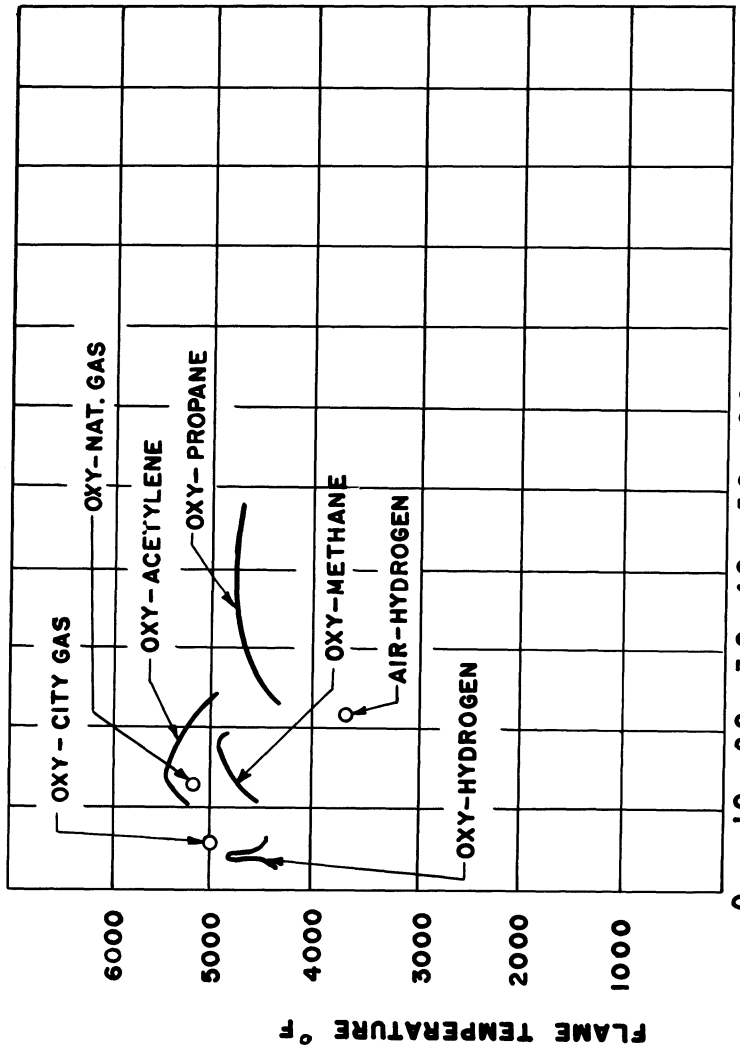


Fig. 41.1—Variation of flame temperature with changing combustion ratios (Fuel gas = 1 vol)

Production

Acetylene is the product of a chemical reaction between calcium carbide (CaC_2) and water. In the reaction the carbon in the carbide combines with the hydrogen of the water, forming gaseous acetylene, while the calcium combines with oxygen to form a calcium-hydroxide residue. The chemical equation is:

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$$
$$\text{Calcium Carbide} + \text{Water} \rightarrow \text{Acetylene} + \text{Calcium Hydroxide}$$

The carbide used in this process is produced by the smelting of lime and coke in an electric furnace. When removed from the furnace and cooled, it is crushed, screened and packed in airtight containers, the most common of which holds 100 pounds of the hard, grayish solid. One pound of carbide will generate approximately 4½ cu ft of acetylene.

Acetylene Generators

Three methods are currently employed in the generation of acetylene: (1) carbide to water, (2) water to carbide and (3) water recession. In the United States the carbide-to-water method is used almost exclusively. The construction of the generator used for this method allows small lumps of carbide to be discharged from a hopper into a relatively large body of water. This type of generator is shown schematically in Fig. 41.2. The details of its construction vary with different manufacturers. All carbide-to-water generators may generally be classified as low pressure or medium pressure. The former operates at 1 psig or less, while the latter produces acetylene from 1 to 15 psig.

The second type of acetylene generator — water to carbide — is used rarely in this country but has a greater popularity in Europe. Fundamentally, the operating principle is the same as that of the carbide-to-water type, but the method differs. Water from a tank is allowed to drip onto a bed of carbide and the gas evolved is piped from the generator. The carbide used in this type of generator is usually in the form of bricks or cakes which do not present too much surface area to the water.

The third type of generator is a modification of the carbide-to-water type. Water is brought into contact with the carbide by raising and lowering the water level. When the water level is raised, the carbide is contacted, gas is generated and the pressure is raised. The pressure of the gas causes the water level to recede and generation ceases. When the gas is drawn off, the pressure lessens and the water is permitted to rise. The water and carbide come into contact and more acetylene gas is developed. The carbide is in the form of cakes. This type of generator is usually used for acetylene lighting where the generator and light are one unit.

The generation of acetylene evolves a considerable amount of heat, which must be dissipated because of the unstable characteristics of acetylene at elevated temperatures. The relatively large volume of water employed in the carbide-to-water generator makes this type highly suitable for the dissipation of the heat. The water-to-carbide type, on the other hand, uses the minimum amount of water, and heat dissipation is slow.

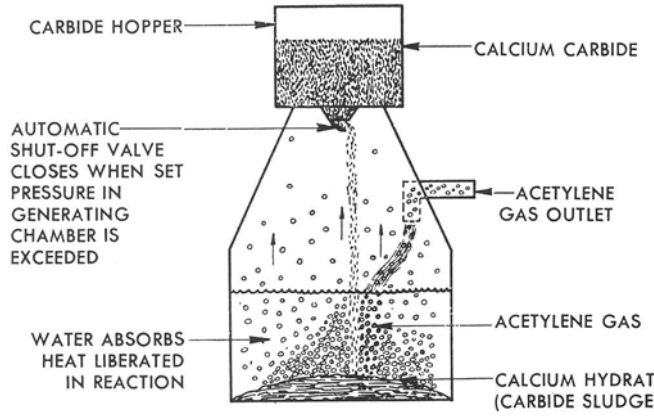


Fig. 41.2—Schematic view of carbide-to-water acetylene generator

Acetylene generators are available in both stationary and portable units in a large range of sizes and gas production rates. Generating capacities of these units range from 12 cfh for small portable units to about 6000 cfh for the large stationary units at industrial installations. Most generators currently in use operate automatically after an initial setting of operating pressure. They may generate gas at the rate at which it is used, or they may be set to generate at a rapid rate to fill a storage unit from which the gas is used as needed. The water-carbide ratio employed in the generation of acetylene differs with the type of installation. Generally, however, the ratio is approximately 1 gallon of water to each pound of carbide cakes.

The volumetric rate of acetylene generation per pound of carbide varies widely with different sizes and types of installations. Single-rated automatic generators should be limited to the development of about 1 cfh of acetylene per pound of carbide. The use of smaller-sized carbide in a double-rated generator will produce 2 cfh per pound of carbide. Generators with large water capacities can exceed this rate for short periods of time.

Acetylene Cylinders

Because free acetylene, under certain pressure and temperature conditions, may dissociate explosively into its constituents, cylinders to be filled with acetylene are initially packed with a porous filler. To the filler is added acetone, a solvent capable of absorbing 25 times its own volume of acetylene per atmosphere of pressure. By so dissolving the acetylene and dividing the interior of the cylinder into small, partly separated cells, a safe acetylene-filled container is produced.

Acetylene cylinders are available in sizes containing from 10 to 380 cu ft of the gas. The cylinders are equipped with fusible safety plugs made of a metal that melts at about 210°F (99°C) and allows the gas to escape if the cylinders should be subjected to excessive heat.

The Oxyacetylene Flame

The complete combustion of acetylene is represented by the chemical equation:

$$2C_2H_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O$$

This equation indicates that 2 volumes of acetylene (C_2H_2) and 5 volumes of oxygen (O_2) react to produce 4 volumes of carbon dioxide (CO_2) and 2 volumes of water vapor (H_2O). It is evident from the equation that, for complete combustion, the volumetric ratio of oxygen to acetylene is 2½ to 1.

In the production of the oxyacetylene flame, the acetylene is mixed in the torch with an approximately equal volume of oxygen, and the additional 1½ volumes of oxygen necessary to complete the combustion is obtained from the air surrounding the flame.

Since the gas mixture issuing from the torch tip does not necessarily contain enough oxygen for complete combustion, the following primary reaction takes place in the inner zone of the flame (called the inner cone) right at the welding tip:

$$2C_2H_2 + 2O_2 \rightarrow 4CO + 2H_2$$

This equation indicates that 2 volumes of acetylene (C_2H_2) and 2 volumes of oxygen (O_2) react to produce 4 volumes of carbon monoxide (CO) and 2 volumes of hydrogen (H_2). This primary reaction produces the brilliant inner cone of the flame which contributes most of the actual heating.

In the outer envelope of the flame the carbon monoxide and hydrogen resulting from the primary reaction burn with oxygen from the surrounding air, forming carbon dioxide and water vapor respectively, as shown in the following two equations:

$$4CO + 2O_2 \rightarrow 4CO_2$$
$$2H_2 + O_2 \rightarrow 2H_2O$$

The oxyacetylene flame is easily contolled by valves on the welding torch. By a slight change in the proportions of oxygen and acetylene fed to the flame through the torch, the chemical characteristics in the inner zone of the flame and, consequently, the action of the inner cone on molten metal can be varied over a wide range. Thus by adjusting the torch valves, it is possible to produce a neutral, oxidizing or reducing flame.

Although acetylene is the fuel gas most widely used in welding and cutting, other fuel gases are often employed for cutting and heating. Among the more common gases used for preheating are propane, hydrogen, city gas and natural gas. These gases, with the exception of hydrogen, are also used for soldering and brazing operations.

Other gases are available under various trade names, but these generally are commercial combinations of the basic hydrocarbon gases.

PROPANE

Propane (C_3H_8) is used primarily for preheating in oxygen cutting or for heating operations. The main source of this gas is the crude oil gas mixtures obtained from active oil and natural gas wells. Propane is also produced in certain oil refining processes and from the recycling of natural gas. It is sold and transported in steel cylinders containing from a few to 100 pounds of the liquefied gas. Large consumers are supplied by tank car and bulk delivery. Small self-contained propane torches are available for home workshop use as well as for incidental heating operations.

HYDROGEN

The relatively low heat content of the oxyhydrogen flame restricts the use of hydrogen, as a fuel gas, to certain brazing operations and to the welding of aluminum, magnesium, lead and similar metals. Other welding processes, however, are largely supplanting gas welding for many of these materials. Hydrogen is also used with oxygen in preheating operations for underwater cutting.

Hydrogen (H_2) is obtained by the following methods:

1. Electrolysis of water.
2. Messerschmitt system (hot steam passed over iron filings).
3. Dissociation of ammonia.
4. By-product of petroleum.

Hydrogen is available in seamless, drawn, steel cylinders charged to a pressure of about 2000 psig at a temperature of 70°F (21°C). It may also be supplied as liquid either in individual cylinders or in bulk. At the point of use, the liquid hydrogen is vaporized into gas.

NATURAL GAS

Natural gas is obtained from wells and distributed by pipelines. Its chemical composition varies widely, depending upon the locality from which it is obtained. The principal constituents of most natural gases are methane (CH_4) and ethane (C_2H_6). The volumetric requirements of natural gas to provide an equivalent amount of heat (or number of btu's) are, as a rule, about 1½ times those of acetylene. Natural gas finds its principal use in the welding industry as a fuel gas for cutting and heating operations.

MISCELLANEOUS FUEL GASES

Manufactured gas is a mixture of carbureted water gas and/or coal gas enriched with gas oils or natural gas. Its use as a preheating gas for cutting is limited by high fuel gas requirements.

Methane (CH_4), ethane (C_2H_6), butane (C_4H_{10}) and other hydrocarbon compounds are used occasionally as fuel gases in oxygen cutting an in heating applications.

A number of gases specifically manufactured or compounded for use as fuel gas for welding and cutting are also employed. This group includes inoculated propane, stabilized methylacetylene propadiene and others. Claims for these gases are improved flame stability, high flame temperature and lower ignition temperatures.

Data on the various fuel gases will be found in Tables 41.1, 2 and 3.

OXYGEN

Oxygen in the gaseous state is colorless, odorless and tasteless. It occurs abundantly in nature. One of its chief sources is the atmosphere, which contains approximately 21% oxygen by volume. Although there is sufficient oxygen in the air to support combustion, the use of pure oxygen speeds up reactions and increases flame temperatures.

Oxygen may be produced from chemical sources, such as mercuric oxide, barium oxide, potassium chlorate or other compounds containing oxygen. It may also be produced by the electrolysis of water, or it may be extracted from the atmosphere. Of these, only the last two methods are of commercial importance in the welding industry where large quantities of oxygen are required.

Oxygen is produced from the electrolysis of water by passing an electric current through water containing an electrolyte, such as caustic soda, to increase its electrical conductivity. The water decomposes, allowing oxygen to collect at the positive pole and hydrogen at the negative pole. Limited commercial quantities of oxygen are produced by this means; the process is used principally for the production of hydrogen.

Most oxygen used in the welding industry is extracted from the atmosphere, which has the following composition by volume: nitrogen, 78.03%; oxygen, 20.99%; argon, 0.94%; carbon dioxide, hydrogen, neon, helium and other rare gases, 0.04%.

In the extraction process, air is compressed to approximately 3000 psig. (some types of equipment operate at much lower pressure), the carbon dioxide and any impurities are removed and the air passes through coils and is allowed to expand to a rather low pressure. The air is substantially cooled during the expansion, then passes over the coils further cooling the incoming air, until liquefaction occurs. The liquid air is sprayed on a series of evaporating trays or plates in a rectifying tower. The nitrogen and other gases boil at lower temperatures than the oxygen and, as these gases escape from the top of the tower, high-purity liquid oxygen remains in a receiving chamber at the base. Some plants are designed to produce liquid oxygen; in other plants gaseous oxygen is withdrawn for compression into cylinders.

TECHNICAL CONSIDERATIONS OF FUEL GASES

FLAME TEMPERATURE

The flame temperature is a physical property of a fuel gas. This temperature will vary depending on the oxygen- (or air-) to-fuel ratio. Although flame temperature gives an indication of the heating ability of the fuel gas, it is only one of the many physical properties that must be considered in evaluating a fuel gas. Flame temperatures are calculated since there is at present no simple method of physically measuring these values. See Table 41.1 and Fig. 41.1.

COMBUSTION RATIO

Column 8 in Table 41.2 indicates the volume of oxygen required for complete combustion of any of the fuel gases. As these data indicate, each unit volume of the fuel gas in question requires the number of unit oxygen volumes listed. These values for oxygen are also known as the oxygen-to-fuel gas combustion ratios (or simply the gas ratios or combustion ratios) for complete combustion. By merely multiplying the fuel gas volumetric rate by this gas ratio, the theoretical volumetric rate of oxygen is found.

If the maximum flame temperature for a particular gas combination is desired, Fig. 41.1 may be used to estimate the actual temperature.

HEAT OF COMBUSTION

The heat of combustion (heating value) of a fuel gas is an important property in determining its heating characteristics. Tables 41.2 and 41.5 give values for the gross heat of combustion per cubic foot of some of the common fuel gases.

COMBUSTION INTENSITY

Flame temperatures and heating values of fuels have been used almost exclusively as the criteria for evaluating fuel gases. These two factors alone, however, do not provide sufficient information to allow complete appraisal of fuel gases for heating purposes. A concept known as combustion intensity or specific flame output is used to evaluate different fuel gas-oxygen combinations. Combustion intensity takes into account the burning velocity of the flame, as well as the heating value of the mixture of fuel gas and oxygen (not of fuel alone) issuing from the tip.

Combustion intensity may be expressed as:

$$J = VH$$

where:

J = combustion intensity in btu per square foot of cone area per second.

V = normal burning velocity of flame in feet per second.

H = heating value of the gas mixture under consideration in btu per cubic foot.

Combustion intensity (J), therefore, is at a maximum when the product of the normal burning velocity of the flame (V) and the heating value of the gas mixture (H) is at a maximum.

Normal burning velocity is a fundamental combustion property. It is the velocity at which a plane flame front moves normal to its surface through the adjacent unburned gas. Values of normal burning velocities for various fuel gases are shown in Fig. 41.3.

Primary, secondary or total combustion intensity may be secured from Figs. 41.4, 41.5 and 41.6. The values of combustion intensity for neutral mixtures of various fuel gases are approximately as given in Table 41.4.

Table 41.4—Combustion intensity, flame area (btu per square foot per second)

Fuel Gas	Primary	Secondary	Total
Acetylene	4600	8100	12,700
Hydrogen	3870	3730	7,600
Methane	4170	2080	6,250
Propane	4500	1000	5,500

Table 41.5—Reaction of various fuel gases with oxygen

Fuel Gas		Reaction with Oxygen	Heating Value in Btu/Cu Ft	Flame Temp. in Oxygen °F
Acetylene	C_2H_2	$C_2H_2 + 2\frac{1}{2}\ O_2 \rightarrow 2\ CO_2 + H_2O$	1483	5,660
Hydrogen	H_2	$H_2 + \frac{1}{2}\ O_2 \rightarrow H_2O$	325	4,820
Methane	CH_4	$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$	1012	4,600
Methyl Acetylene	C_3H_4	$C_3H_4 + 4\ O_2 \rightarrow 3\ CO_2 + 2\ H_2O$	2406	5,300
Propane	C_3H_8	$C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$	2509	4,600

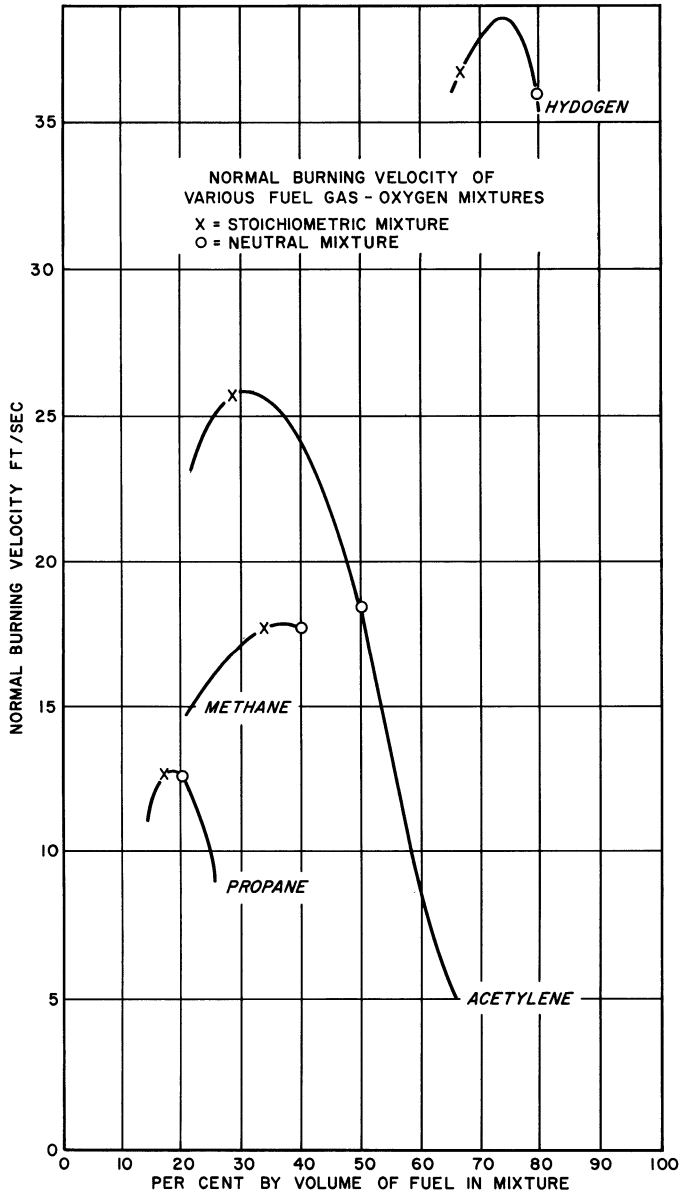


Fig. 41.3—Normal burning velocity of various fuel gas-oxygen mixtures

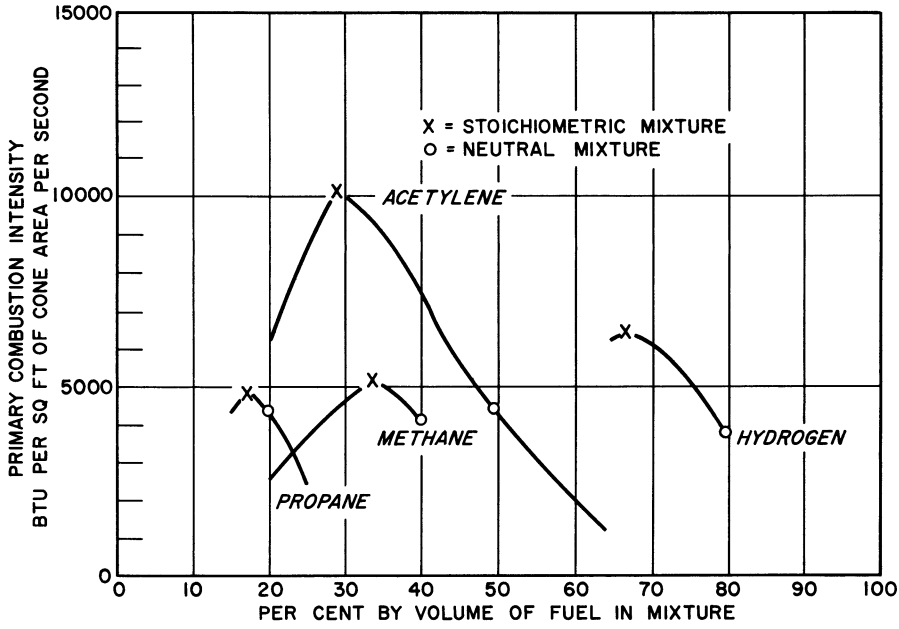


Fig. 41.4—Primary combustion intensity of various fuel gas-oxygen mixtures

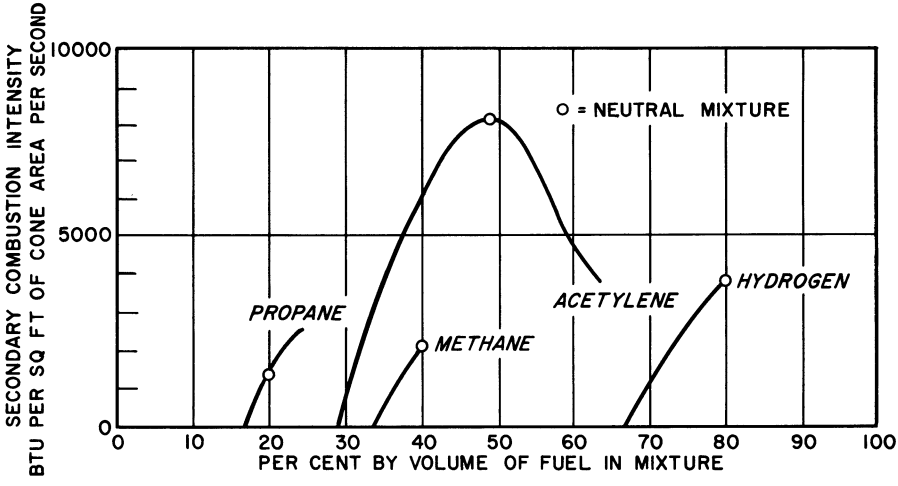


Fig. 41.5—Secondary combustion intensity of various fuel gas-oxygen mixtures

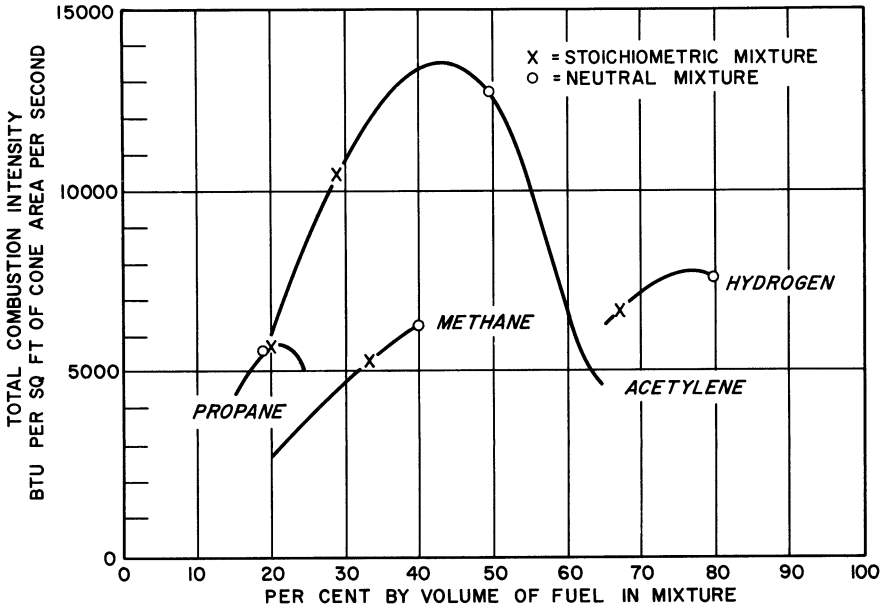


Fig. 41.6—Total combustion intensity of various fuel gas-oxygen mixtures

CHEMICAL REACTIONS

Table 41.5 is a convenient listing of the principal characteristics of some of the major fuel gases used in welding and cutting. Some of the reactions that take place when these gases are burned with oxygen are quite complex; the chemical reaction shown in the table is the complete chemical reaction.

Table 41.5 also gives the heating value in btu per cubic foot as well as the flame temperature when burned with oxygen.

GAS DISTRIBUTION

Gas is distributed to various sections of an industrial plant in single cylinders, from portable manifolds, from stationary piped manifolds, from generators and by pipelines fed from bulk supply systems.

SINGLE CYLINDERS

Individual cylinders of gaseous oxygen and acetylene provide an adequate supply of gas for welding and cutting torches consuming limited quantities of gas. Cylinder trucks are used extensively to provide a convenient, safe support for a cylinder of oxygen and a cylinder of acetylene. The gas can be transported readily by such means.

Oxygen is transported to the user in individual cylinders as a compressed gas or as a liquid; there are also several bulk distribution methods. Gaseous oxygen in cylinders is usually under a pressure of approximately 2200 psig. Cylinders of various capacities are used, holding approximately 70, 80, 122, 244 and 300 cu ft of oxygen. Liquid oxygen cylinders contain the equivalent of approximately 3000 cu ft of gaseous oxygen. These cylinders are used for applications which do not warrant a bulk oxygen supply system but which are too large to be supplied conveniently by gaseous oxygen in cylinders. The liquid oxygen cylinders are equipped with liquid-to-gas converters.

A single cylinder of acetylene cannot be used if the volumetric demand is high, since acetone may be drawn with the acetylene from the cylinder. It has, therefore, become standard practice to limit the withdrawal of acetylene from a single cylinder to an hourly rate not exceeding one seventh of the cylinder's volumetric contents.

Cylinders for liquefied fuel gas contain no filler material. These welded steel or aluminum cylinders hold the liquefied fuel gas under pressure. The pressure in the cylinder is a function of the temperature.

These liquefied fuel gas cylinders have relief valves which are set for 375 psig, a pressure reached at approximately 200°F (93°C). Should these temperatures be reached, the rapid discharge of fuel gas through the relief valve causes the cylinder to cool down and the relief valve to close. In a fire, the cylinder relief valve opens and shuts intermittently until all the contents of the cylinder have been discharged or the source of the extreme heating of the cylinder has been removed.

MANIFOLDS

Individual cylinders cannot supply high rates of gas flow, particularly for continuous operation over long periods of time. Manifolding of cylinders is one answer to this problem. A reasonably large volume of fuel gas is provided by this means, which can be discharged at a moderately rapid rate.

Manifolds are of two types— portable and stationary.

Portable manifolds may be installed with a minimum of effort and are useful where moderate volumes of gas are required for jobs of a non-repetitive nature, either in the shop or the field.

Stationary manifolds are installed in shops where even larger volumes of gas are required. Such a manifold feeds a pipeline system distributing the gas throughout the plant. Such an arrangement enables many welding operators to work from this common pipeline system without interruption. Alternately, it may supply large automatic gas welding equipment.

BULK SYSTEMS

To satisfy the large consumption of some industries, gaseous oxygen may be transported from the producing plant to the user as a compressed gas in multi-cylinder portable banks or in long, high-pressure tubes mounted on truck trailers which connect directly to the user's pipeline system. The trailers may hold as many as 30,000 to 50,000 cu ft in the larger units and 10,000 cu ft in the smaller units.

Bulk oxygen may also be distributed as a liquid in large, insulated containers mounted on truck trailers or railroad tank cars. The liquid oxygen is transferred to an insulated storage holder on the consumer's property. The oxygen is withdrawn, converted to gas and passed into the distribution pipelines, as needed, by means of automatic regulating equipment. For users having medium-large consumption, the liquid oxygen may be converted to gas by equipment on the truck, pumped under high pressure into storage tubes, and permanently connected into the user's distribution piping system.

OTHER SYSTEMS

When stationary manifolds, truck trailers or bulk supply systems are used as a source of oxygen, and large acetylene generators are used to produce acetylene in a consumer's plant, the gases are distributed by pipelines to the points of use. The pipelines should be designed properly to handle and distribute the gases in sufficient volume and without undue pressure drop. Pipelines should incorporate all necessary safety devices such as relief valves, bursting disks and hydraulic arrestors on acetylene systems. By use of pipelines an ample, uninterrupted supply of gas is available at all times, and the changing of cylinders is eliminated. Acetylene and fuel gas pipelines usually parallel the oxygen lines. Fig. 41.7 illustrates typical welding station layouts.

Connections to the pipeline at points of use are made by station drops fitted with suitable valves, regulators and, in some types of installations, relief valves, filters and hydraulic back-pressure valves. Hydraulic back-pressure valves and relief valves used on an acetylene or a fuel gas station drop should be vented to the outdoors.

SAFE PRACTICES

Oxygen by itself does not burn or explode, but it does support combustion. Oxygen under high pressure may react violently with oil or grease. Cylinders, fittings and all equipment to be used with oxygen should be kept away from oil and grease at all times. Oxygen cylinders should never be stored near highly combustible materials. Oxygen should never be used in pneumatic tools, to start internal combustion engines, to blow out pipelines, to dust clothing or to create a head pressure in tanks. For further information see Section 1, Chapter 9, Sixth Edition.

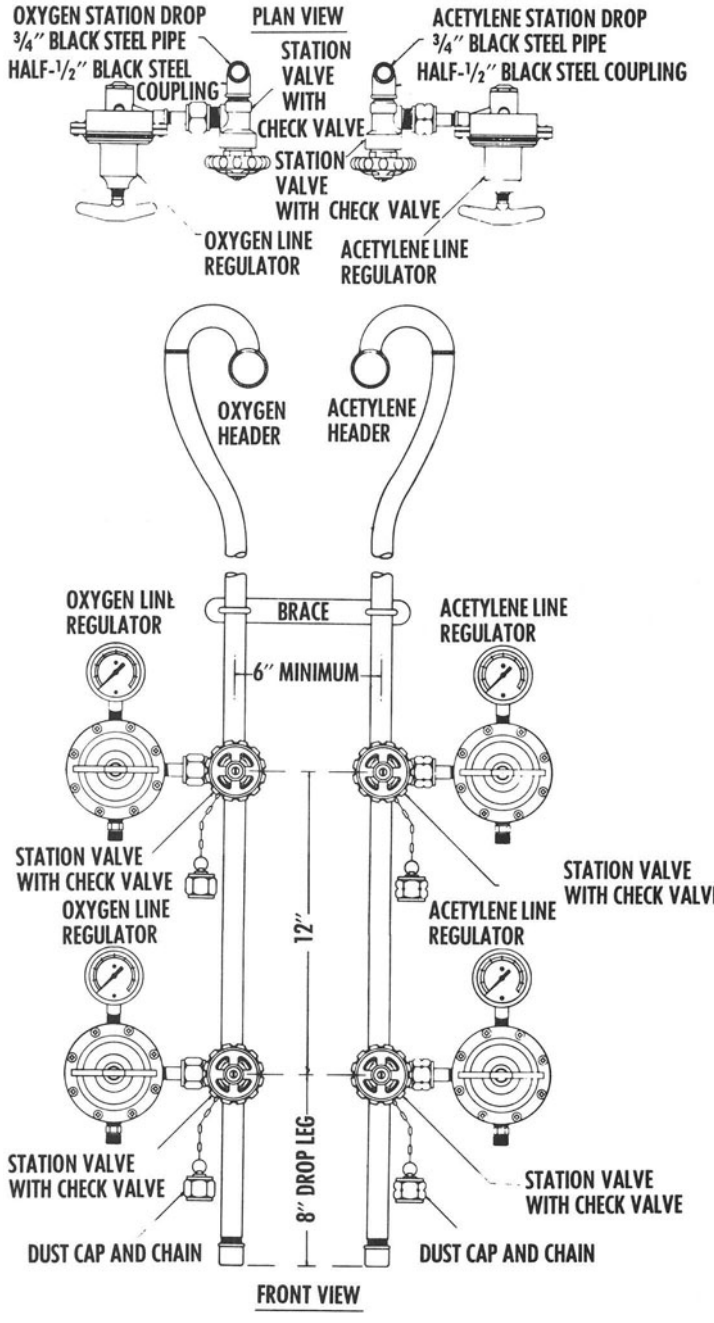


Fig. 41.7—Typical double oxygen and acetylene station drop

Acetylene is a fuel gas and will burn readily. It must therefore be kept away from open fire. Acetylene cylinder and manifold pressures must always be reduced through gas pressure-reducing regulators and pipeline pressures should be controlled through suitable pipeline regulators. Cylinders should always be protected against excessive temperature rises and should be stored in well-ventilated, clean and dry locations free from other combustibles. They must be stored and used with the valve end up. Loose carbide should not be scattered about or allowed to remain on floors, as it will absorb moisture from the air and generate acetylene.

Acetylene in contact with copper, mercury or silver, especially if impurities are present, may form acetylides. These compounds are violently explosive and can be detonated by a slight shock or by the application of heat. No alloy containing copper in excess of 67% should be used in any acetylene system, unless such alloys have been found to be safe in the specific application by experiment or test.

Fuel gas cylinders, other than acetylene, also contain gas under pressure and should be handled with care. These cylinders should likewise be stored in clean, dry locations.

Liquid cylinders are constructed with a vacuum between the inner and outer shell. They should be handled with extreme care to prevent damage to the internal piping and the loss of this vacuum. Such cylinders should always be transported and used in an upright position.

Cylinders can become a hazard if tipped over. The greatest care should be exercised to avoid this possibility. Acetylene cylinders, in particular, should always be used in an upright position. When gas is taken from an acetylene cylinder that is lying on its side, acetone is readily withdrawn. This contaminates the flame and will result in welds of inferior quality. It is standard practice to fasten the cylinders on a cylinder truck or to secure them against a rigid support. All hoses connecting the equipment should be kept as short as possible and free from sharp twists.

EQUIPMENT

The relationship among the basic tools required in gas brazing and welding is shown in Fig. 41.8 which illustrates two gas cylinders (one fuel gas, the other oxygen), gas regulators for reducing and controlling the cylinder pressures, hoses for conveying the gases to the torch, and the torch and tip combination where the gases are controlled, mixed and burned.

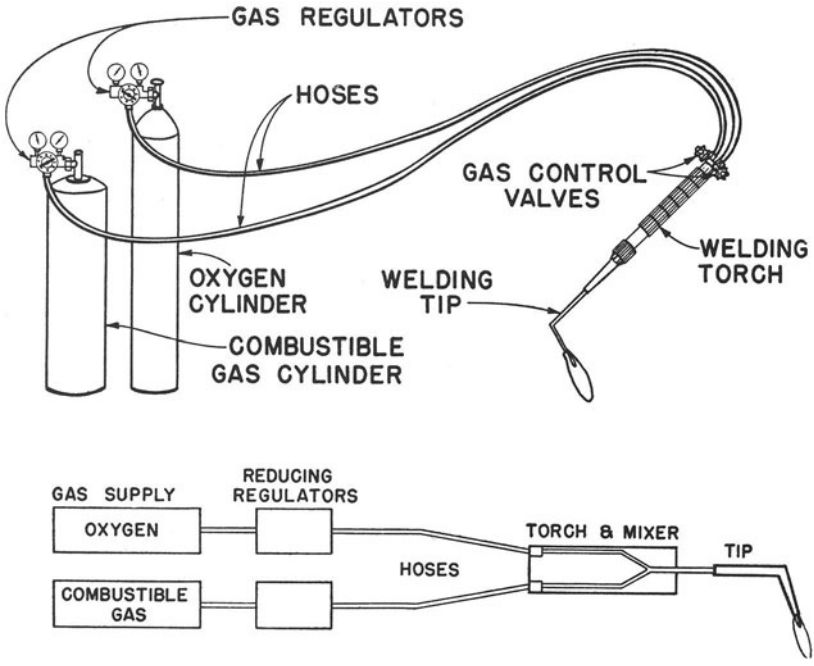


Fig. 41.8—Basic gas welding equipment

Each of these units plays an essential part in the control and utilization of the heat necessary for operations such as gas welding, brazing and heating. The heat is obtained from the combustion of the gases, but the effectiveness of the heat is governed, to a large extent, by the skill of the welder. Proper training of the welder and careful selection of the equipment used are essential to the production of high-quality work.

A variety of equipment is obtainable for most welding operations. Some of this equipment is designed for general use and some is produced for specific operations. Care should be taken to select the most suitable equipment for the particular operation. It is highly important in oxyacetylene welding that the correct mixture of gases and tip size be used.

WELDING TORCHES

The welding torch is a device used for mixing and controlling the flow of gases to the tip. It also provides a means of holding and directing the tip. A simplified schematic drawing of the basic elements of a welding torch is given in Fig. 41.9. There are two throttling or control valves. The gases, after passing the valves and handle, are directed together by the gas mixer at the front end. The tip is shown as a simple tube, narrowed down at the front end to produce a suitable welding cone. Sealing rings or surfaces have been provided in the torch head or on the mixer seats to facilitate leaktight makeup.

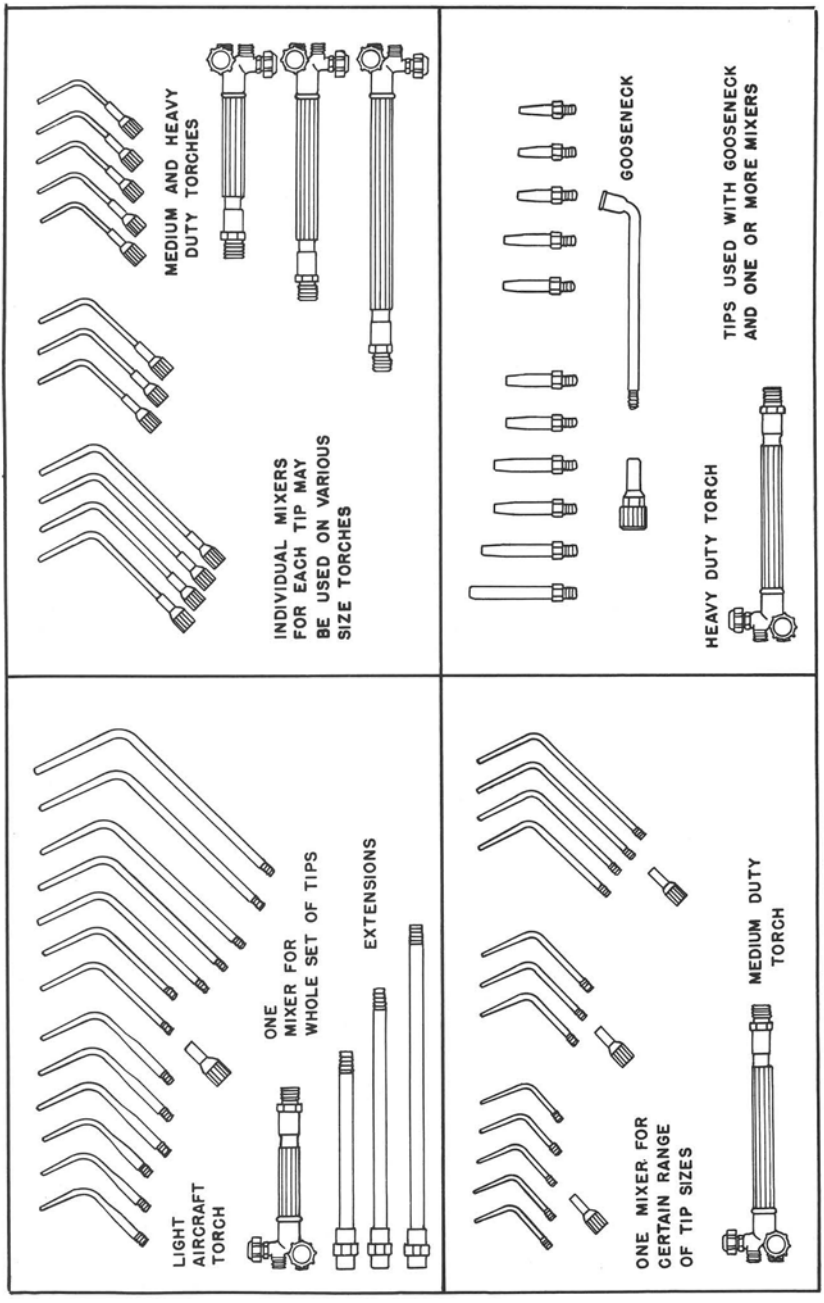


Fig. 41.9—Basic elements of a welding torch

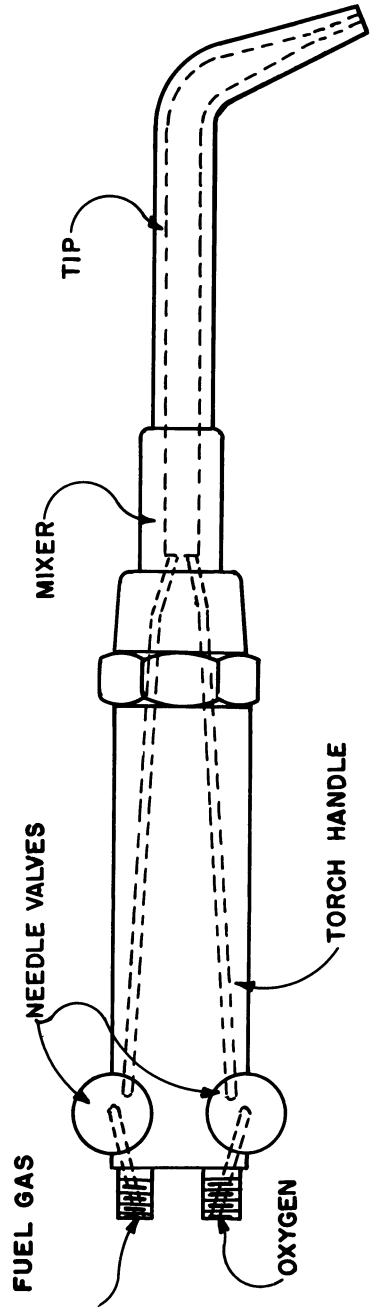


Fig. 41.10—Various torch, tip and mixer combinations

The fuel-gas hose fitting on all torches has a left-hand thread, making it possible to screw on only the left-hand hose nuts used on fuel gas hose. The other fitting, used for oxygen, has a right-hand thread.

Modern torches are manufactured in a variety of sizes ranging from the small torch for extremely light (low gas flow) work to the extra heavy torches (high gas flow) used generally for localized heating operations. A typical small welding torch used for sheet metal and aircraft welding will pass acetylene at volumetric rates ranging from about ¼ to 35 cu ft per hour. The medium-sized torch is designed to provide for acetylene flows from about 1 to 100 cu ft per hour. Heavy-duty heating torches may provide for acetylene flows as high as 400 cu ft per hour.

Types of Torches

There are two general classes of torches: the positive- or equal-pressure type and the injector type.

The positive-pressure type torch (also called medium-pressure) requires that the gases be delivered to the torch at pressures generally above 1 psig. In the case of acetylene the pressure should be between 1 and 15 psig. Oxygen generally is supplied at approximately the same pressure. There is, however, no restrictive limit on the oxygen pressure. It can, and sometimes does, range up to 25 psig on the larger sizes of tips when used in positive-pressure torches.

The injector (or low-pressure) type operates at an acetylene pressure as low as 1 psig (a pressure which can easily be supplied by the low-pressure type of acetylene generator). Oxygen, on the other hand, is supplied at a pressure ranging from 10 to 40 psig, necessarily increasing as the tip size is increased. This oxygen aspirates or draws in the acetylene and mixed with it before both gases pass into the tip.

Care of Torches

Each welding torch either has a gas mixer unit as an integral part, or provision is made to attach a mixer by screwing it onto the front end of the torch (Fig. 41.10). The welding tip must be screwed into place. This means that the front portion of a welding torch should not be mishandled, or difficulty will be experienced in obtaining a perfect gas seal. When attaching mixers to the front end of torches, particular care should be exercised to prevent the seating surfaces from being scored. Slight damage to these seating surfaces will cause gas leaks and frequent popping sounds. Also, escaping acetylene may burn at the leak.

Welding torches are built to withstand rough usage, but the following rules should be observed when handling them:

1. Keep torches away from all oil and grease.
2. If the throttle valve does not shut off when hand tightened in the normal manner, do not use a wrench to tighten or seat the valve stem. If foreign matter cannot be blown off the seat, remove the stem assembly and wipe the seat clean before reassembling.
3. Never clamp the torch handle tightly in a vise, as this may collapse the handle and injure the gas tubes inside.
4. Keep the mixer seat free of dust and other foreign matter at all times.
5. Before using a torch for the first time, check the packing nuts on the throttle valves to ensure they are tight. Some manufacturers ship torches with these nuts loose.

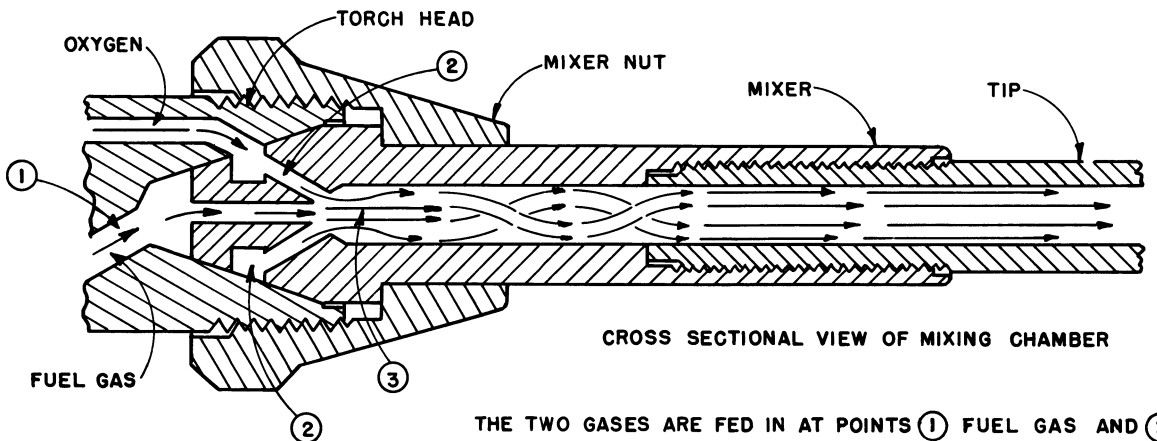
Gas Mixers

Figure 41.9 illustrates a mixing chamber wherein acetylene and oxygen come together before passing into the welding tip proper. In this respect, the action of the mixing chamber is similar to that of an automobile carburetor which mixes air and gasoline vapor. A well-designed gas mixing chamber, or gas mixer, must be able to perform well all of the following essential functions:

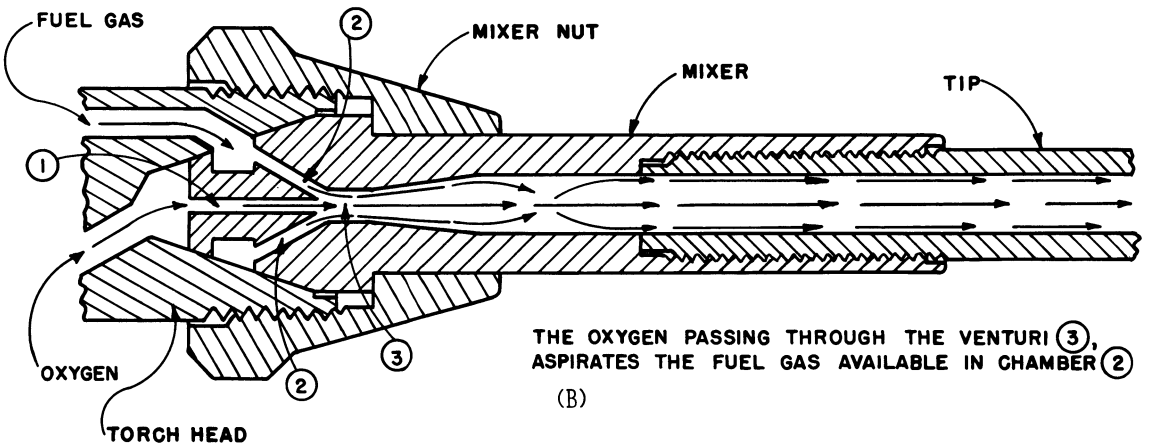
1. Mix gases thoroughly for proper combustion.
2. Arrest flashbacks that might occur through improper operation.
3. Stop any flame from traveling farther back than the mixer.
4. Permit, in some designs, a range of tip sizes to be operated by the one size of mixer.

Figure 41.11a shows one type of positive-pressure mixer. The volumes of the two gases have already been controlled by the throttling or needle valves. Acetylene enters through orifice 1 while the oxygen enters at orifice 2. There are usually several holes for one of the gases, to provide for better mixing and to deter any flashbacks. The gas in the annular chamber, which feeds all holes marked 2, must be at a pressure high enough to ensure the proper volumetric gas flow into chamber 3. It can be seen that the pressure gradient of the gas along paths 2 would tend to prevent any flame from proceeding back upstream along this path of gas flow. This is more clearly illustrated in Fig. 41.12 which shows a typical gas pressure gradient existing across a torch and tip combination. Here again it can be seen that the gas pressure decreases as the gas flows downstream.

The typical injector type of gas mixer shown in Fig. 41.11b is essentially similar to the positive-pressure type (Fig. 41.11a). The main difference in operation is that the acetylene is at a pressure of 1 psig or lower, while the oxygen pressure may be from 10 to 40 psig. The injector is so designed that the oxygen, as it emerges from hole 1 into venturi chamber 3, creates a vacuum which aspirates or sucks the proper volume of acetylene into the gas mixture from the gas ports 2. A comparative study of Figs. 41.11a and b will clarify the differences of construction between the two types of mixers.



(A) positive-pressure type



(B) injector-type

Fig. 41.11—Basic elements of welding torch mixers

AN EXAMPLE OF PRESSURE DROPS FOR OXYGEN IN HOSES*

HOSE DIAMETER – INCHES			HOSE LENGTH** 7 FT. INLET PRESSURE – 10 PSI				HOSE LENGTH** 25 FT. INLET PRESSURE – 60 PSI			
3/16	FLOW RATE, CFH		10	20	30	50	100	150	250	350
	PRESSURE DROP, PSI		0.2	0.4	0.9	2	4	7	17.5	27
1/4	FLOW RATE, CFH		20	40	100	160	100	250	500	
	PRESSURE DROP, PSI		0.1	0.2	1	2	3	5	11	
5/16	FLOW RATE, CFH		50	100	200	300	100	250	500	1000
	PRESSURE DROP, PSI		0.1	0.5	1.5	3.5	2	3	5	20
3/8	FLOW RATE, CFH		250	500			250	500	1000	2000
	PRESSURE DROP, PSI		0	7			2	4	7	30
1/2	FLOW RATE, CFH						500	1000	2000	3000
	PRESSURE DROP, PSI						2	3.5	8.5	17

* PRESSURE DROPS FOR ACETYLENE, WHERE APPLICABLE, WILL BE APPROXIMATELY THE SAME AS THOSE FOR OXYGEN.

** HOSE LENGTH INCLUDES STANDARD FITTINGS. WHEN MULTIPLE LENGTHS OF HOSE ARE USED, INTRODUCING SPLICERS, COUPLINGS AND EXCESS LENGTHS, FLOW RESTRICTIONS INCREASE AND PRESSURE DROP IS GREATER THAN SHOWN ABOVE. IN ACTUAL SERVICE, DAMAGED OR CLOSED GLANDS ARISING FROM OVER-TIGHTENING OR EXTENSIVE USE WILL INTRODUCE RESTRICTIONS TO FLOW AND INCREASE PRESSURE DROP.

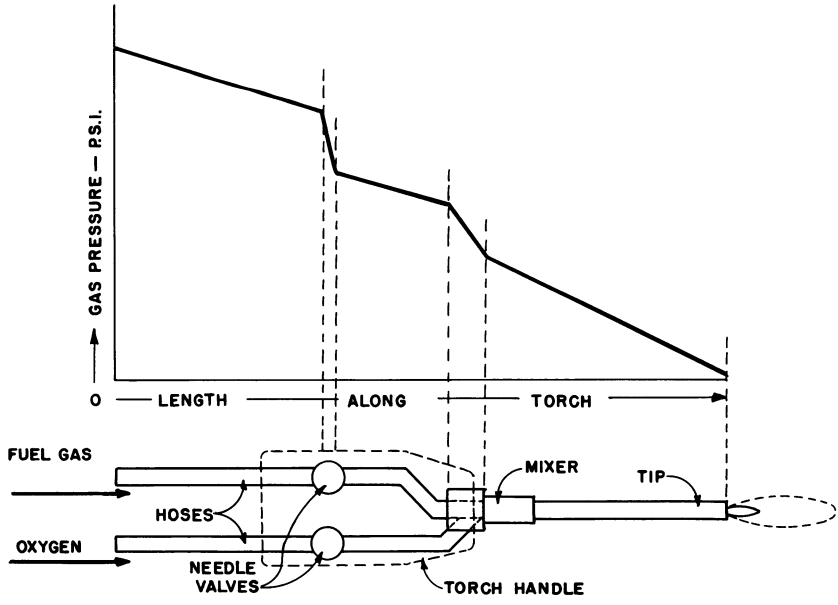


Fig. 41.12—Pressure loss along a torch, mixer and tip combination

WELDING TIPS

The welding tip is that portion of the torch through which the gases pass just prior to their ignition and burning. The tip enables the welder to guide the flame and direct it to the work with maximum ease and efficiency.

Tips are generally made of a nonferrous metal such as copper or a copper alloy. Such material have high thermal conductivity and their use reduces the danger of burning the tip at high temperatures.

Tips are manufactured mainly by drilling bar stock to the proper orifice size or by swaging tubing to the proper diameter over a mandrel. The bore in both types must be smooth in order to produce the required flame cone. The front end of the tip should likewise be shaped to permit easy use and provide a clear view of the welding operation being performed.

Welding tips are available in a great variety of sizes, shapes and constructions (Fig. 41.10). Two general methods of using tip and mixer combinations are employed. One class uses a tip and mixer unit that provides the proper mixer for each size of tip, and the other general class employs one or more mixers for the entire range of tip sizes. In the latter class the tip unscrews from its mixer, and each size of mixer has a particular thread size to prevent improper grouping of a tip and mixer.

A single mixer is used for some classes of welding. It has a so-called goose-neck into which the various sizes of tips may be screwed.

Since tips generally are made of copper or of a copper alloy (relatively soft materials), care must be taken to guard them against damage. The following precautions should be observed:

1. Tips should be cleaned, when necessary, using tip cleaners designed for this purpose.
2. Tips should never be used for moving or holding the work.
3. Tip seat and/or threads always should be absolutely clean and free from foreign matter in order to prevent scoring when tightening the tip nut.

When performing a welding operation care should also be taken to obtain the correct flame adjustment. Improper flame characteristics will nullify correct torch, mixer and tip selection. Detailed information about the proper methods for obtaining the desired flame characteristics is given elsewhere in this chapter.

A linear relation exists between the thickness of a steel piece and the size of tip that can best be used (Fig. 41.13). When a series of welding tips is selected for a variety of thicknesses of metal, the metal thickness range covered by one tip should slightly overlap that covered by the next tip.

Volumetric Rate of Acetylene Flow

The important factor in determining the usefulness of a torch tip is the action of the flame on the metal. If it is too violent it may blow the metal out of the molten pool. Under such conditions the volumetric flow rates of acetylene and oxygen have to be reduced to a point at which the metal can be

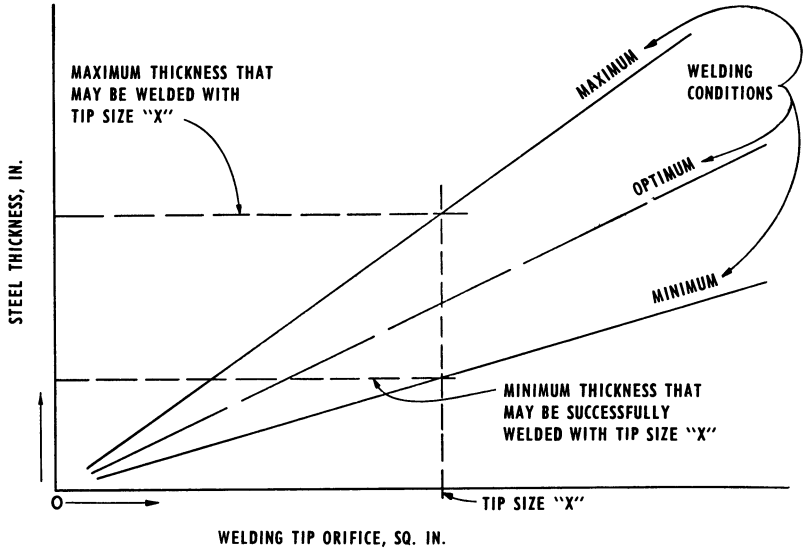


Fig. 41.13—Welding tip size vs metal thickness. See manufacturer's data for specific information

welded. This point represents the maximum volumetric flow rate that can be handled by a given size of welding tip. As a general rule, the larger the volumetric rate of gas that may be handled by a specific size of tip, the greater the heat. The flame may also be too soft for easy welding. When the flame is too soft the gas volumetric flow rates must be increased.

Tips having a hooded or cup-shaped end designed for some of the slower-burning gases, such as propane, are available from most equipment manufacturers. These tips are usually used for heating, brazing or soldering.

Flame Cones

The purpose of a welding flame is to raise the temperature of metal to the point where it can be welded. This can be accomplished most easily when the welding flame (or cone) produced by the tip permits the heat to be directed easily. Consequently, the cone characteristics become important. Laminar or streamlined flow becomes of paramount importance throughout the length of the tip and especially so during the final run through the front portion of the tip. A high-velocity flame cone presents striking proof of the velocity gradient extending across a circular orifice when the existing flow is laminar (Fig. 41.14). Since the greatest velocity exists at the center of the stream, the flame length at the center is likewise the greatest. Similarly, since the velocity of the gas stream is lowest at the walls of the tip (bore) where the flowing friction is greatest, that portion of the flame bordering the wall is the shortest.

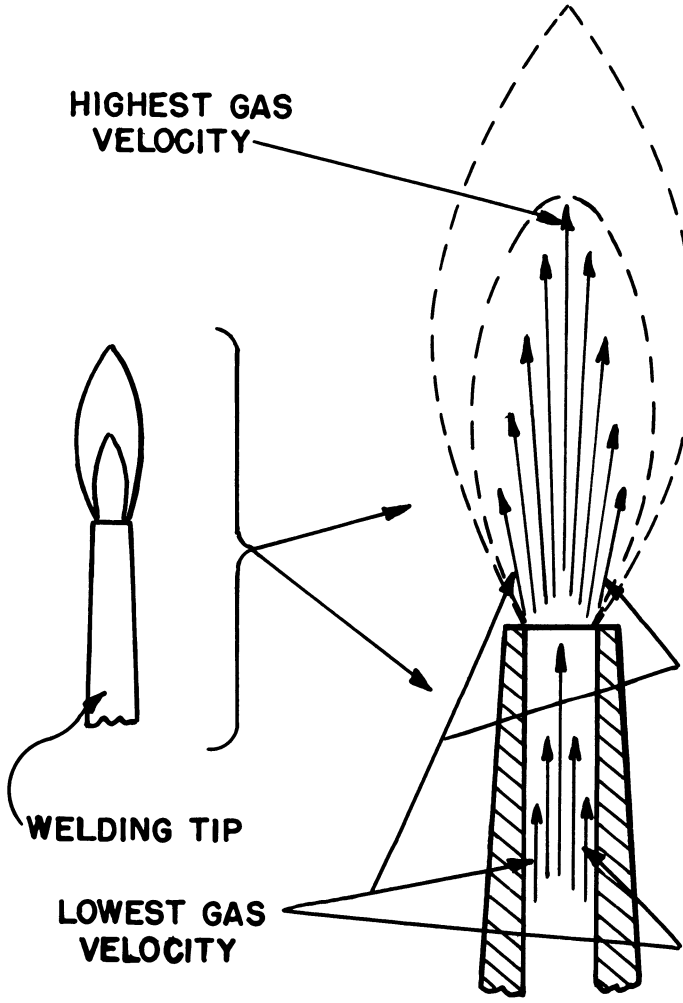


Fig. 41.14—Vector representation of laminar flow in a welding torch tip

From the analysis of the principles that underlie the formation of a flame cone, it is possible to understand the flow conditions that exist along the last portion of the gas passageway in a tip. The shape of the flame cones will depend upon a number of factors such as the smoothness of bore, the ratio of lead-in to final run diameter, and the sharpness of neck-down.

Generally speaking, the cone produced by a small tip will vary from a pointed to a semipointed shape. Cones from medium-sized tips will vary from a semipointed to a medium shape, and cones from a large-sized tip will vary from a semiblunt to a blunt shape (Fig. 41.15).

GAS REGULATORS

A gas regulator may be defined as a mechanical device for automatically maintaining a relatively constant reduced delivery pressure even though the inlet pressure and flow rate change. The four necessary and principal elements that constitute a pressure-reducing regulator are illustrated in Fig. 41.16 and may be listed as follows:

1. An adjusting screw that controls the thrust of the bonnet spring.
2. A bonnet spring that transmits to a diaphragm the thrust created by the adjusting screw and spring.
3. A diaphragm connected with the mating seat member.
4. A valve element consisting of a nozzle and a mating seat member.

The bonnet spring tends to hold the valve open while the gas pressure created on the underside of the diaphragm tends to allow the valve to close. When gas is withdrawn, the pressure under the diaphragm is reduced, thus further opening the valve and admitting more gas, until the forces on either side of the diaphragm are equal.

A given set of conditions, such as constant inlet pressure, constant volumetric rate of flow and constant outlet pressure, will produce a balanced condition whereby the nozzle and its mating seat member will remain at a fixed relationship to each other.

Basic Types of Regulators

There are two basic types of pressure-reducing regulators:

1. Stem type or inlet pressure closing (sometimes referred to as inverse or negative type) illustrated in Figs. 41.16a and 41.17.
2. Nozzle type or inlet pressure opening (sometimes referred to as direct-acting or positive type) illustrated in Fig. 41.16b.

Stem Type Regulators. — In the stem type regulator, the inlet pressure tends to close the seat member (pressure closing) against the nozzle. The outlet pressure of this type of regulator has a tendency to increase somewhat as the inlet pressure decreases. This increase is caused by a decrease of the force produced by the inlet gas pressure against the seating area, as the inlet pressure decreases.

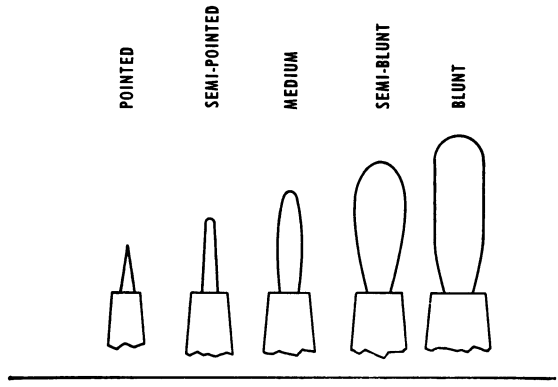


Fig. 41.15—Representative cone shapes produced by welding and heating tips

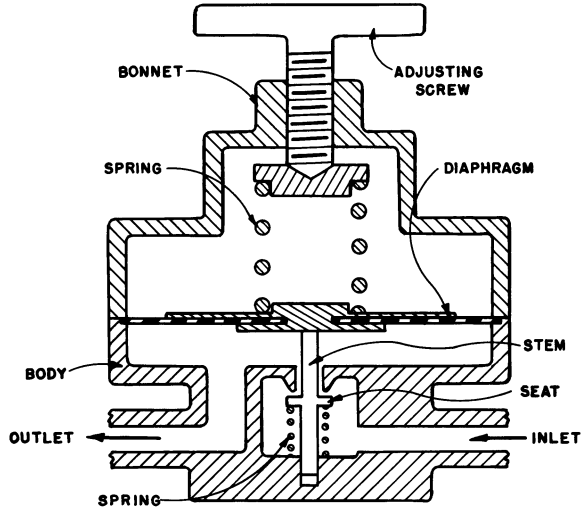
The gas outlet pressure for any particular setting of the adjusting screw is regulated by a balance of forces between the bonnet spring thrust and the opposing forces created by (1) the outlet pressure against the underside of the diaphragm, plus (2) the force created by the inlet pressure against the seating area. When the inlet pressure decreases, its force against the seat member decreases, allowing the bonnet spring force to move the seat member away from the nozzle. Thus, more gas pressure is allowed to build up against the diaphragm to re-establish the balanced condition.

Nozzle Type Regulators. — In the nozzle type of regulator the inlet pressure tends to move the seat member away (pressure opening) from the nozzle, thus opening the valve. The outlet pressure of this type of regulator decreases somewhat as the inlet pressure decreases, because the force tending to move the seat member away from the nozzle is reduced as the inlet pressure decreases. A small outlet pressure on the underside of the diaphragm is then required to close the seat member against the nozzle.

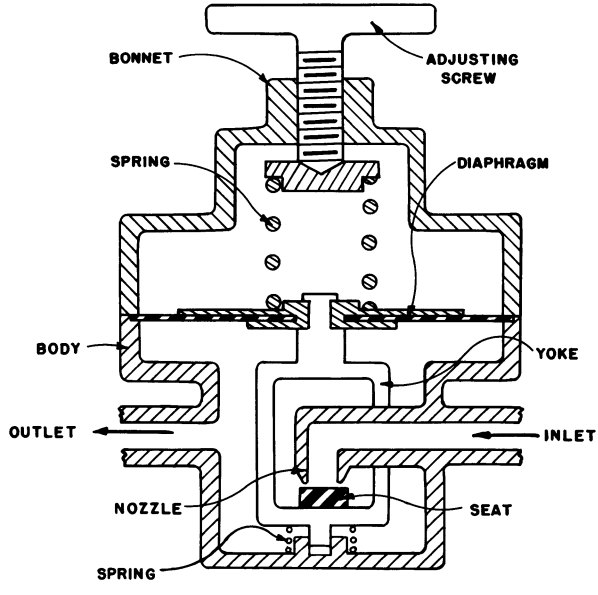
Two-Stage Regulators

The two-stage regulator was developed for more precise regulation over a wide range of varying inlet pressures. A two-stage regulator, as illustrated in Figs. 41.16c and 41.18 is actually two single-stage regulators in series and produced as one unit.

The outlet pressure from the first stage is usually preset to deliver a specified pressure to the inlet of the second stage. In this way, a practically constant delivery pressure may be obtained from the outlet of the regulator, even though the supply pressure should vary (as in depleting an oxygen cylinder from its initial pressure of approximately 2200 psig to 100 psig).


BONNET
ADJUSTING SCREW
SPRING
DIAPHRAGM
STEM
BODY
SEAT
OUTLET
INLET
SPRING

(A)


BONNET
ADJUSTING SCREW
SPRING
DIAPHRAGM
BODY
YOKE
OUTLET
INLET
NOZZLE
SEAT
SPRING

(B)

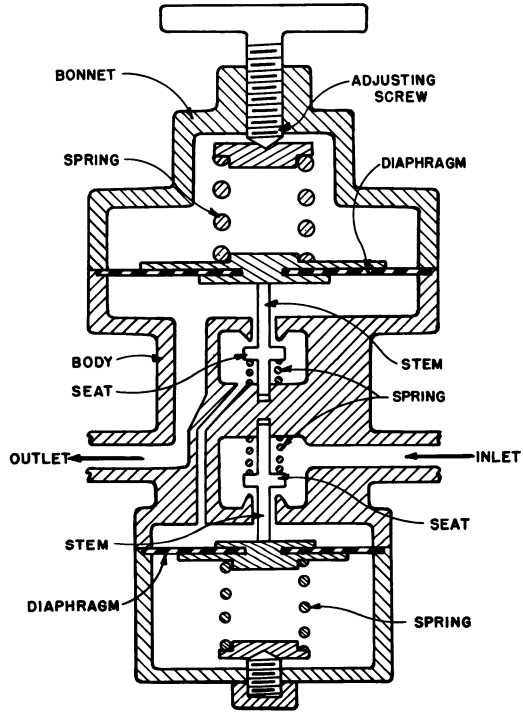


Fig. 41.16—Typical gas regulators (A) single-stage stem type (B) single-stage nozzle type (C) two stage

The combinations employed to make a two-stage regulator are as follows:

1. Nozzle type first stage and a stem type second stage.
2. Stem type first stage and a nozzle type second stage.
3. Two stem types (as illustrated in Fig. 41.16c).
4. Two nozzle types.

Regardless of the combination used, the increase or decrease in outlet pressure is usually so slight (and apparent only at very low inlet supply pressures) that, for all practical purposes, the variation in delivery pressure is disregarded in welding or cutting operations. Two- stage regulators are suggested for precise work, such as continuous machine cutting, in order to maintain a constant working pressure and a controlled volumetric flow rate at the welding or cutting torch.

Applications of Regulators in Gas Welding

Many kinds of regulators are produced for various applications. When gases are utilized from single cylinders, the regulators need not have very high capacities, probably a maximum of 1500cfh. When gas cylinders are manifolded, or a bulk delivery system is used, high-capacity regulators to supply large-volume distribution lines may have to flow as much as 50,000 cfh or more. Distribution-line station regulators are normally low-pressure types (up to 500 psig inlet pressure) and are available in various sizes depending upon the volumetric demand at the particular station. Because acetylene distribution lines are not permitted to carry more than 15 psig, the regulators must, in many cases, have a high volumetric capacity with a relatively low inlet pressure.

Regulator Inlet and Outlet Connections

The cylinder outlet connections are of different sizes and shapes to preclude the possibility of connecting to the wrong cylinder a regulator made for a particular gas or pressure. Regulators must, therefore, be made with different inlet connections to fit the cylinders. The Compressed Gas Association (CGA) has formulated a complete set of noninterchangeable cylinder valve outlet connections. A few of these connections are listed in Table 41.6.

Regulators should be used only for the service for which they were designed. Oxygen regulators, in particular, should never be used for any other service than for oxygen. Even traces of oil or foreign matter in an oxygen regulator can cause a violent explosion.

Regulator outlet fittings also differ in size and thread, depending upon the gas and regulator capacity. Oxygen outlet fittings have right-hand threads and fuel outlet fittings have left-hand threads with grooved nuts. Table 41.7 shows pertinent hose size and thread data as revised by the Compressed Gas Association.

Table 41.6—Cylinder valve outlet connections

Gas	CGA Standard Connection No.	Thread Size and Type
Acetylene	510	0.885"-14 NGO-LH-INT
Acetylene (Alternate Standard)	300	0.825"-14 NGO-RH-EXT
Acetylene (Canada only)	410	0.850"-14 NGO-LH-EXT
Acetylene (Small valve series)	200	0.625"-20 NGO-RH-EXT
Acetylene (Small valve series)	520	0.895"-18 NGO-RH-EXT
Argon	580	0.965"-14 NGO-RH-INT
Butane	510	0.885"-14 NGO-LH-INT
Butane (Alternate Standard)	300	0.825"-14 NGO-RH-EXT
Carbon Dioxide	320	0.825"-14 NGO-RH-EXT
Helium	580	0.965"-14 NGO-RH-INT
Helium (Alternate Standard)	350*	0.825"-14 NGO-LH-EXT
Hydrogen	350	0.825"-14 NGO-LH-EXT
Nitrogen	580	0.965"-14 NGO-RH-INT
Nitrogen (Alternate Standard)	590	0.965"-14 NGO-LH-INT
Oxygen	540	0.903"-14 NGO-RH-EXT
Propane	510	0.885"-14 NGO-LH-INT
Propane (Alternate Standard)	350*	0.825"-14 NGO-LH-EXT
Propane (Alternate Standard)	300	0.825"-14 NGO-RH-EXT

*obsolete effective January 1, 1972

Abbreviations:
NGO — National Gas Outlet
RH — Right Hand
LH — Left Hand
INT — Internal
EXT — External
From: American Standard "Compressed Gas Cylinder Valve Outlet and Inlet Connections (B57.1 — 1955)

Table 41.7—Hose size and thread data

Hose Sizes (I.D.)	Thread Size
3/16, 1/8	3/8-24 NF-2
3/8, 5/16, 1/4, 3/16, 1/8	9/16-18 NF-2
1/2, 3/8, 5/16, 1/4	7/8-14 NF-2
3/4, 5/8, 1/2, 7/9	1-1/4-12 NF-2

Recommended Practices for the Safe Use of Regulators

The following safety precautions should be observed when dealing with regulators:

1. Clean cylinder valve outlets with a clean, lint free, dry cloth and blow dust from the outlet by opening the valve momentarily before connecting the regulator to it. This is known as cracking the valve.
2. The regulator adjusting screw should be released (i.e., backed out) before opening the cylinder valve.
3. Always open cylinder valves very slowly so that the high-pressure gas does not surge into the regulator. When doing this, stand off to one side of the regulator rather than directly in front.
4. Check gages periodically to ensure correct readings.

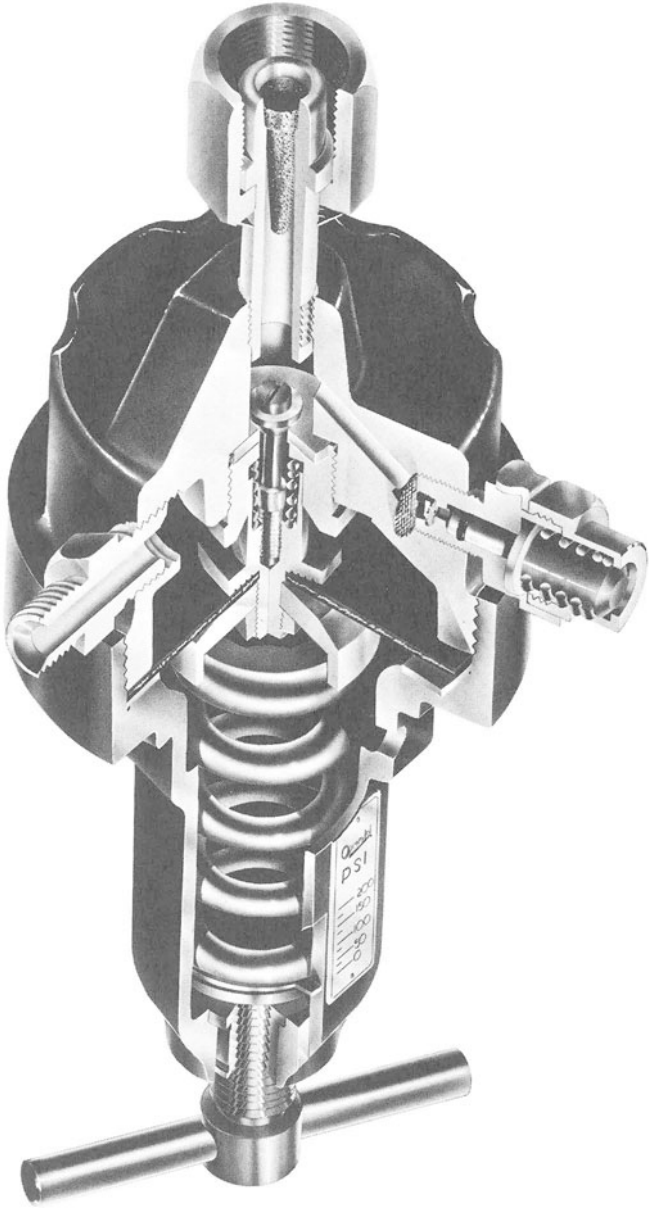


Fig. 41.17—Cutaway view of single-stage type regulator

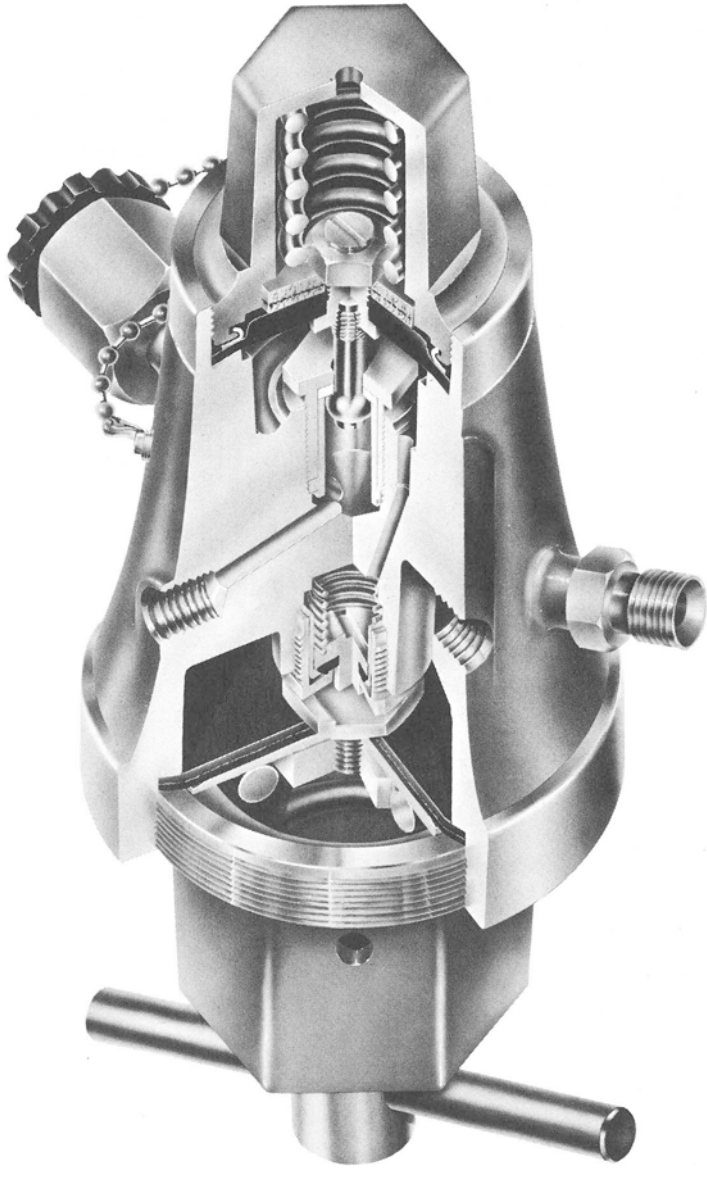


Fig. 41.18—Cutaway view of two stage regulator

5. Adjusting screws should be turned in slowly to protect the regulator diaphragm from damage caused by a sudden surge of high-pressure gas.
6. Always use the correct size wrench to connect the regulator to the cylinder valve outlet. Never force a connection.
7. Never use oil or grease on a regulator. A special lubricant sometimes is applied to equipment. The only lubricant that should be used is that specified by the manufacturer and it should be used only when specified.
8. If a leak is suspected, use a grease-free soapy water solution.
9. Regulators should be repaired by qualified, trained mechanics. Manufacturers' standard parts only should be used.

PORTABLE MANIFOLDS

Two types of portable manifolds are in general use.

In one type, shown in Fig. 41.19a, the cylinders are joined by tees connected to the individual cylinder valves and by leads, or pigtails, successively joining tee to tee. The gas from each cylinder passes through its tee and flows into the main gas stream to a single regulator, properly supported, serving the entire group of cylinders.

In the second type of portable manifold (Figs. 41.19b and c), the cylinders (usually from two to five in number) are connected by means of individual cylinder leads (pigtails) to a common coupler block, from which they are connected to a single, common pressure-reducing regulator.

These systems are extremely flexible and permit the manifolded cylinders to be located near the point of use. Such manifolds can be assembled rapidly when needed.

STATIONARY MANIFOLDS

A stationary manifold may be installed where very large volumes of gas are regularly required or where a centralized gas supply is desired. This type of manifold consists of an adequately supported high-pressure header to which a number of cylinders are connected by means of pigtails. One or more permanently mounted regulators reduce and regulate the pressure of a gas flowing from the manifold into the plant piping system.

An example of a stationary manifold is illustrated in Fig. 41.20. In this type of stationary manifold, two banks of cylinders are used. One bank of cylinders supplies the system, while the other is held in reserve. When the bank in use becomes exhausted, the other is placed on the line. In this way, uninterrupted service is assured.

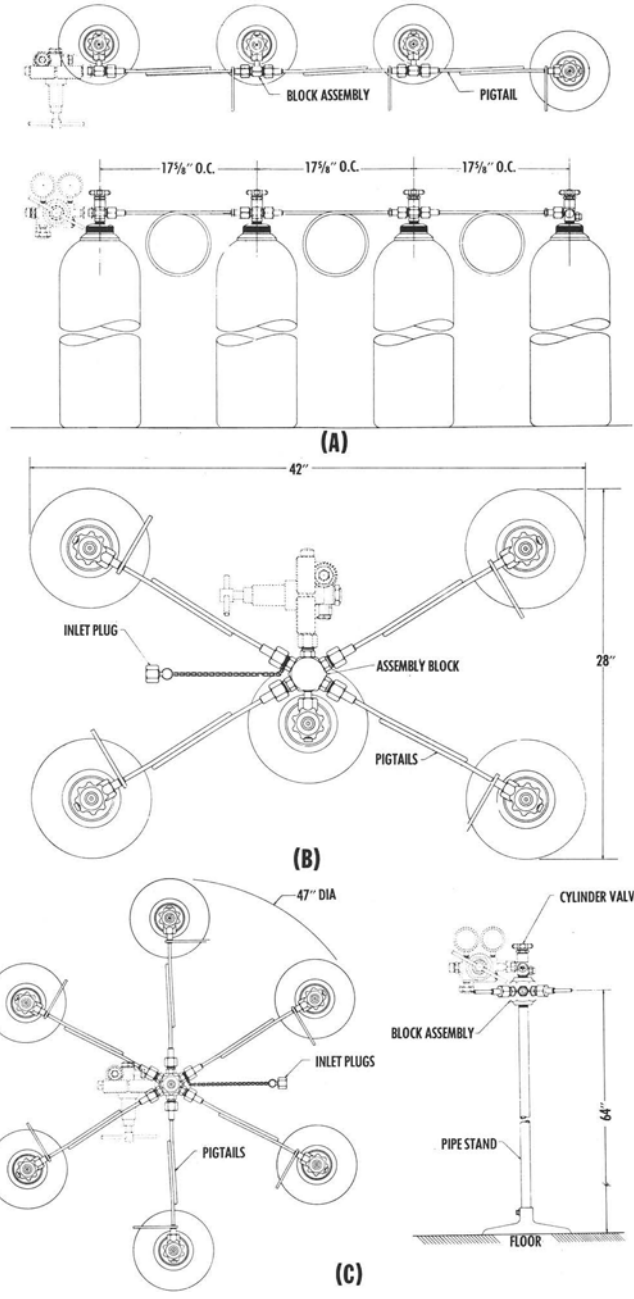


Fig. 41.19—Typical arrangements for portable oxygen manifolds. (A) 4 cylinder manifold (B) 5 cylinder manifold (C) 6 cylinder manifold

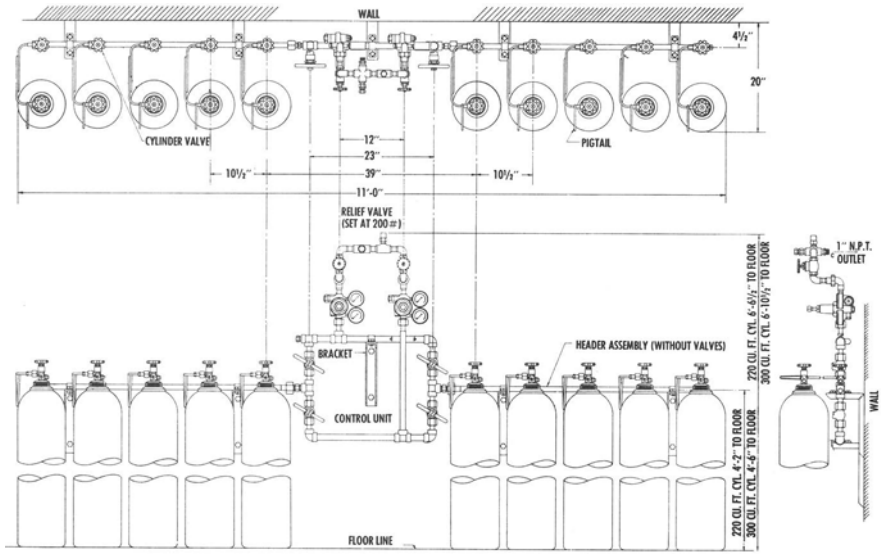


Fig. 41.20—Typical arrangement for stationary gas manifold

REGULATIONS AND SAFE PRACTICES FOR MANIFOLDS AND PIPELINES

The rules set forth in the current issue of "The Standards of the National Board of Fire Underwriters for the Installation and Operation of Oxy-Fuel Gas Systems for Welding and Cutting as Recommended by the National Fire Protection Association" (NFPA Pamphlet No. 51-69*) should govern in the installation of oxygen and acetylene manifolds and pipelines. Local regulations or ordinances should be consulted also to be sure of compliance. Manifolds should, in all cases, be obtained from reliable manufacturers and installed by personnel familiar with proper construction and installation practices.

The principal regulations published in 1969 governing fuel gas and oxygen manifolds are covered briefly below. (Consult the latest edition of the Standards for complete details.)*

General (for All Manifolds)

1. Manifolds must be of substantial construction. The design and materials shall be suitable for the particular gas and the intended service.
2. The pressures of the gas cylinders connected to and discharged simultaneously through a common manifold shall be approximately equal.

*Obtainable from the National Fire Protection Association, 60 Batterymarch Street, Boston, Massachusetts 02110

Fuel Gas Manifolds

1. Fuel gas cylinders connected to one manifold inside a building shall be limited to a total gas capacity not exceeding 3000 cubic feet. A manifold having a total gas capacity exceeding 3000 cubic feet shall be located outdoors or in a separate room.
2. More than one such stationary fuel gas manifold may be located in the same room if separated by at least 50 feet.
3. Where it is necessary to manifold fuel gas cylinders having an aggregate gas capacity in excess of 3000 cu ft, the cylinders shall be located outside, or in a special building or separate room constructed in accordance with the provisions of the regulations pertaining to such buildings or enclosures.
4. Special buildings or rooms, if provided, shall have no other occupancy, except that they may be used for the storage of cylinders containing fuel gases and drums of calcium carbide. Such buildings or rooms shall have no open flames for heating or lighting and shall be well ventilated.

Oxygen Manifolds

1. Oxygen manifolds shall not be located in an acetylene generator room or in close proximity to cylinders of combustible gases.
2. There should be a fire-resistant partition of one of the types of construction specified (elsewhere in the regulations) between the oxygen manifold and the combustible gas cylinders, unless they are well separated by a minimum distance of 20 feet.
3. Oxygen manifolds shall be separated by a minimum distance of 20 feet from highly flammable material, especially oil, grease or any substance likely to cause or accelerate fire.
4. Oxygen manifolds, to which cylinders having an aggregate capacity of more than 6000 cu ft of oxygen are connected, shall be located outdoors or in a special building.
5. If located inside a building (i.e., other than one directly associated with the production of acetylene, the storage of calcium carbide or the storage and manifolding of gases used in welding and cutting) having other occupancy, such manifolds shall be located in a separate room of fire-resistant construction, or in an area of fire-resistant construction with no combustible material within 20 ft of the manifold.

Pipeline Systems

In connection with pipeline systems, the 1969 regulations provide in part the following rules (consult the latest edition of the Standards for complete details):

1. For oxygen piping, steel, wrought iron, brass or copper shall be used. (Note: Refer to the Standards for weights of pipe and fittings to be used for different service pressures.)
2. For acetylene piping, steel or wrought iron pipe only shall be used. (Note: Refer to the Standards for weights of pipe and fittings to be used.)

3. Generally, all piping not specifically for use with oxygen or acetylene shall be of wrought iron, steel, brass or copper pipe or of seamless copper, brass or stainless steel tubing. (Note: Refer to the Standards for weights of pipe and/or tubing and fittings to be used for different service pressures.)
4. All piping shall be tested and proved gastight at 1½ times its maximum working pressure and shall be thoroughly purged of air before being placed in service. Any medium used for testing oxygen lines must be oil free.

Other rules for safety mentioned previously, concerning installation and operation of gas supply systems and equipment, plus the safety rules suggested in Section 1, Chapter 9, Sixth Edition, should be followed rigorously.

Hydraulic Seals. — An important protective device is the hydraulic seal (or back-pressure valve) which acts to prevent any backfires from passing into the manifold system, the generator or the pipelines (see Fig. 41.21). Essentially, the seal prevents passage of flame through the liquid mixture and also prevents the reverse flow of oxygen or oxyacetylene mixture back into the manifold or pipeline supply. These water seals must be of an approved type. The proper water level must be maintained at all times to ensure reliable and safe operation.

WELDING RODS

The properties of the metal deposited during welding should closely match those of the base metal. Because of this requirement, welding rods of various chemical compositions have been devised for the welding of many ferrous and nonferrous materials. Obviously, it is important that the correct welding rod be selected.

The welding process itself influences the filler metal chemistry, since certain elements tend to disappear during deposition. Filler metals that may be used to join almost all base materials in common use are available, as well as filler material for braze welding, brazing and soldering. The standard diameters vary from 1/16 to 3/8 in., and the standard lengths for drawn rods are 24 and 36 inches.

The chemical analysis of welding rods must be within the limits specified for that particular rod. There are many proprietary rods on the market recommended for specific applications. Filler metal should be free from blowholes, pipes, nonmetallic inclusions and any other foreign matter. The metal should deposit smoothly.

Allowances for changes taking place during welding are made in the chemistry of good welding rods, in order that the deposited metal will be of the correct composition. These changes are to be expected, but they should occur without undue sparking or spitting. Deposits should be made with free-flowing metal that unites readily with the base metal to produce sound, clean welds (Table 41.8).

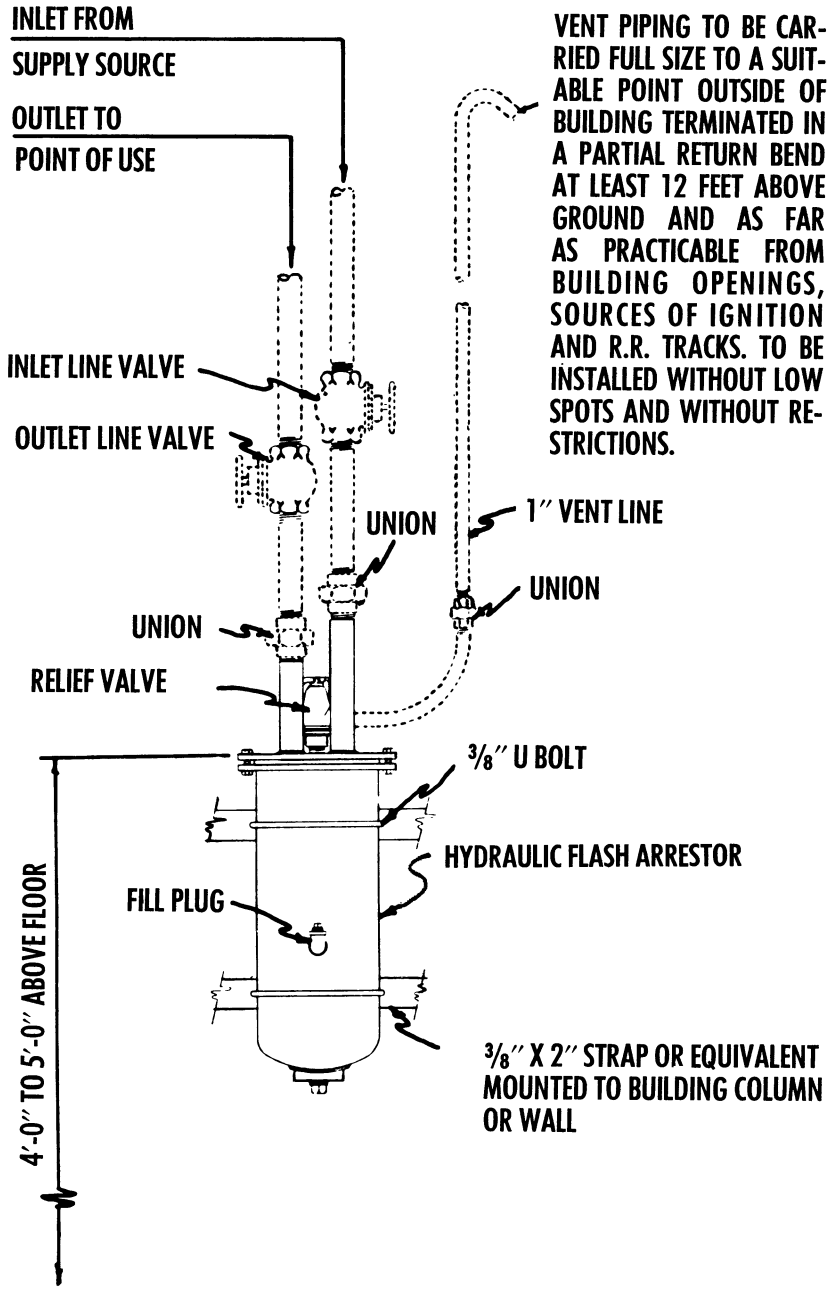


Fig. 41.21—Schematic diagram of piping arrangement for hydraulic flash arrestor installation. This arrangement is suitable only for acetylene gas.

Table 41.8— Welding data—ferrous metals

Metal	Flame Adjustment	Flux	Welding Rod
Steel, cast	Neutral	No	Steel
Steel pipe	Neutral	No	Steel
Steel plate	Neutral	No	Steel
Steel sheet	Neutral	No	Steel
	Slightly oxidizing	Yes	Bronze
High-carbon steel	Reducing	No	Steel
Wrought iron	Neutral	No	Steel
Galvanized iron	Neutral	No	Steel
	Slightly oxidizing	Yes	Bronze
Cast iron, gray	Neutral	Yes	Cast iron
	Slightly oxidizing	Yes	Bronze
Cast iron, malleable	Slightly oxidizing	Yes	Bronze
Cast iron pipe, gray	Neutral	Yes	Cast iron
	Slightly oxidizing	Yes	Bronze
Cast iron pipe	Neutral	Yes	Cast iron or base metal composition
Chromium-nickel steel castings	Neutral	Yes	Base metal composition 25-12 chromium-nickel steel
Chromium-nickel steel (18-8) and (25-12)	Neutral	Yes	Columbium stainless steel or base metal composition
Chromium steel	Neutral	Yes	Columbium stainless steel or base metal composition
Chromium iron	Neutral	Yes	Columbium stainless steel or base metal composition

In maintenance and repair work it is not always necessary that the composition of the welding rod match that of the base metal. A steel welding rod of nominal strength can be used to repair parts made of alloy steels broken by overloading or accident. An extreme example of this apparent side-stepping of the rules is the use of silver brazing alloys in the repair of tools such as milling cutters made of high-speed tool steel. Every effort should be made, however, to match the filler metal and base metal. Where it is necessary to heat treat a steel part after welding, carbon can be added to a deposit of mild steel by the judicious use of the carburizing flame. It is preferable, however, to use a welding rod of low-alloy steel.

The AWS Committee on Filler Metal has prepared a number of specifications. Many of the gas welding filler metals meet these specifications. In the chapters on the various metals and alloys in Section 4 will be found information on welding and on the selection of filler materials. Reference should also be made to Section 5.

FLUXES

One of the most important factors in weld quality is the removal of oxides from the surface of the metal to be welded. Unless the oxides are removed, fusion may be difficult, the joint may lack strength and inclusions may be present. The oxides will not flow from the weld zone but will remain to become entrapped in the solidifying metal, interfering with the addition of filler metal. These conditions may occur when the oxides have a higher melting point than the base metal, and a means must be found to remove the oxides. Fluxes are applied for this purpose.

Steel and its oxides and slags, which form during welding, do not fall into the above category and no flux is needed. Aluminum, however, forms an oxide with a very high melting point, and the oxide must be removed from the welding zone before satisfactory results can be obtained. Certain substances have been found that will react chemically with the oxides of most metals, forming fusible slags at welding temperature. These substances, either singly or in combination, have been developed and compounded to make efficient fluxes.

A good flux should assist in removing the oxides occurring during welding by forming fusible slags that will float to the top of the molten puddle and not interfere with the deposition and fusion of filler metal. It should protect the molten puddle from atmospheric oxygen and prevent the absorption and reaction of other gases in the flame, without obscuring the welder's vision or hampering his manipulation of the molten puddle.

During the preheating and welding periods, the flux should clean and protect the surfaces of the base metal and, in some cases, the welding rod. Flux should not be used as a substitute for base metal cleaning during joint preparation. Flux is an excellent metal cleaner, but if its strength is used for this purpose, it will be useless for its primary functions.

Flux may be prepared as a dry powder, as a paste or thick solution, or as a preplaced coating on the welding rod. Some fluxes operate much more favorable if they are used dry. Braze welding fluxes and fluxes for use in cast iron are usually in this class. These fluxes are applied by heating the end of the welding rod and dipping it into the powdered flux. Enough will adhere to flux adequately until the flux-coated portion of the rod is consumed. Dipping the hot rod into the flux coats another portion. Dropping some of the dry powder on the base metal ahead of the welding zone will sometimes help, especially in the repair of dirty and oil-soaked castings.

Fluxes in paste form are usually painted on the base metal with a brush, and the welding rod can either be painted or dipped. Commercial precoated rods can be used without further preparation, and when additional flux is required it can be placed on the base metal. Sometimes a precoated rod will have to be dipped in powdered flux if the flux is melted off too far from the end of the rod.

The common metals and welding rods requiring fluxes are bronze, cast iron, brass, silicon bronzes, stainless steel and aluminum.

ACCESSORIES

In addition to the equipment and materials described above, an almost limitless variety of auxiliary equipment may be used in the process of gas welding. Only a brief description of such items is included here.

One of the most universally required articles is the friction lighter, which should always be used to ignite the gas.

Other accessories, such as tip cleaners, cylinder trucks, clamps, holding jigs and fixtures, gas savers for automatically shutting off the torch flames, and devices for entraining liquid flux into the acetylene stream for brazing operations, are also important auxiliary aids for gas welding.

Welders should at all times use goggles or eyeshields as a protection against the excessive glare and radiated heat of the flame and molten metal. Suitable gloves, leather aprons, sleeves and leggings should also be worn. Additional information on this subject may be obtained in Section 1, Chapter 9, Sixth Edition.

OXYACETYLENE WELDING

PRINCIPLES OF OPERATION

The oxyacetylene welding torch serves as the medium for mixing the combustible and combustion-supporting gases and provides the means for applying the flame at the desired location. A range of tip sizes is provided for obtaining the required volume or size of welding flame, which may vary from a short, small-diameter needle flame to a flame 3/16 in. or more in diameter and 2 in. or more in length.

The inner cone or vivid blue flame of the burning mixture of gases issuing from the tip is called the working flame. The closer the end of the flame's inner cone is to the surface of the metal being heated or welded, the more effective is the heat transfer from flame to metal. The oxyacetylene flame can be made soft or harsh by varying the gas flow. Too low a gas flow for a given tip size will result in a soft, ineffective flame sensitive to burnback. Too high a gas flow will result in a harsh, high-velocity flame that is hard to handle and will blow the molten metal from the puddle.

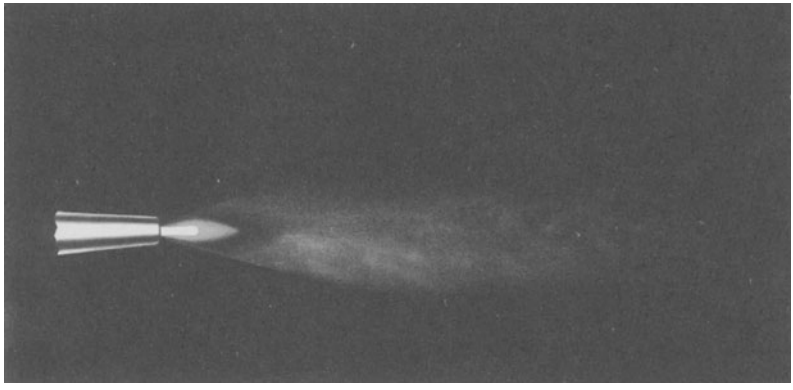
The chemical action of the flame on a molten pool of metal can be altered by changing the ratio of the volume of oxygen to acetylene issuing from the tip. Most welding is done with a neutral flame having approximately a 1:1 gas ratio. An oxidizing action can be obtained by increasing the oxygen flow, and a carburizing action will result from increasing the acetylene flow. Both adjustments are valuable aids in welding.

Flame Adjustment

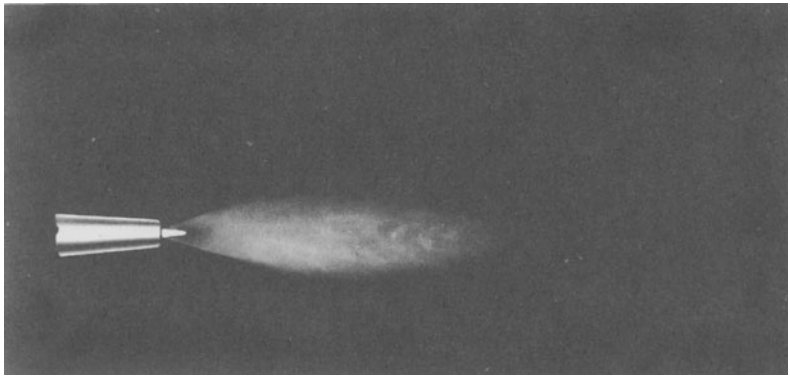
Torches should be lighted with a friction lighter or a pilot flame. The instructions of the equipment manufacturer should be observed when adjusting operating pressures at the regulators and torch valves before the gases issuing from the tip are ignited. Three types of flame adjustment are shown in Fig. 41.22.

The neutral flame is obtained most easily by adjustment from an excess-acetylene flame, which is recognized by the feather extension of the inner cone. The feather will diminish as the flow of acetylene is decreased or the flow of oxygen is increased. The neutral flame is obtained just at the point of disappearance of the "feather" extension of the inner cone.

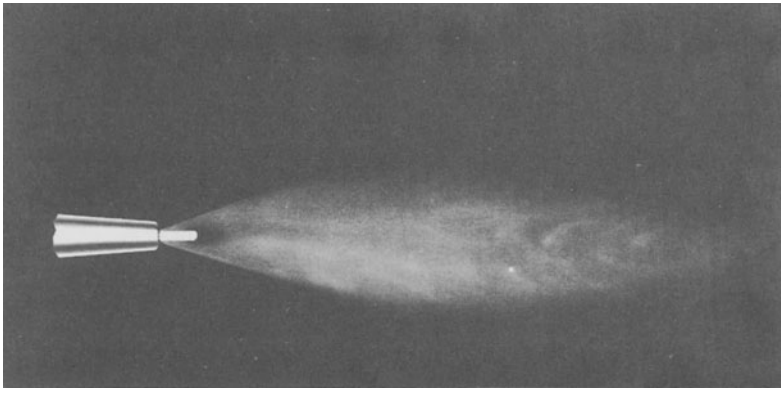
A practical method of determining the amount of excess acetylene in a flame when a reducing or carburizing flame is desired, is to compare the length of the feather with the length of the inner cone, measuring both from



(a)—Oxyacetylene flame—carburizing



(b)—Oxyacetylene flame—oxidizing



(c)—Oxyacetylene flame—neutral

Fig. 41.22—Three types of flame adjustment

the torch tip. A 2X excess-acetylene flame has an acetylene feather that is double the length of the inner cone. Starting with a neutral flame adjustment, the welder can produce the desired acetylene feather by increasing the acetylne flow (or by dcreasing the oxygen flow).

The oxidizing flame adjustment is sometimes given as the amount by which the length of the inner cone should be reduced — for example, one tenth. Starting with the neutral flame, the welder can increase the oxygen (or decrease the acetylene) until the length of the inner cone is decreased the desired amount.

Specifications requiring a reducing flame and mentioning the length of the feather should be adhered to closely, since the carbon pickup in the weld is determined by the excess acetylene in the flame. Where oxidizing flames are necessary, the degree of adjustment is usually determined by the action of the flame on the molten metal. This is especially true in the braze welding of brass or braze welding of steel.

Technique

Oxyacetylene welding may be performed with the torch tip pointed forward in the direction in which the weld progresses. This method is called the forehand technique (see Fig. 41.23a). The tip can also be pointed back toward the weld that has been deposited, and this method is called the backhand technique (Fig. 41.23b). Each technique has its advantages, depending upon the application.

In general, the forehand method is recommended for welding material up to 1/8 in. thick, because it provides better control of the small weld puddle, resulting in a smoother weld at both top and bottom. The puddle of molten metal is small and easily controlled. A great deal of pipe welding is done using the forehand technique, even in 3/8 in. wall thicknesses.

Increased speeds and better control of the puddle are possible with the backhand technique when metal 1/8 in. and thicker is welded. The recommendation that material greater than 1/8 in. thick be welded with the backhand technique is based on careful study of the speeds normally achieved with this technique and on the greater ease of obtaining fusion at the root of the weld. Backhand welding may be used with a reducing flame when it is desired to melt only the smallest possible amount of steel in making the joint. The increased carbon content obtained from the reducing flame lowers the melting point of a thin layer of steel and increases welding speed. This technique greatly increases the speed of making pipe joints where the wall thickness is 1/4 to 5/16 in. and the groove angle is reduced. Backhand welding is also sometimes used in surfacing operations.

Base Metal Preparation

Cleanliness along the joint and on the sides of the base metal is of the utmost importance. Dirt, oil and oxides can cause blowholes, incomplete fusion, slag inclusions and porosity in the weld.

The spacing between parts to be joined should be considered carefully. The root opening for a given thickness of material should permit the gap to be bridged without difficulty, yet should be large enough to permit full penetration. Specifications for root openings should be adhered to rigidly.

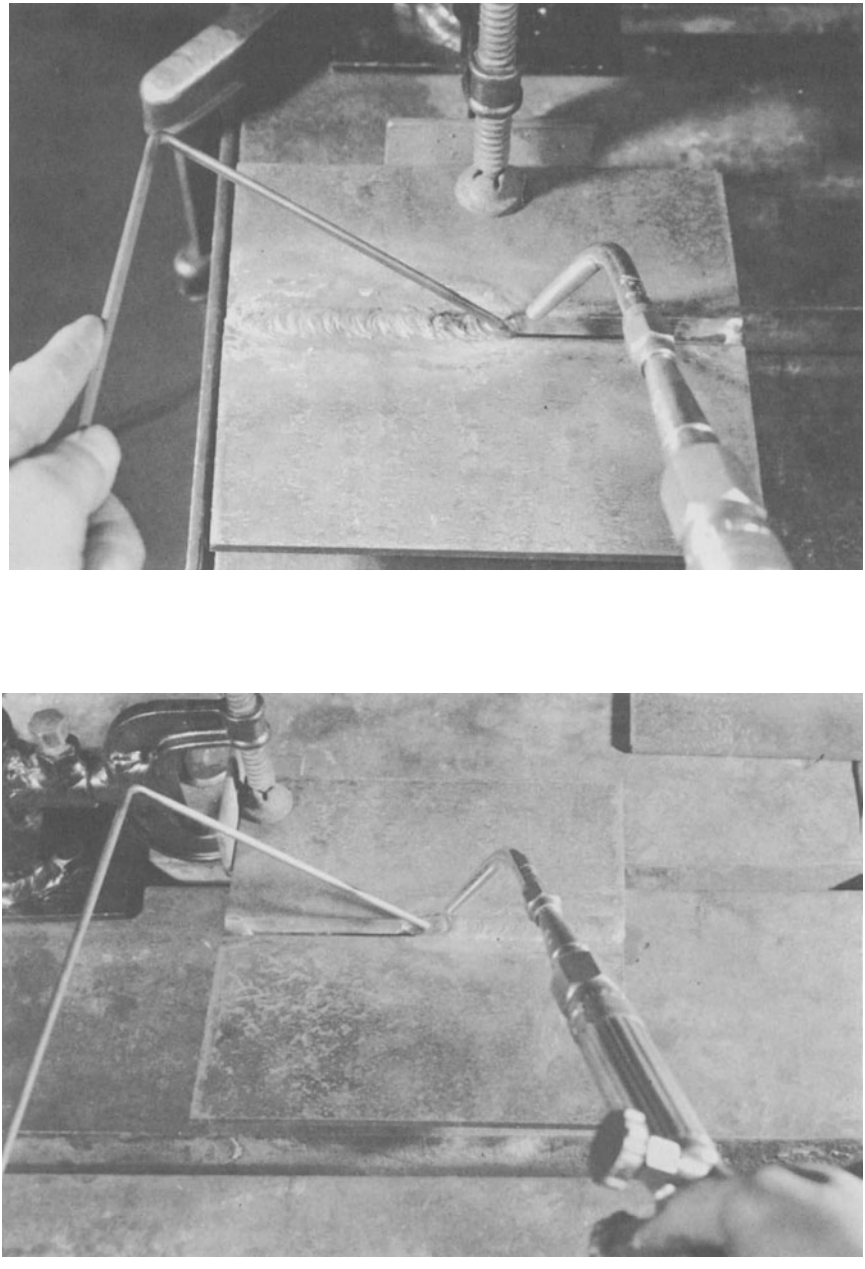


Fig. 41.23—Basic oxyacetylene torch-filler metal manipulation techniques: A (top)—Forehand technique, B (bottom)—Backhand technique

The thickness of the base metal at the joint determines the amount of edge preparation for welding. Thin sheet metal is easily melted completely by the flame. Thus edges with square faces can be butted together and welded. This type of joint is limited to material approximately 3/16 in. or less in thickness. For thicknesses of 3/16 to 1/4 in., a slight root opening is necessary for complete penetration, but filler metal must be added to compensate for the opening.

Joint edges 1/4 in. and greater in thickness should be beveled. Beveled edges at the joint provide a groove for better penetration and fusion at the sides. The angle of bevel for oxyacetylene welding varies from 35 to 45° which is equivalent to a variation in the included angle from 70 to 90°, depending upon the application. A root face 1/16 in. wide is provided, but feather edges are sometimes used. Plate thickness 3/4 in. and above are double beveled when welding can be done from both sides. The root face can vary from 0 to 1/8 inches. Beveling both sides reduces by approximately one-half the amount of filler metal required. Gas consumption per foot of weld is also reduced.

An edge preparation with straight sides is easiest to obtain. This edge can be machined, chipped, ground or oxygen cut. The thin oxide coating on an oxygen-cut surface does not have to be removed, because it is not detrimental to the welding operation or to the quality of the joint. The bevel angle can be oxygen cut to any desired value. See Section 1, Chapter 8, Sixth Edition, for further details and sketches. Reference should also be made to Sixth Edition, Chapter 42.

MULTILAYER WELDING

Multilayer welding is used when maximum ductility of a steel weld in the as-welded or stress-relieved condition is desired or if several layers are required in welding thick material. Multilayer welding is accomplished by depositing filler metal in successive passes along the joint until it is filled. Since the area covered with each pass is small, the weld puddle is reduced in size. This procedure enables the welder to secure complete penetration and to avoid icicles and overheating while the first layers are being deposited. The smaller puddle is more easily controlled and thus the welder can avoid oxides, slag inclusions, cold shuts (joint discontinuity caused by insufficient localized temperature to cause materials to coalesce) and incomplete fusion with the base metal.

An increase in ductility in the deposited steel results from grain refinement in the underlying layers as they are reheated. The final layer will not possess this refinement unless an extra layer is added and removed, or unless the torch is passed over the joint to bring the last deposit up to a normalizing temperature.

Gas welding is not recommended in welding the high-strength heat treatable materials, especially when they are being fabricated in the heat-treated condition. In welding the heat-treated materials the slow rate of heat input in gas welding can cause metallurgical changes in the heat-affected area and destroy the heat-treated base metal properties. This type of material should be welded with one of the arc welding processes. Interpass welding temperature on the final passes is generally held between 300 and 450°F (149 and 232°C), and in addition, the heat energy (Joules per in.) must be maintained within the limits recommended by the manufacturers of the material being welded.

EFFECTS OF OXYACETYLENE WELDING

One of the greatest problems in all welding operations is to prevent the desirable properties of a metal from being adversely affected by the heat of welding. Precautions taken while setting up can minimize distortion. Correct design can often prevent complications from arising; controlled cooling may avoid undesirable metallurgical changes.

One of the characteristics of oxyacetylene welding is the steep temperature gradient across the base metal surrounding the joint. This temperature gradient causes distortion of the pieces being joined. Various procedures are available to control or reduce the distortion. Figure 41.24 illustrates representative temperature conditions surrounding the pool of molten metal transverse to the joint line. A somewhat similar pattern exists in a longitudinal direction, but the temperature gradients are not symmetrical.

Parts to be welded should be tack welded securely in place before strength welds are applied. The section least subject to distortion should be welded first, thus forming a rigid structure for the balance of the assembly.

When the design of the structure permits welding from both sides, distortion can be minimized by welding alternately on each side of the joint. Strongbacks or braces can be applied to sections most likely to distort. The welds may be peened to correct distortion. This method, if properly carried out, can overcome severe warpage. A wandering or backstep sequence of welding may be used to control distortion. This method consists primarily of making short welds, with intervening sections left unwelded until the initial welds have partly cooled. A weldment should be so designed that distortion during welding will be minimized.

Metallurgical Effects

The temperature of the base metal varies during welding from melting temperature in the weld puddle to room temperature in the areas most remote from the heat. When steels are involved, the area near and in the weld is heated considerably above the transformation temperature of the steel. This results in a coarse grain structure in the weld and adjacent base metal. The coarse grain structure can be refined by a normalizing heat treatment (heating to 1500 to 1600°F (816 to 871°C) and cooling in air) after welding.

Hardening of the weld and adjacent base metal, heated to above the transformation temperature of the steel, can occur if the steel contains sufficient carbon and the cooling rate is high enough. Hardening can be avoided in most hardenable steels by using the torch to keep heat on the weld for a short time after the weld is completed. If air-hardening steels are welded, the best heat treatment is a full furnace anneal of the welded item. Hardness in the weld zone usually should be avoided because of the corresponding lack of ductility and susceptibility to cracking.

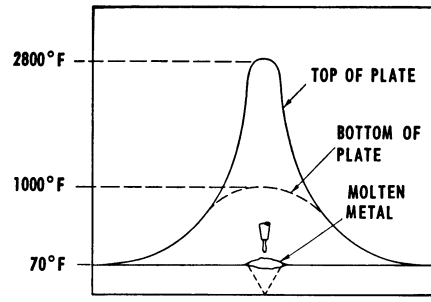


Fig. 41.24—Temperature pattern transverse to joint during welding, ½ in. thick plate

The oxyacetylene flame allows a degree of control to be maintained over the carbon content of the deposited metal and over the portion of the base metal that is heated to its melting temperature. When an oxidizing flame is used a rapid reaction results between the oxygen and the carbon of the metal. Some of the carbon is eliminated in the form of carbon monoxide, and the steel itself and other constituents are also oxidized. When the torch is used with an excess-acetylene flame, carbon is introduced into the weld puddle.

Upon being heated to a temperature range between 800 and 1600°F (427 and 871°C), carbide precipitation occurs in unstabilized austenitic stainless steel. These carbides gather at the grain boundaries and lower corrosion resistance in the areas adjoining the weld. If this occurs, a further heat treatment after welding is required, unless the steel has been stabilized by the addition of columbium or titanium and welded with the aid of a columbium-bearing welding rod. The columbium combines with the carbon and minimizes the formation of chromium carbide. All the chromium is left dissolved in the austenitic matrix which is the form in which it can resist corrosion to the greatest extent.

Another factor to be considered in welding is the possible tendency toward hot shortness of the material (a marked loss in strength at high temperatures). Some of the copper-base alloys have this tendency to a high degree. If the base metal has this tendency, it should be welded with care to prevent hot cracking in the weld zone. Allowances should be made in the welding technique used with these materials, and jigging or clamping should be done with caution. Proper welding sequence and multilayer welding with narrow string beads help to reduce hot cracking.

Oxidation and Reduction

Certain metals have such a high affinity for oxygen that oxides form on the surface almost as rapidly as they are removed. In oxyacetylene operations these oxides are usually removed by means of fluxes. This affinity for oxygen can be a very useful characteristic in certain welding operations. Manganese and silicon, for example, are elements common to plain carbon steel. They are important in oxyacetylene welding because they react with oxygen when the metal is molten.

The reaction produces a very thin slag covering that tends to prevent any oxygen from contacting the weld metal and prevents the formation of gas pockets. When the viscosity of the slag covering is properly controlled, the molten metal may be kept in position even against the pull of gravity. The action of these elements in oxyacetylene welding is the same as in steelmaking. They are used to produce clean, deoxidized metal in open-hearth or electric furnaces. The correct manganese and silicon content in steel welding rods is therefore important.

The type of flame used in welding various materials plays an important part in securing the most desirable deposit of weld metal. The proper type of flame with the correct welding technique can be used as a shielding medium which will reduce the oxidizing and nitrogenizing effect of the atmosphere on the molten metal. Such a flame also has the effect of stabilizing the molten weld metal and preventing the burning-out of carbon, manganese and other alloying elements.

The proper type of flame for any application is determined by the type of base and filler metal involved, the thickness of the base metal and the position of welding. For most metals a neutral flame is used. An exception is the welding of aluminum where a slightly carburizing flame is used. For specific information, reference should be made to the appropriate chapters in Section 4, Metals and Their Weldability.

Weld Quality

The appearance of a weld does not necessarily indicate its quality. If defects exist in a weld, they can be grouped into two broad classifications: those that are apparent to visual inspection and those that are not. A visual examination of the underside of a weld will determine whether complete penetration has been obtained or whether there are excessive globules of metal. Inadequate joint penetration may be due to insufficient chamfering of the edges, too wide a root face, too great a welding speed or poor torch and welding rod manipulation.

Oversized and undersized welds can be observed readily. Weld gages have been developed which make it easy to determine whether a weld has excessive or insufficient reinforcement. Undercut or overlap at the sides of the welds can usually be detected through visual inspection.

Although other defects such as incomplete fusion, porosity and cracking may or may not be externally apparent, excessive grain growth or the presence of hard spots cannot be determined visually. Incomplete fusion may be a result of insufficient heating of the base metal, too rapid travel or gas or dirt inclusions. Porosity is a result of included gases, usually carbon monoxide, which may be avoided by more careful flame manipulation and adequate fluxing where needed. Hard spots and cracking are a result of metallurgical characteristics mentioned under Metallurgical Effects. For further details see Section 1, Fundamentals of Welding Metallurgy.

Inspection

The term inspection usually implies the formal inspection, prescribed by a code or by the requirements of a purchaser, given to welds and welded structures and covering the type of construction involved. As far as welding is concerned, the minimum requirements of the codes are inflexible and must be met. Codes vary somewhat in their requirements with respect to the testing and inspection of the finished structure. For further details see Section 1, Chapter 6, Sixth Edition.

METALS WELDED

Oxyacetylene welding is used on the whole range of commercial ferrous and nonferrous metals and alloys. As in any welding process, however, physical dimensions and chemical composition may limit the weldability of certain materials and pieces.

In gas welding the temperature range through which the metal is taken is almost the same as that of the original casting procedure. The base metal in the weld area loses those properties that were given to it by heat treatment or cold working. The ability to weld such materials as high-carbon and high-alloy steels is limited by the equipment available for heat treating after welding. These metals are commonly welded with success when the size or nature of the piece permits postheat treating operations.

The welding procedure for wrought iron and plain carbon steels is straightforward and offers little difficulty to the welder. Sound welds are produced in other materials by approximate variations in technique, heat treating, preheating and fluxing.

The oxyacetylene welding process can be used for welding metal of considerable thickness and for the usual assemblies encountered in maintenance and repair (Fig. 41.25). Cast iron machinery frames that are one or more feet in thickness at the fracture point have been repaired by braze welding or by welding with a cast iron filler rod.

Iron and Steel

Low-carbon, low-alloy steels, cast steels and wrought iron are the materials most easily welded by the oxyacetylene process. Fluxes are not required when welding these materials.

In oxyacetylene welding, straight carbon steels having more than 0.35% carbon are considered high-carbon steels and necessitate special care to maintain their particular properties. Alloy steels of the air-hardening type also require precautions to maintain their properties, even though the carbon content may be 0.35% or less. The joint area usually is preheated in order to retard the cooling of the weld caused by conduction of heat into surrounding base metal. Slow cooling prevents the hardness and brittleness associated with rapid cooling.

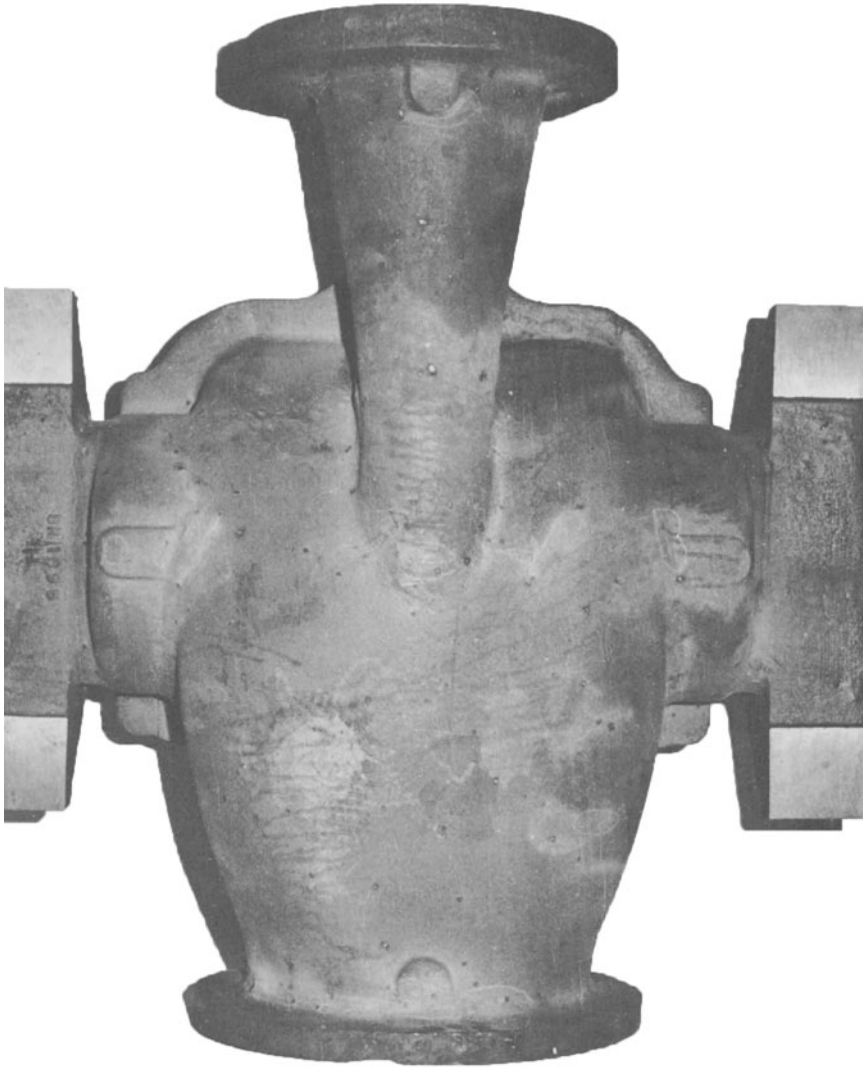


Fig. 41.25—Large cast iron casing repaired by gas welding. Casing has a vertical dimension of 48 in.

If hardening occurs, a postheat treatment is necessary. The welder should use a carburizing flame for welding and should be careful not to overheat the base metal and burn out the carbon. The preheating temperature required depends upon the composition of the steel to be welded. Temperatures of from 300 to 1000°F (149 to 538°C), have been used.

In addition to proper preheat temperature it is important that this preheat be maintained uniformly during welding. A uniform temperature is maintained by protecting the part with a covering formed by an asbestos blanket (Fig. 41.26). Other means of shielding can also be used to retain the temperature in the casting. Generally the maximum temperature during welding should not exceed the preheat temperature by more than 150°F (66°C). High welding or interpass temperatures cause excessive shrinkage forces than can bring about either distortion or cracking at the weld or other sections. In the welding of circular structures made from brittle metals, such as cast iron, this type of cracking frequently occurs. Sections with excessive locked-up structural stresses such as the water boxes shown in Fig. 41.26 are typical examples.

Modifications in procedures are required for stainless and similar steels. Because of their high chromium or chromium-nickel content, these steels have a relatively low heat conductivity. A smaller flame than that used for equal thicknesses of plain carbon steel is recommended. Because chromium oxidizes easily, a neutral flame is employed to minimize oxidation. A flux is used to dissolve oxides and protect the weld metal. A welding rod of high-chromium or nickel-chromium steel supplies the filler metal. Table 41.8 summarizes the basic information for welding ferrous metals.

Cast iron, malleable iron and galvanized iron all present particular problems in welding by any method. The gray cast iron structure in cast iron can be maintained through the weld area by use of preheat, a flux and an appropriate case iron welding rod.

Nodular iron requires materials in the welding filler metal that will assist in promoting nodularization of the free graphite to maintain ductility and shock absorption of the heat-affected area. Manufacturers of welding filler metal should be consulted to obtain information on preheat and interpass temperature control for the filler material being used.

Although there are instances in which cast iron materials are welded without preheat, particularly in salvage work, preheat of 400 to 600°F (204 to 316°C) with control of interpass temperature and provision for slow cooling will assure more consistent results. Protection such as the asbestos covering shown in Fig. 41.26 can be used to assure slow and uniform cooling. Care should be taken that venting or localized cooling is not allowed to occur because of exposed areas or a break in uniform covering such as a tear in the blanket.

It is also important to stress that in the salvage of cast iron, removal of all foundry sand and slag is necessary for consistent repair results. Test work on vessels as shown in Fig. 41.27 consistently produces weld joints equal to or greater in strength than the stress relieved vessel.

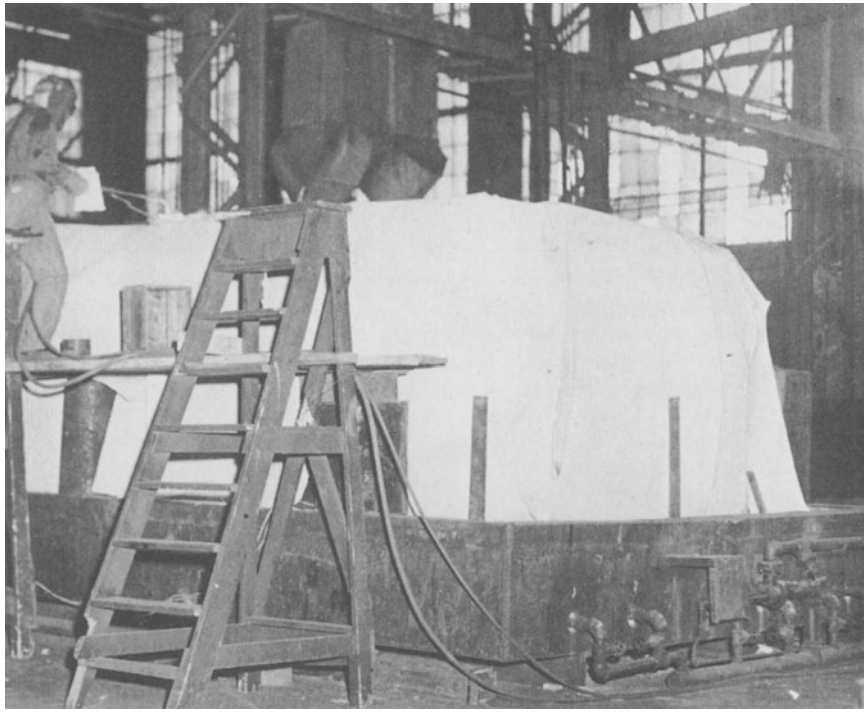


Fig. 41.26—Large cast iron water box being salvaged by gas welding using cast iron filler rod. The casting is preheated to 600° F in a large preheating box. Preheat temperature is maintained with an asbestos blanket.

Nonferrous Metals

The particular properties of each nonferrous alloy should be considered when selecting the most suitable welding technique. When the necessary precautions are taken, little difficulty due to the nature of the metal should be encountered.

Aluminum, for instance, gives no warning by changing color prior to melting, but appears to collapse suddenly at the melting point. Consequently, practice in welding is required to learn to control the rate of heat input. Aluminum and its alloys suffer from hot shortness and should be supported adequately in all the areas heated during the welding. Finally, any exposed aluminum surface is always covered with a layer of oxide that, combining with the flux, forms a fusible slag that floats on top of the molten metal.

When copper is welded, allowances for the chilling of the weld, due to the very high thermal conductivity of copper, are necessary. Preheating is often required. Considerable distortion can be expected in copper because the coefficient of thermal expansion is higher than in other commercial metals. These characteristics obviously pose difficulties that must be surmounted for satisfactory welding.



Fig. 41.27—Welding on cast iron pressure vessel. Inset shows welded vessel

MANUAL WELDING OPERATIONS

A welding torch that may be held in the hand can be classed as manual. Most oxyacetylene welding is done manually. It is important, therefore, that the equipment be suitable for the operation and that the welder be trained in its use. The regulators for any particular size of torch should have adequate gas capacity for the flow rates required. Oxygen cutting may also be done by the welder, using either a cutting attachment on a welding torch or a separate cutting torch. See Section 1, Chapter 9, Sixth Edition, for safety precautions in the use and handling of welding and cutting equipment.

AUTOMATIC WELDING OPERATIONS

When high production rates of welded parts are required, automatic or semi-automatic welding machines are used. Gas-welded tubing is an example of an almost continuous type of welding operation. Parts such as washing machine tubs, sheet steel tanks and containers are welded individually. The gas control system for automatic welding employs regulators, valves and other equipment designed for continuous operation. Special welding heads or burners are required. Many of these are the multiflame type.

The flexibility of manual operations is not possible in automatic welding. Consequently, parts to be welded must be formed to higher standards. In manual operations widely spaced joints could be filled by torch manipulation and additional deposits of filler metal, but this would not be possible in automatic welding. Accurate alignment of groove edges in the jigs or other holding devices is necessary. This factor should be considered at the design stage.

The nature of the work will determine whether the machine provides for movement of the material under the torch or movement of the torch over the joint. Tube and circumferential welding is best done by moving the work. Relatively short longitudinal welds in cylindrical shapes usually are made by moving the torch, since the jigs may be heavy and massive. Careful attention should be given to securing the proper distance from the abutting edges of the joint to the edge of the jig or clamp. If this distance is too small, enough heat may be removed from the weld puddle to make welding difficult. If the distance is too great, poor alignment is apt to occur when heat buckles the joint area. The correct distance sometimes must be determined by experiment. A rod feed of the gravity type, or a force feed by means of rollers contacting the rod, is used where filler metal is needed to make the weld.

Automatic operations are often advantageous for repetitive welding and brazing applications. The items required for the heating system include the following: shut-off valves, filters and hydraulic back-pressure valves, regulators, flowmeters, gas flow adjusting valves, automatic shut-off valves, torches or mixing blocks, and usually special burners or tips. Indexing tables or straight line conveyors may be necessary to move the workpieces to and from the heating zone. When cycle heating is necessary, a timer is used to operate the automatic shut-off valves.

A great deal of attention must be given to the design of the special heating burners and tips usually required for automatic operation. Heat must be applied at the correct locations and in the required amount. Water cooling should be provided, since burners must operate for long periods without overheating. Many types of special burners are necessary to perform the various heating operations and for heating in combination with metal forming and closing operations. It is necessary in most operations to design a special heating burner that will fit the contour of the piece and provide the proper distribution of heat as desired.

BRAZE WELDING

The main requirements for acceptable results in braze welding is cleanliness of the joint edges. The surfaces to be joined should be clean and free of oil, dirt and rust. In the presence of a suitable flux and the right amount of heat, the filler metal will flow and wet the joint surfaces. The joint can be completed in one pass, or successive passes can be made if the groove is large.

When malleable iron is welded, the melting of the base metal converts the heat-affected zone to white or hard cast iron. Braze welding with filler metal having a lower melting point produces a minimum change in the base metal characteristics and effects a high-strength joint generally equivalent to the strength of the filler metal.

SURFACING OPERATIONS

Many surfacing operations are conducted with the oxyacetylene process. The objective of all surfacing operations is to produce a surface layer of metal possessing properties not possessed by the base metal. In this manner a very hard, abrasion-resistant or corrosion-resistant surface may be spread upon the surface of a mild steel part, thus prolonging its usefulness.

The surfacing operation offers a simple, economical means of producing parts that may have up to 25 times the life of steel under similar conditions of service. Surfacing materials may be of the work-hardening type or of alloys that are hard in the as-welded condition. Some alloys contain no iron but are made of cobalt, chromium and tungsten. Others are iron-base alloys containing approximately 5 to 6% alloy addition.

Broken edges, gear teeth and mismachined surfaces can be built up by depositing layers of metal similar in composition to the base metal. The built-up surfaces can be machined and heat treated so that they will have properties similar to the original piece (Fig. 41.28). This application makes it possible to reclaim many types of damaged pieces, thus reducing replacements.

Extensive overlay application not possible with the arc welding processes, for instance the application of materials high in zinc content such as admiralty metal, can be accomplished with the gas welding torch. Automatic procedures are used for this type of overlay application such as on tube sheets or heat exchangers where admiralty metal is fed by a standard automatic arc welding wire feeder into a gas welding torch flame. In this application two 1/8 in. diameter wires have been fed through one wire feed head. A block-type gas heating burner attached to this head is used as the means for heating and melting the admiralty wire. The carbon steel plate must be cleaned by sand blasting and then fluxed by brushing on a standard brazing flux.

APPLICATIONS

The wide field of possible applications, as well as the convenience and the economy of oxyacetylene welding are recognized in most metalworking industries. The process is used for fabricating sheet metal, tubing, pipe and other metal shapes in industries such as aircraft, industrial piping and automotive. It is also used in laying pipelines of small and medium diameter up to 2 inches.

The process is almost universally used and accepted in the field of maintenance and repair, where its flexibility and mobility result in great savings of time and labor. The typical, self-contained unit of an oxygen cylinder and an acetylene cylinder on a two-wheeled stand can be readily moved about in a plant. It can be carried easily into the field on a small truck wherever a breakdown may have occurred. Oxyacetylene welding is particularly suited to the shops, machine shops and automobile repair shops. It is equally useful in shops devoted entirely to welding, the main business of which may be the repair of large and small industrial, agricultural and household equipment.

The same gases and equipment can be used in cutting, brazing, soldering, heat treating, surfacing and welding. This makes the oxyacetylene process particularly attractive from the viewpoint of initial investment.

In maintenance welding it is important that the surfaces to be welded be as clean as possible. When such conditions cannot be obtained and the first pass is deposited with excessive porosity and some cracking, welding should be stopped and the first pass removed by chipping or grinding before continuing. In cases where normally a one-pass weld would be required and it is known that cleanliness of joint preparation is not satisfactory, a small bead should be applied and then removed by grinding before applying the strength weld.

OXYHYDROGEN WELDING AND BRAZING

PRINCIPLES OF OPERATION

The formula for the combustion of oxygen and hydrogen in the oxyhydrogen welding process is represented by the classical equation for the formation of water vapor from oxygen and hydrogen: $2H_2 + O_2 \rightarrow 2H_2O$. Visual observation cannot be employed in adjusting an oxhydrogen flame to obtain the theoretical proportions of 2 volumes of hydrogen to 1 volume of oxygen. The flame is almost invisible and does not provide any distinguishable index of gas proportions. It is therefore standard practice in oxyhydrogen welding to employ torch-supplied, volumetric ratios of hydrogen to oxygen 2½:1 to 6:1. (The term, torch supplied, is used to indicate oxygen supplied from a cylinder or pipeline as distinguished from oxygen derived from the atmosphere.)

In practice the welder usually adjusts the oxygen-hydrogen ratio so as to obtain the most heat, but not quite to the point where oxide forms on the weld puddle. An increase in the proportion of hydrogen results in a lowering of the flame temperature. The resultant reducing flame eliminates the danger of an oxidizing condition. Control of the volumetric proportions is secured through adjustment of the hydrogen regulator. Excess hydrogen will not cause any ill effects, since the reducing atmosphere does not leave any carbon deposits.

Oxyhydrogen welding employs flames with relatively low heat content. It is used principally in the welding of metals having low melting points, such as aluminum and lead. There have been limited applications of this process in the welding of steel in light-gage sections and on small parts. The oxyhydrogen flame is used, to a limited extent, for braze welding and brazing operations where lower heat inputs are desired. The heat effects are not as great as with other welding processes because of the lower heat content, the flame, and warping and residual stresses are sometimes less.

WELD QUALITY

The quality of welds produced with the oxyhydrogen process is equal to that obtained with other processes, provided good welding practice is observed. Any weld defects encountered are attributable to the same sources as those in other welding processes. The most difficult problem in oxyhydrogen welding is flame adjustment. If an oxidizing flame is used, there is little visible evidence in the flame to guide the welder. When the metal is melted, however, the condition will immediately become apparent, because of the formation of oxide.



Fig. 41.28—Building up a railroad passenger car journal box with bronze welding rod

EQUIPMENT

Oxyhydrogen welding is very similar in most respects to oxyacetylene welding, and much of the equipment used in the latter process is suitable for oxyhydrogen welding. The same torches, mixers, tips and hose are used for both. A standard oxygen welding regulator is used on the oxygen cylinder. A regulator specifically designed for the use with hydrogen must be employed with the hydrogen cylinder.

It may be advantageous to manifold both the oxygen and the hydrogen where a number of welding operations are carried on simultaneously, such as in production line welding. It is customary to supply both gases to a properly designed piping system with station drops at the points of gas usage. In automatic brazing operations using silver alloys, multiflame tips connected to standard torches have been used to a limited extent. These multiflame tips were primarily designed for oxyacetylene welding and are merely adapted to oxyhydrogen welding.

In order to obtain equal heating effects, a larger size tip than is necessary for oxyacetylene welding will be required for oxyhydrogen welding and brazing because of the lower heat content of the flame.

GASES

The properties, use, storage and distribution of oxygen are covered elsewhere in this chapter. The earliest method of hydrogen production was by the electrolysis of water, but present production is by either; (1) the catalytic steam-methane reforming process or ; (2) as a by-product of various chemical processes. Hydrogen is shipped at a pressure of about 2000 psi in cylinders and up to 2400 psi in the tube trailers complying with the regulations of the Department of Transportation (D.O.T.). The hydrogen in these cylinders has a purity of 99.5% or better. The conventional hydrogen cylinder is similar in appearance to any oxygen cylinder but can always be distinguished by its color marking and different cylinder valve threads.

The procedure for the connection of an oxyhydrogen welding outfit, as well as the applicable safety regulations, are similar to those detailed for oxyacetylene welding equipment. The fact that hydrogen is a colorless, odorless and tasteless gas must be recognized, and care should be exercised to prevent its escape in unventilated spaces.

APPLICATIONS

The oxyhydrogen flame finds use in the welding of aluminum and its alloys, particularly in the thinner sections. The lower heat content of the flame makes control of the molten metal easier than with the oxyacetylene flame. Joint designs, welding techniques and the use of filler metal and flux are the same with oxyhydrogen welding as with oxyacetylene welding.

Gas welding of the nonheat treatable aluminum alloys can be accomplished with the oxyhydrogen welding process. However, the gas tungsten-arc and gas metal-arc welding processes are replacing gas welding on aluminum due to their greater speed, which minimizes distortion. The heat treatable aluminum alloys are generally not welded with the gas welding processes.

The welding of lead (often erroneously referred to as lead burning) is another field for the oxyhydrogen flame. The lower heat content of the flame is ideal for this low-melting-point metal. Oxyhydrogen welding is preferred for lead up to about ¼ or ⅜ in. thick. For greater thicknesses the oxyacetylene flame is generally used because of the greater heat input required. Another advantage of oxyhydrogen welding is that there is no deposit of carbon, which accelerates corrosion in welded lead assemblies.

Magnesium and its alloys represent another field for oxyhydrogen welding. The welding of magnesium is similar in many respects to the welding of aluminum.

The oxyhydrogen flame finds limited use in torch brazing using silver brazing alloys. In such applications the operations are usually mechanized, the oxyhydrogen flame affording a means of controlling the extent of heating. Usually the heat is applied through flat tips, each equipped with a multiplicity of small, closely spaced orifices. The parts to be brazed, after being cleaned, fluxed and having the alloy preplaced, are mechanically fed through the zone of the heating flames.

WELDING WITH OTHER FUEL GASES

PRINCIPLES OF OPERATION

Hydrocarbon gases such as propane, butane, city gas and natural gas, due to their oxidizing characteristics, are not suitable for welding ferrous materials. In some instances, with care in flame adjustment and use of flux, most nonferrous and ferrous metals can be braze welded. It is important to use tips designed for the fuel gas being employed. These gases are extensively used for brazing and soldering operations using both mechanized and manual methods.

These fuel gases have relatively low flame propagation rates, with the exception of some manufactured city gases containing considerable amounts of hydrogen. When standard welding tips are used, the maximum flame velocity is so low that it interferes seriously with heat transfer from the flame to the work. The highest flame temperatures of the gases are obtained at high oxygen-to-fuel gas ratios (see Fig. 41.1). These ratios produce highly oxidizing flames, a condition which prevents satisfactory welding of most metals.

Tips should be used employing flame-holding devices, such as skirts, counterbores and holder flames, to permit higher gas velocities before the flame leaves the tip. This makes it possible to use these other fuel gases for many heating applications with excellent heat transfer efficiency.

EQUIPMENT

Standard oxyacetylene equipment, with the exception of the fuel gas regulator, can be used to distribute and burn these gases. Special regulators may be obtained for use with these gases. Suitable heating and cutting tips are available also. City gas and natural gas are supplied by pipelines; propane and butane are stored in cylinders or delivered in liquid form to storage tanks on the user's property. Delivery is made by pipeline equipment at the points of use.

The plumbing, refrigeration and electrical trades use propane in small cylinders for many heating and soldering applications. The torches are designed to use air from the atmosphere as the combusion-supporting gas. The propane flows through the torch at a supply pressure of from 3 to 60 psi and serves to aspirate the air. The torches are used for soldering the joints in copper pipelines, light brazing jobs and for soldering electrical connections.

The usual safety precautions should be observed when using these fuel gases. Storage and distribution systems should be installed according to the applicable national, state or local codes.

AIR-ACETYLENE WELDING AND HEATING

PRINCIPLES OF OPERATION

When a fuel gas is burned with air, the flame temperature is lower than that obtained when the same gas is burned with oxygen. Air contains approximately 80% by volume of nitrogen, which is neither a fuel gas nor supports combustion. Acetylene burned with air, therefore, produces even lower flame temperatures than the gas combinations discussed earlier in this chapter. The total heat content is also lowered. The air-acetylene flame is suitable only for welding light sections of lead, light brazing and soldering operations.

EQUIPMENT

Torches for use with air-acetylene generally are designed to aspirate the proper quantity of air from the atmosphere to provide combustion. The acetylene flows through the torch at a supply pressure of from 2 to 15 psi and serves to aspirate the air. For light work, the acetylene usually is supplied from a small cylinder that is easily transportable.

APPLICATIONS

Air-acetylene is used for welding lead up to approximately ¼ in. in thickness. Perhaps the greatest field of application, however, is in the plumbing and electrical industry. The process is used extensively for soldering copper tubing with sweat-type joints. Another field of application is torch brazing with silver brazing filler metal.

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CHAPTER 42

OXYGEN CUTTING

AUXILIARY OXYGEN CUTTING PROCESSES

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CHAPTER 42

OXYGEN CUTTING

AUXILIARY OXYGEN CUTTING

PROCESSES

FUNDAMENTALS OF PROCESS

DEFINITION AND GENERAL DESCRIPTION

OXYGEN CUTTING is defined by AWS as a group of cutting processes wherein the severing or removing of metals is effected by means of the chemical reaction of oxygen with the base metal at elevated temperatures. In the case of oxidation-resistant metals the reaction is facilitated by the use of a chemical flux or metal powder. This flux may be in the form of a metallic or chemical powder, an abrasive agent or a mixture of both.

The introduction of the first oxygen cutting torch into this country shortly after 1900 caused a profound change in industrial practices having to do with the shaping of steel. Use of this process is now widespread; it can easily be used to shape many parts in a wide range of sizes and thicknesses which can only be worked with difficulty by other metal-shaping processes. Since the cut products are generally used in the "as-cut" condition, and the process is completely adaptable to welding and mechanical joining operations of all types, oxygen cutting has resulted in more economical construction and greatly increased production.

The oxygen cutting torch is a portable tool that can be taken to the work. It has been used to cut metal up to 94 in. in thickness. Because the cutting oxygen jet has a 360° cutting edge, it provides a rapid means of cutting not only straight lines, but can easily and economically cut many different shapes to required dimensions without expensive handling equipment.

PRINCIPLES OF OPERATION

Oxygen cutting is a means by which ferrous metal is severed by a rapid chemical reaction between the iron or its alloys and a confined high purity oxygen stream. A small area of the metal is preheated to the oxygen ignition temperature* of the ferrous metal and a stream of pure oxygen is impinged on the heated area. The oxygen rapidly oxidizes the metal in a narrow section, which becomes the kerf as the molten oxide and metal are removed by the kinetic energy of the oxygen stream.

The oxygen cutting process employs a torch and a tip or nozzle whose functions are: (1) to mix the fuel gas and preheat oxygen in the right proportion to produce the initial heating and continuous preheating effects, and (2) to supply a uniformly concentrated stream of high-purity oxygen to the reaction zone for the purpose of oxidizing and removing the molten materials. The torch unit is then conveyed across the material to be cut, at a speed sufficient to produce a continuous cutting action. This motion may be accomplished either manually or mechanically. The accuracy of the manual method depends largely on the skill of the operator; the machine method produces more accurate results with a superior finish.

CHEMISTRY OF OXYGEN CUTTING

The process of oxygen cutting is based on the capacity of high-purity oxygen to combine rapidly with iron that has been heated to the kindling temperature. Thus, when iron or steel is heated to its oxygen ignition temperature and brought into contact with high-purity oxygen, the iron is rapidly oxidized.

The balanced chemical equations** for this reaction are:

$$Fe + 0 \rightarrow FeO + \text{heat (63,800 cal.)} \quad \text{first reaction}$$

$$3Fe + 2O_2 \rightarrow Fe_3O_4 + \text{heat (267,800 cal.)} \quad \text{second reaction}$$

$$2Fe + 3/2O_2 \rightarrow Fe_2O_3 + \text{heat (196,800 cal.)} \quad \text{third reaction}$$

The third reaction occurs to some extent in heavier cutting operations, with the first and second predominating. Stoichiometrically, 4.6 cubic feet of oxygen will oxidize 1 pound of iron to Fe_3O_4, but in practical cutting operations, the amount of oxygen used is appreciably less. This is because not all of the iron is completely oxidized to Fe_3O_4. Some unoxidized or only partly oxidized metal is removed by the kinetic energy of the rapidly moving oxygen stream. Analysis of the slag has shown that, in some instances, over 30% is iron that has not been oxidized.

The heat generated by the combustion of iron to its oxides melts some of the iron adjacent to the reaction surface. Although this molten iron is swept away by the rapidly moving stream of oxygen and iron oxide, the concurrent oxidizing reaction heats the layer of iron at the active cutting front. Because this oxidation is not an instantaneous process, the heat developed by oxidation of the iron removed from an upper level of kerf is liberated at a lower level. In

*The oxygen ignition temperature is the temperature at which the material will ignite when subjected to an atmosphere of high-purity oxygen.

**"Thermodynamic Properties of 65 Elements, Their Oxides, Halides, Carbides and Nitrides," Bureau of Mines, 1965, Bulletin 605.

addition it is necessary to make up the thermal defficiency at the uppermost level where the oxidation reaction is just beginning by means of the preheating flames of the torch nozzle. These flames burn continuously while the torch is in motion.

The alloying elements that change iron to steel, when present in small amounts, are oxidized or dissolved in the slag without markedly interfering with the progress of the cut. However, when alloying elements are present in appreciable amounts, the effect on the cutting process must be considered. Steels containing oxidation-resistant elements can be oxygen cut, although when certain elements are present in large quantities (e.g., carbon, chromium, nickel, etc.) the technique required is different from that used with the plain carbon or with low-alloy steels.

DRAG

When the speed with which the nozzle travels across the work is such that the oxygen stream enters the top of the kerf and exits from the bottom of the kerf along the axis of the nozzle, the cut will have zero drag and is called a drop cut. If the speed of cutting is increased or if the quantity of cutting oxygen is below the recommended value, the portion of the oxygen jet farthest from the cutting nozzle will not be strong enough to carry on the controlled reaction, nor will it have sufficient energy to carry the products of the reaction straight through the work. The most distant part of the cutting stream will lag behind the portion nearest to the nozzle. The amount of this lag, measured along the line of cut, is referred to as the drag. A 10% drag means that the far side of the cut is behind the near side of the cut by an amount equal to 10% of the thickness of the material being cut. If for any reason the piece is not severed, the cut is referred to as a non-drop cut.

An increase in cutting speed usually results in an increase in the amount of drag, and may be accompanied by a decrease in quality. There is also a strong possibility of loss of cut at excessive speeds. Reverse drag may be obtained with too great a cutting oxygen flow or too slow a speed. However, under these conditions poor quality cuts usually result. Cutting stream lag resulting from incorrect torch alignment is not considered to be drag.

KERF

Kerf is defined as the space from which metal has been removed by a cutting process. It is the gap created by the removal of material by the cutting jet as it progresses across the material being cut. Kerf width is important for a number of reasons. Control or governing of kerf width plays an important part in the accuracy with which material can be cut to specified dimensions. Maintenance of a uniform kerf width from the torch side to the far side of the cut governs the squareness of the cut edge. Kerf width is a function of the size of nozzle, type of nozzle used, speed of cutting and flow rates of cutting oxygen and preheating gases. As the thickness of the material being cut increases, it is necessary to use greater oxygen flows and nozzles or tips with larger cutting oxygen passages in order to obtain a sufficient quantity of oxygen to cut through the material. The width of the kerf therefore increases as the thickness of the material being cut increases.

Cutting at speeds below those recommended for best quality cuts usually results in irregularities in the kerf width as the oxygen stream melts, washes away and oxidizes additional quantities of the material on each side of the cut. Excessive preheat flow rate results in undesirable melting and widening of the kerf at the top. Kerf width is especially important when shape cutting. In laying out work or when designing templates, compensations must be made for kerf width. In general, on materials up to 2 in. thick, kerf width can be maintained within ± 1/64 inch.

PREHEATING TIME

Preheating time refers to the time required for the preheat flames to heat the base metal to ignition temperature; that is, to a temperature high enough that when the oxygen cutting jet is directed onto the heated areas, rapid oxidation will be initiated and the cutting operation will begin.

CLASSIFICATION OF OXYGEN CUTTING PROCESSES

MANUAL CUTTING

In manual cutting operations the cutting tip or nozzle is directed so that the preheat flames and the cutting jet impinge along the line of cut or in the area to be pierced or severed. Where a better quality cut is desired, or for reasons of convenience, the operator may employ a guide for the torch to maintain a given nozzle or tip-to-work distance, and to move the torch along a given path without lateral deviation. In Europe extensive use is made of one or more wheels to support the head of the torch, leaving the operator free to move the torch at fairly regular speed along the line of cut.

MACHINE CUTTING

In machine cuttting a machine functions as torch holder, locater, and speed-of-cut regulator in lieu of the operator used for manual cutting. The torch permits easy adjustment of the nozzle or tip with respect to the work—normally with a rack and pinion arrangement. Where the material to be cut is not flat, the torch may be equipped with a device that automatically maintains the correct nozzle or tip-to-work height. This device may employ a sensing and actuating device that is mechanical, electrical or pneumatic. A riding wheel

type that is sometimes used is shown in Fig. 42.1. The machines, whether of the small tractor or tricycle type or of the more elaborate shape cutting variety, are designed so that, regardless of the path being traversed, the cutting speed remains constant at a preset value. The maintenance of a fixed nozzle height and speed, together with the proper nozzle size and recommended preheat gas and cutting oxygen flow, results in a high-quality cut surface with good dimensional qualities. A tractor-type machine, used for long straight cuts or circle cuts, may operate on tracks or on the work without tracks. Shape cutting is done with a more elaborate machine (usually track mounted) that follows some type of template, either mechanically or optically, or responds to signals from such devices as numerical tape control. Other machine cutting operations include the nicking or severing of billets, blooms and rounds (either hot or cold) stack cutting and the preparation of plate edges for welding.

SEVERING CUTS

Oxygen cutting is used to facilitate handling of material in preparation of scrap for remelting, for removal of risers on casting and in demolition work. In these cases, the object usually is to reduce the size of the pieces for easier handling or to remove unwanted material; the quality of the cut surface is unimportant. The speed of cutting is generally the most important consideration.

OPERATION

HIGH-SPEED CUTTING

High-quality as well as high-speed cuts are obtained when divergent bore nozzles are used. However, where speed is the prime consideration, and lower quality surfaces are acceptable, oversize cylindrical bore nozzles are generally used. Such high-speed cutting is frequently done with at least a 10% drag. High-speed cutting is generally limited to material 4 in. thick or less.

HIGH-QUALITY CUTTING

Essentials of high-quality cut surfaces are: squareness of top edge, smoothness of cut surface, squareness of the cut face with regard to top and bottom surfaces (on a horizontal member), absence of tenacious slag adhering to the surface farthest from the torch and production of a drop cut. These characteristics are desired on plates where edges are being prepared for welding, for "as-cut" fabrication or for good fitup, or for any application requiring good dimensional features. High-quality cuts can be obtained with either cylindrical or divergent bore nozzles. However, attention must be paid to the nozzle selection, cutting oxygen pressure and flow, cutting speed and the quantity and type of preheat flame. Light drag lines on cut surfaces are inherent and are not considered detrimental to quality.

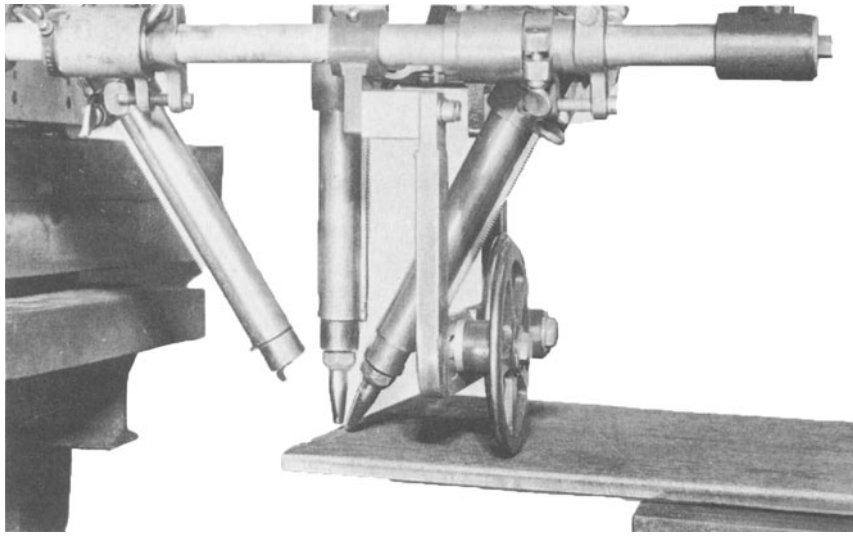


Fig. 42.1.—Riding wheel device used to maintain constant distance between work and cutting torch tip.

OXYGEN CUTTING

TECHNIQUE

Since the oxygen cutting process involves the continuous direction of a jet of high-purity oxygen onto an area of iron or steel that has been previously heated to the ignition temperature, the basic equipment employs preheating flames operating in conjunction with a high-purity oxygen stream. Both elements are supplied by a torch and nozzle combination that can be attached to fuel gas and oxygen sources. Torch and nozzles vary in design, depending on the specific type of cutting to be done.

Oxygen cutting torches are equipped with separable units called cutting tips or nozzles in which the oxygen cutting jet is surrounded, at a proper distance, by a number of preheating flames (Fig. 42.2). With this arrangement the torch may be moved in any direction without losing the effect of the preheating flames. In addition, a uniform distribution of the preheating flames around the cutting oxygen stream helps to stabilize the stream and ensures a smoother cut surface, particularly during the cutting of heavy sections. Individual valves are generally so arranged that controls are available for the preheating fuel gas, the oxygen for preheating and the oxygen used for cutting.

In all oxygen cutting the preheating gases are first lighted, either with a spark lighter or pilot light, and the pressures adjusted so that the flames are uniform in length and shape and stable, with or without the cutting oxygen flowing. The preheating flames are then directed toward the spot where the cut is to be started and are allowed to impinge upon this area until the color of the spot indicates that the metal is at its kindling or ignition temperature. The

cutting oxygen valve is then opened, and with the preheat flames still burning, the torch is advanced at a steady rate along the line of the cut. When the cutting is started within the workpiece (pierce start), the procedure must be modified to prevent the slag from blowing back on the nozzle. This can be achieved in handcutting by holding the nozzle at a slight angle or by moving the torch slowly in the direction of the cut until a hole has been pierced. In machine cutting the torch is moved in the cutting direction until the hole is pierced.

For machine cuts, auxiliary devices are available that permit rapid starts by employing high flow rates of preheating gases. The devices automatically or manually reduce the high starting flow rates to the desired low flow rate for cutting.

For oxygen cutting of square cuts, the nozzle is held perpendicular to the workpiece at a uniform distance above the surface. Usually this distance is such that the ends of the inner cones of the preheating flame just clear the surface of the metal. The placement of the preheat flames with respect to the kerf has an effect on quality, and must be properly oriented in the nozzle for each type of cutting. The torch is advanced steadily at the proper speed. If the speed of traverse is too great, the slag and oxide emerging from the bottom of the cut will trail behind or lag at too great an angle. When this happens, there is imminent danger of the stream failing to penetrate the steel completely. Regardless of whether the worker is using manual or machine cutting equipment, he must closely observe the slag emerging from the far side of the cut or the general nature of the course pursued by the oxygen and slag stream as it traverses through the steel, adjusting the speed of travel accordingly. If the movement is too fast, the cut may be lost completely and have to be restarted. If the movement is too slow, gouging and loss of quality may result.

FUEL GASES

A number of fuel gases may be used for the preheat flames in oxygen cutting. To determine which fuel gas to select for a particular application, an evaluation must be made of the various types of work to be done. Some of the factors to be considered when selecting the fuel gas are:

1. Time differentials for preheating in starting cuts on square edges, rounded corners, and when piercing holes for cut starts.
2. Effect on cutting speeds for straight line, shape and, particularly, bevel cutting.
3. Effect of items 1 and 2 on work output.
4. Cost of the fuel gas in cylinder, bulk and pipeline volumes.
5. Cost of the preheat oxygen required to burn the fuel gas efficiently.
6. Ability to use the fuel gas efficiently on operations such as scarfing, grooving, welding, heating and brazing, in addition to cutting, if required.
7. Ease of handling and availibility of fuel gas containers when mobility of operation is required.

For best results, it is essential that the torches and nozzles employed be designed for the particular fuel gas used.

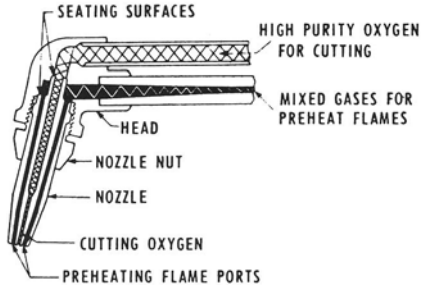


Fig. 42.2.—Closeup of torch head and nozzle showing preheating flame ports.

The functions of the preheat flames in the cutting operation are three-fold:

1. To raise the temperature of the steel to the ignition point in order to start and continue the cutting reaction.
2. To "condition" the cutting oxygen stream: i.e., the flames provide a protective shield between the cutting oxygen stream and the atmosphere. The flames also provide a transfer of heat energy to the oxygen stream that assists in propagating the cutting action, particularly in the lower depths of the cut.
3. To dislodge from the upper surface of the steel any rust, scale, paint or other foreign substance that would stop or retard the normal forward progress of the cutting action.

A preheat intensity that is sufficient to raise the steel to the ignition temperature rapidly will also be adequate for rapid and highly economical cutting. However, high quality, economical cutting can also be carried out at considerably lower preheat intensities than that normally required for rapid starting. In this latter case, auxiliary devices are used so that a high intensity preheat is employed for the starting operation and the flames are reduced to the lower preheat intensity for the cutting operation.

The fuel gases most commonly used for oxygen cutting are acetylene, natural gas and propane.

Acetylene

Acetylene gas is widely used as a fuel gas for oxygen cutting. Its chief advantages are: availability, high flame temperature and widespread familiarity of users with its flame characteristics.

The high flame temperature and heat transfer characteristics are particularly important for bevel cutting and for operations in which the starting time (such as for short cuts) is an appreciable fraction of the total time for cutting.

Natural Gas

The low cost and ready availability of natural gas in industrial areas make it a useful fuel for the preheating flames of cutting torches. Its characteristics as a fuel gas for oxygen cutting operations are much like those of propane. The same cutting tips are generally used for both propane and natural gas. Best operation requires 1¾ to 2 volumes of natural gas to 1 volume of preheat oxygen.

Propane

Propane is used regularly for oxygen cutting in a number of plants because of its availability, lower cost and ease of use. For proper combustion during cutting, propane requires 4 to 4½ times its volume of preheat oxygen. When oxygen costs are high this ratio offsets the economic benefits derived from the use of this low-cost fuel gas.

Other Fuel Gases

City gas (manufactured), coke oven and blast furnace gas (where it is available at low cost as a by-product of some other process) are sometimes used for fuel gas. The disadvantages of low heating value, low flame temperature and very low supply pressure usually result in changing to other fuel gases as they become available. Hydrogen, used in areas where it is similarly available as a low-cost by-product, was once employed almost exclusively for underwater cutting. It can safely be compressed to high pressures and regulated to overcome the pressure exerted by the water at salvage operations depths. Natural gas, which can be similarly compressed, is replacing hydrogen for underwater salvage operations, however.

A number of gases are specifically manufactured or compounded for use as oxygen cutting fuel gas. This group includes inoculated propane, stabilized methyl-acetylene and others. Claims for these gases include improved flame stability, higher flame temperature and lowered ignition temperature.

EFFECT OF OXYGEN PURITY

Oxygen used for cutting operations should have a purity of 99.5% or higher, since any decrease in purity from this level reduces the efficiency of the cutting operation. A 1% decrease in oxygen purity will result in a decrease in cutting speed of approximately 25% and an increase of about 25% in the cutting oxygen consumption. The quality of the cut will be impaired and the amount and tenacity of the adhering slag will increase. At oxygen purities below 95%, the familiar cutting action disappears and is replaced by a melt and wash action that is usually unacceptable for commercial operations. It is known that these changes are due to the chemical nature of oxygen cutting, although the precise ratios of cutting oxygen purity and cutting speeds, for example, have not been agreed upon.

EFFECTS OF PROCESSES

METALLURGICAL AND PHYSICAL

As explained previously, a large quantity of heat is liberated in the kerf when steel is cut with the oxygen jet. Much of this heat is transferred to the sides of the kerf, thereby heating the area adjacent to the kerf to a temperature above the critical temperature of the steel. Since the torch is constantly moving forward, the source of heat quickly moves on and the mass of cold metal near the kerf acts as a quenching medium, rapidly cooling the heated metal. The steel hardens to a degree that depends on the amount of carbon and alloying elements present, as well as the thickness of the material being cut.

A study of heat-affected zones from cutting operations shows that:

1. The depth of the heat-affected zone depends not only on the carbon and alloy content but also on the thickness of the base metal and the cutting speed employed.
2. Hardening of the heat-affected zones of constructional carbon steels of 0.25% maximum carbon is not critical in the thicknesses usually cut.
3. As might be expected, the higher carbon and alloy steels are hardened to such a degree that the thickness becomes critical.
4. The hardness effect progressively decreases as the distance from the kerf increases.

Typical examples of the heat effect of oxygen cutting are tabulated in Table 42.1. For most applications of oxygen cutting, the affected metal need not be removed. For unusual uses or with high alloy steels, the heat-affected zone may be removed by machining, grinding or other suitable means.

Bend and tensile tests made with specimens prepared from structural steel containing less than 0.25% carbon have shown that generally the detrimental effect of sawing or shearing are more severe than those of oxygen cutting.

From the results of tests and studies it is evident that the oxygen-cut surface of the lower carbon steels are at least equal in mechanical properties to the uncut metal. Most codes recognize this fact. The ASME Boiler and Pressure Vessel Code specifies that, "the edges must be uniform and smooth and must be freed of all loose scale and slag accumulations before welding." It further states that, "the discoloration which may remain on the flame-cut surface is not considered to be detrimental oxidation." The ASME Boiler and Pressure Vessel Code does not permit the welding of oxygen-cut surfaces in steel of over 0.35% carbon content.

Table 42.1—Approximate depth of heat-affected zone in oxygen cut steels*

Thickness, In.	Depths of Penetration, In.	
	Lower Carbon Steels	High Carbon and Alloy Steels
>1/2	>1/32	1/32
1/2	1/32	1/32 to 1/16
6	1/8	1/8 to 1/4

* The depth of penetration of the fully hardened zone is considerably thinner than the depth of the complete heat-affected zone.

CHEMICAL CHANGES

In addition to the phase changes resulting from oxygen cutting, there are chemical changes that extend to a slight depth. Samples taken from near the cut surface of carbon steels show a slightly higher carbon content than samples taken at a greater depth. The increase in carbon near the surface occurs whether the preheating flames are fed by a gas containing carbon, such as acetylene, or by a carbon-free gas such as hydrogen. Investigators have concluded that the carbon increase is from four potential sources:

1. Migration of carbon from the colder to the hotter metal.
2. Progressive precipitation of ferrite toward the high temperature at the face of the cut.
3. Absorption of carbon from the molten metal in the kerf.
4. Selective oxidation of the ferrite leaving the higher carbon cementite.

Nickel acts like carbon, concentrating at the surface of the cut; chromium and copper do the opposite; manganese and silicon are not appreciably affected. In general, these effects are minor.

EFFECTS OF ALLOYING ELEMENTS

Alloying elements have two possible effects on the oxygen cutting process: they may make the steel more difficult to cut and they may give rise to hardened or heat-checked cut surfaces. The first effect is roughly evaluated in Table 42.2.

HEAT TREATMENT

Plain carbon steels containing 0.25% carbon or less, in normal plate thicknesses, are not as a rule subject to cut surface hardening or cracking as a result of temperature or chemical changes due to oxygen cutting. An exception may be heavy sections or castings.

As the carbon content increases, or alloys are added, steels become more responsive to the heat treatment effect. It is therefore advisable to preheat the higher carbon and higher alloy steels before employing oxygen cutting. For steels with a carbon content greater than 0.25%, or any alloy steel that is

hardenable, preheating should always be employed. The need for preheating, greater for the heavier sections than for the lighter sections, becomes a requirement when heavy sections are to be cut to intricate shapes. Shapes with acute angles involving high stress concentrations should be preheated and stress relieved.

Preheating the work accomplishes several useful purposes:

1. It increases the efficiency of the cutting operation by permitting higher speeds thereby reducing the total amount of oxygen and fuel gas required to make the cut.
2. It reduces the temperature gradient set up by the cutting operation. This in turn reduces or gives more favorable distribution to the cooling stresses and prevents the formation of quenching or cooling cracks. Distortion is also reduced.
3. It reduces the hardness of the cut surface by reducing the rate of cooling.
4. It reduces the alloy migration toward the cut face by lowering the temperature differential between the cut face and the body of the metal.

The temperature used for preheating generally varies from 200 to about 1300°F (93 to 704°C), depending upon the size and type of steel to be cut. The majority of carbon and alloy steels requiring preheating may be cut with the steel preheated to the 400 to 600°F (204 to 316°C) temperature range. When the preheat temperature exceeds 1200 or 1300°F (204 to 316°C) the cutting operation approaches that of hot cutting. This is discussed in another section of this chapter. It should be noted here that the higher the temperature, the more rapid is the reaction of the oxygen with the iron; it is therefore possible to cut faster when the metal is preheated. But it is essential that the temperature be fairly uniform; if the outside of the metal being cut is at a lower temperature than the interior, the oxidation reaction will proceed more energetically in the interior than at the top and botom. The result is often the formation of large pockets in the interior that will either give rise to an unsatisfactory cut or to such slag pollution at lower levels that it will be impossible for the oxygen stream to penetrate the steel completely. Consequently, it is important that cutting be begun as soon as possible after the material is removed from the preheating furnace.

If preheating should prove impractical because of lack of facilities, the heat treatment effect and stresses incident to cutting may be reduced by other means. In the case of very light cutting this may be accomplished by passing the cutting torch, with the preheating flames lighted and the cutting oxygen turned off, slowly over the line of the cut until the metal in this region is raised to the approximate temperature desired. While one such pass may suffice, two or more passes generally yield better results. Another method which gives better results is to preheat the metal by means of an auxiliary multiflame heating tip mounted so as to precede the cutting tip.

To minimize the internal stresses set up in the steel by the oxygen cutting process, it is possible to utilize annealing, normalizing or stress-relieving processes subsequent to the cutting operation. By proper postheat treatment, all traces of metallurgical changes caused by oxygen cutting are eliminated. If a furnace is not available to carry out the heat treatment, or if it is impractical to use a furnace because of size, the cut surface may be reheated to the proper temperature by means of multiflame heating tips.

Table 42.2—Effect of alloying elements on resistance of steel to oxygen cutting

Element	Effect of Element on Oxygen Cutting
Carbon	Steels up to 0.25% carbon can be cut without difficulty. Higher carbon steels should be preheated to prevent hardening and cracking. Graphite and cementite (Fe_3C) are detrimental but cast irons containing 4% carbon can be cut by special techniques or processes described in later pages of this chapter.
Manganese	Steels of about 14% manganese and 1.5% carbon are cut with difficulty and for best results should be preheated.
Silicon	Silicon, in amounts usually present, has no effect. Transformer irons containing as much as 4% silicon are being cut. Silicon steel containing considerable amounts of carbon and manganese must be carefully preheated and post-annealed for best physical properties.
Chromium	Pure chromium reacts with oxygen only at very high temperatures. Steels up to 5% chromium are cut without much difficulty when the surface is clean. Higher chromium steels, such as 10% chromium steels, require special technique (see section on Oxidation Resistant Materials) and the cuts are rough when the usual oxyacetylene cutting process is used. In general, carburizing preheat flames are desirable when cutting this type of steel. The recently developed flux injection and iron powder cutting processes, described in a later section, enable cuts to be readily made in the usual straight chromium irons and steels as well as in stainless steel.
Nickel	Steels containing up to 3% nickel, if the carbon is not too high, may be cut by the normal oxygen cutting processes; up to about 7% nickel content, cuts are very satisfactory. Cuts of excellent quality may be made in the usual engineering alloys of the stainless steels (18-8 to about 35-15 as the upper limit) by the flux injection or iron powder cutting processes.
Molybdenum	This element affects cutting about the same as chromium. The pure metal is difficult to cut. Aircraft quality chrome-molybdenum steel offers no difficulties. High molybdenum-tungsten steels, however, may be cut only by means of special technique.
Tungsten	The pure metal may be cut if heated to a sufficient temperature. The usual alloys up to 12 or 14% may be cut very readily, but cutting is difficult with a higher percentage of tungsten. The limit seems to be about 20% tungsten.
Copper	In amounts up to about 2%, copper has no apparent effect.
Aluminum	Unless present in large amounts (on the order of 10%) the effect of aluminum is not appreciable.
Phosphorus	This element has no effect in amounts usually tolerated in steel.
Sulfur	Small amounts, such as are present in steels, have no effect. With higher percentages of sulfur, the rate of cutting is reduced and sulfur dioxide fumes are noticeable.
Vanadium	In the amounts usually found in steels, this alloy may improve rather than interfere with cutting.

OPERATING INFORMATION

Quality

In the production of components by oxygen cutting, the quality of the cut component is dependent on four factors: (1) metallurgical, (2) physical, (3) dimensional and (4) surface roughness. The first two categories have been covered previously and reliable reference values have been established and standardized for them. This is also somewhat true of the third category, but is not the case with the fourth—surface roughness. Parts identical in size, strength and analysis may differ considerably in the quailty of their surfaces. However, the quality of the surfaces could be adequate for the correct functioning of the parts in their intended service.

Acceptable quality is dependent on the job requirements. In cutting for scrapping operations, the only criterion is to part the material quickly with no consideration of surface roughness. When cutting high strength material to be used at high working stress, the surface roughness and dimensional tolerance are of utmost importance. In many of the latter applications, the cut surface must subsequently be ground and the corner rounded. Finally, the resulting cut must have a satisfactory slag condition. This again is dependent on the work. In scrap cutting it would not be considered, while in most production work there should be little or no firmly adhering slag.

Drag lines are inherent to oxygen cutting, being the line markings on the face of a cut. Fig. 42.3 shows typical drag conditions. The amount of drag is usually no criterion in considering surface roughness. However, too long a drag will result in a corner that is not completely severed at the completion of the cut. When all other conditions are correct, the drag lines would be the surface roughness. In oxygen cutting it is possible to approach 200 rms in surface roughness, with 800 to 1200 rms being average. Drag lines are also an indication of the conditions being used to make the cut.

Surface roughness of an oxygen cut surface of a particular thickness and type of steel is dependent on many variables, the most significant being:

1. Size and shape of the cutting oxygen orifice.
2. Cutting oxygen flow rate.
3. Cutting speed.
4. Purity of the oxygen.
5. Intensity (flow rate) of the preheat flames and the preheat oxy-fuel gas ratio.
6. Cleanliness and planeness of the exit end of the nozzle.
7. Condition of the steel surface.
8. Quality of steel, i.e., freedom from segregations, inclusions, etc.

Figures 42.4 and 42.5 show typical edge conditions resulting from variation in the cutting procedure.

For any given cut, the variables listed should be evaluated so that the quality of cut required may be obtained with the minimum aggregate cost in oxygen, fuel gas, labor and overhead.

Dimensional tolerance and surface roughness must be considered together when judging the quality of a cut; they are somewhat dependent on each other. Most specifications include dimensional tolerances. These include straightness of edge, squareness of edge and permissible variation in plate width, all of which are primarily a function of the cutting equipment and its mechanical operation. When the torch is held rigidly and advanced at a constant speed, as in machine-guided oxygen cutting, dimensional tolerances can be maintained within narrow limits. The degree of longitudinal precision of a machine guided cut depends primarily on such factors as the condition of the equipment, trueness of guide rails, clearances in the operating mechanism and the uniformity of speed control of the propelling unit. In addition to equipment, dimensional control is dependent on control of thermal expansion of the material being cut. Lack of adherence to dimensional tolerance may result from buckling of the material when sheet or thin plates are involved, warpage resulting from the



Fig. 42.3.—Typical drag conditions in 1 in. thick specimens (left), 0.11 in. drag with lower corner completely severed; (center) 0.20 in drag with corner completely severed; (right) 0.22 in. drag with lower corner not compltely severed.

heat being applied to one edge or shifting of the material while it is being cut. With reasonable care and observation of the foregoing factors, cut surfaces in ordinary steel 6 in. in thickness can be held true as to cross-sectional squareness within $\pm 1/16$ inch. Cuts in thinner sections can be held within proportionally smaller limits.

Properly made machine-guided torch cuts are smooth with square edges and usually require no further finishing. Fig. 42.6 shows the condition of an oxygen-cut edge compared to rolled and sheared edges.

Precision cutting, either straight line or shape cutting, demands attention to all variables. The operations should therefore be planned carefully to minimize the effect of the variables. For instance, when trimming both sides of a plate, warpage will be lessened if two torches are mounted, one on each side, so that both cuts are made simultaneously and in the same direction. Distortion can often be controlled when making irregular cuts in plates by inserting wedges in the kerf following the cutting torch to limit the expansion of the metal. In cutting openings in the middle of a plate, it may be found advantageous from the standpoint of minimizing distortion to make a series of unconnected cuts leaving the cut out section attached to the plate in a number of places until the cut has been almost completed; the connecting parts can then be cut through last. Thin gage material is often stack cut, not only increasing production but also eliminating warping and buckling. Thin plate has also been cut submerged in water to remove the heat caused by cutting and thus minimize or prevent distortion.

PLATE EDGE PREPARATION

The beveling of plate edges before welding is a necessity in many applications, both to insure proper dimensions and fit, and to allow proper welding techniques to be employed. Beveling may employ a single torch or multiple torches operating simultaneously. Other forms of plate edge preparation such as "U" and "J" grooving are also used. These processes are covered later in this chapter.

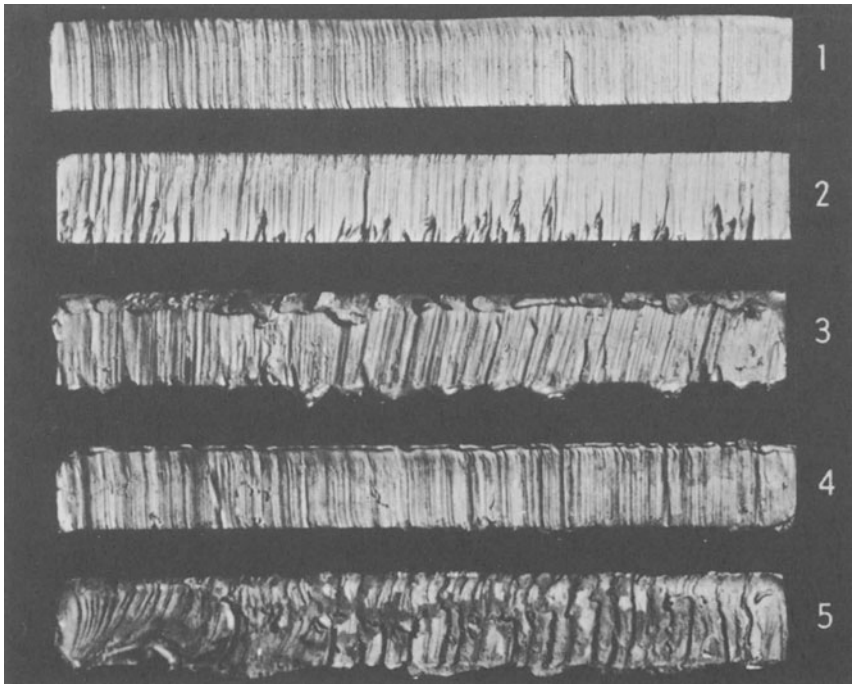


Fig. 42.4.—Typical edge conditions resulting from oxygen cutting operations. (1) Good cut in 1 in. plate. The edge is square and the draglines are essentially vertical and not too pronounced. (2) Preheat flames were too small for this cut with the result that the cutting speed was too slow, causing bad gouging at the bottom. (3) Preheating flames were too long, with the result that the top surface has melted over, the cut edge is irregular, and there is an excessive amount of adhering slag. (4) Oxygen pressure was too low, with the result that the top edge has melted over because of the slow cutting speed. (5) Oxygen pressure was too high and the nozzle size too small, with the result that control of the cut has been lost.

In single torch beveling, the amount and type of preheat is a dominant factor. At angles less than 15° from the vertical, the loss of preheat efficiency is small; however, as the angle increases above 15° the loss in heat transfer from the preheat flames to the plate becomes appreciable and considerably greater preheat input is required, particularly for thicknesses up to one inch.

Best results are obtained by adjusting the nozzle very close to the work and employing the following oxy-fuel gas ratios:

1.5 oxygen to 1 acetylene
4.7 oxygen to 1 propane
2 oxygen to 1 natural gas

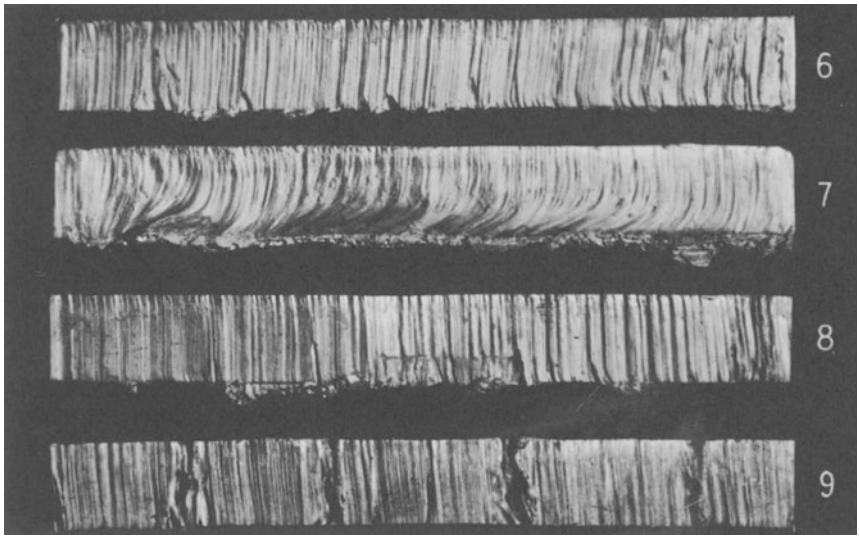


Fig. 42.5.—Typical edge conditions resulting from oxygen cutting operations. (6) Cutting speed was too slow, with the result that the irregularities of the draglines are emphasized. (7) Cutting speed was too fast, with the result that there is a pronounced break in the dragline and the cut edge is irregular. (8) Torch travel was unsteady, with the result that the cut edge is wavy and irregular. (9) Cut was lost and not carefully restarted, with the result that bad gouges were caused at the restarting point.

An auxiliary torch (with only preheat flames burning) mounted perpendicular to the work or an auxiliary adapter (used in a single torch), which divides the preheat and applies a portion of it at right angles to the work, may be used to obtain faster beveling speeds. Either method actually consumes less total preheat gases than a single angled nozzle.

Highest quality of cut face is not always obained at the highest cutting speed. The cut face finish can usually be improved by operating at slower speeds. When speed is reduced to obtain improved surface finish, the preheat flow should be correspondingly decreased to prevent excessive melt-down of the top edge.

With multiple torch operations, the preheat effect and overall operation is basically similar to vertical cutting. Figures 42.7, 42.8 and 42.9 illustrate the different settings to obtain three basic edges. In each case, torch position variables A and B are governed by plate thickness, nozzle size and speed of cutting. Nozzles lead one another as much as is practical without interrupting the cutting action of the three cutting oxygen streams. When dimensions A and B are too great, however, the cutting action does not continue beyond the kerf of the leading torch. This causes the oxygen stream to be deflected into the kerf and results in a gouging action, a rough surface and usually a light adherence of dross to the underside of the prepared edge.

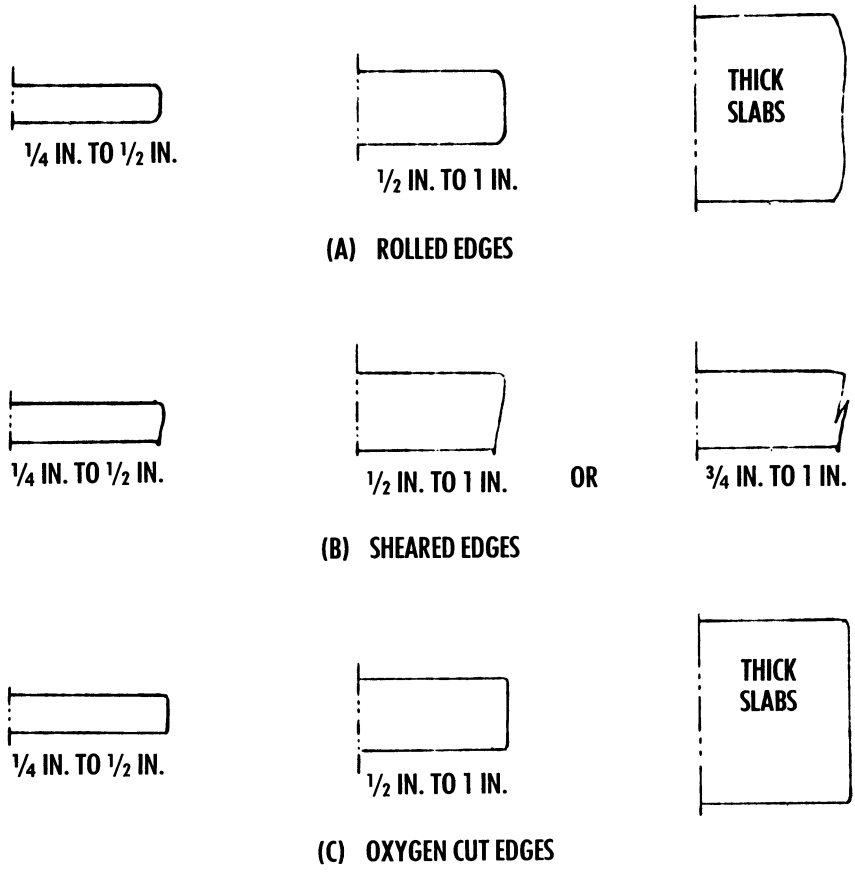


Fig. 42.6.—Typical rolled, sheared and oxygen cut edges.

The proper positioning of the torches in a lateral direction for multibevel cutting is usually accomplished by trial and error. This can be costly, resulting in lengthy reworking or possible scrap. The use of a simple machined template, which is typical of the desired edge geometry, is quite useful for torch alignment. A kerf-centering device is attached to each nozzle. The torches are then properly angled and adjusted to the edge template. The multitorch cutting head is now ready to duplicate the template profile (Fig. 42.10). In order to obtain close tolerances when preparing plate edges, precise conveying equipment is necessary. For reproducibility, accuracy and maximum efficiency, the large gantry and rail type equipment is available. Such apparatus may be classified in the same category as a machine tool. A plate can easily be located on the cutting bed. A 3-gantry type unit would be located at their respective positions and 4 sides of the plate are prepared concurrently. Camber and angular cuts are also producible. (Fig. 42.11).

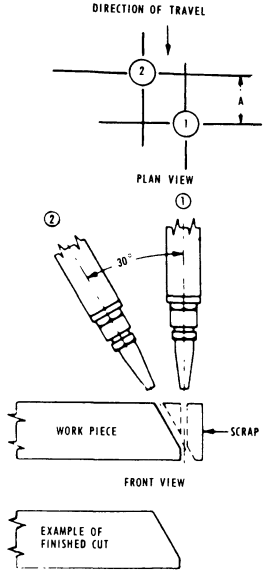


Fig. 42.7.—Multiple-torch machine oxygen cutting procedure used in typical plate edge preparations.

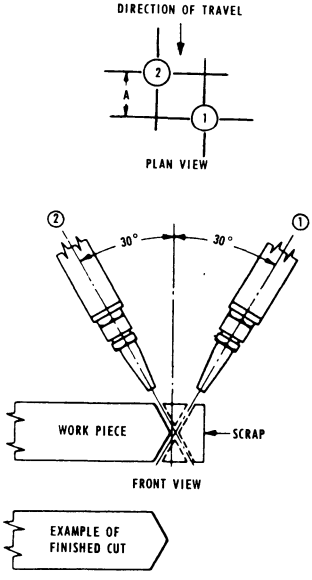


Fig. 42.8.—Two oxygen cutting torches employed in machine cutting and simultaneous plate edge preparations.

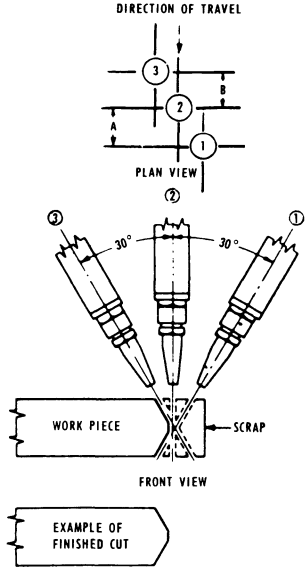


Fig. 42.9.—Three oxygen cutting torches used to simultaneously sever and shape a plate edge.

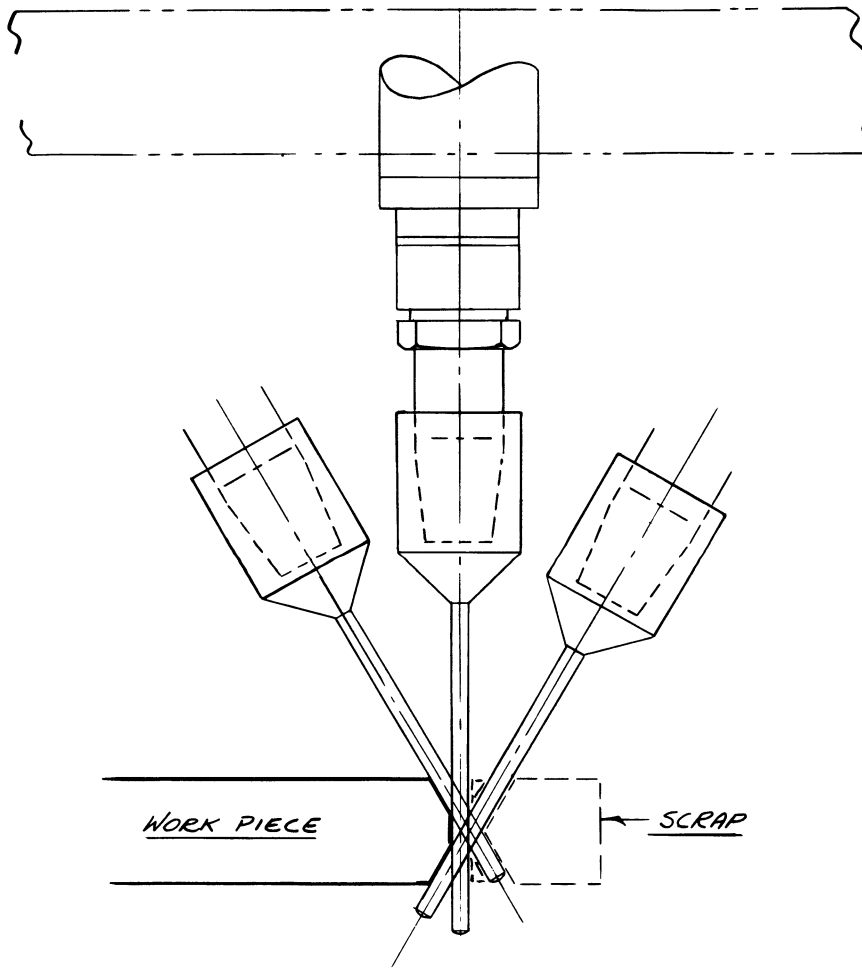


Fig. 42.10.—Kerf centering and bevel angle setting device.

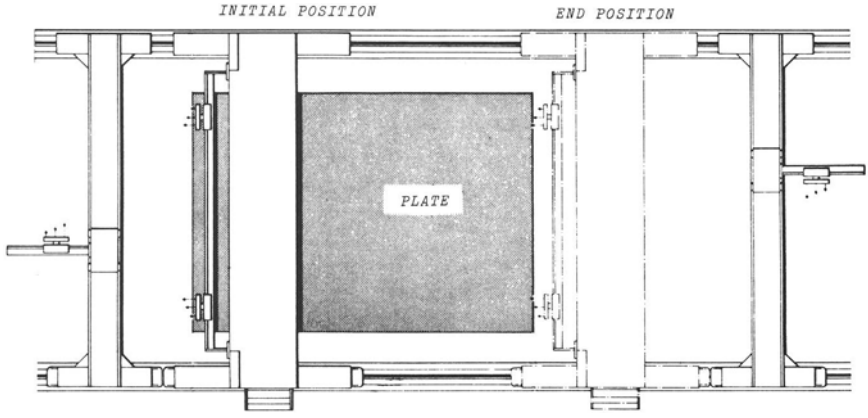


Fig. 42.11.—Portal type "S" Flame Cutting Machine.

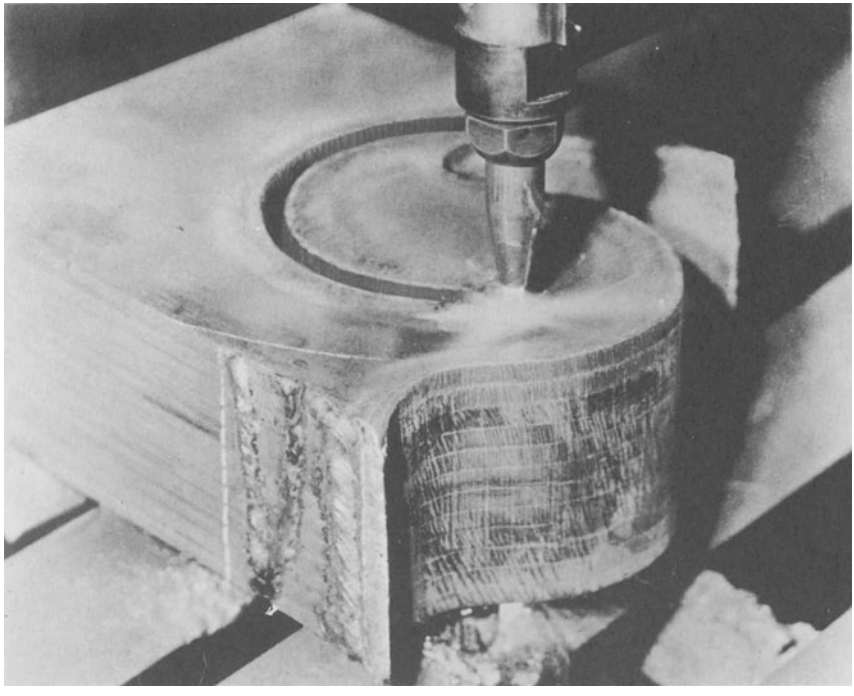


Fig. 42.12.—Typical stack cutting procedure (Note welding bead to hold plates in proper alignment.)

STACK CUTTING

Stack cutting is the cutting of multiple layers of material (each usually less than 1/2 in. in thickness) as though they were one thick piece of material. Stack cutting, properly prepared and executed, has many advantages to offer. Foremost is increased productivity at lower cost since both cutting time and fuel consumption are somewhat less than proportional to thickness cut. Also, the resulting patterns usually have edges that are highly stressed, squarer and more free of burrs, slivers and drag as compared to sheared plates. Fig. 42.12 illustrates a typical stack cutting operation.

It is of utmost importance that the stack be formed as nearly as possible into a solid slab. Sufficient clamps should be used to eliminate all air gaps, especially along the line of cut. Obvious conditions such as uneven, bent, buckled or warped material should be corrected or replaced. Sheared plates should be piled with the burred edges all facing the same direction. Foreign matter on the surface is generally removed by wire brushing followed by an air blast. Extreme cases might require pickling or sand blasting. To facilitate cut starts, consideration should be given to straight vertical alignment of one side of the stack.

The total thickness is generally determined by the required dimensional tolerance of the cut piece. Best tolerances are achieved at approximately 2 in. with a gradual deterioration up to 6 inches. When cut piece size permits, multiple torch stack cutting can be applied.

Even when extreme care has been exercised, there is always the possibility of a torch pop-out with, perhaps, loss of the entire stack. The application of flux cutting and powder cutting processes greatly minimizes this hazard. These combustible additives to the cutting stream assist in propagating the reaction down through the cut to the extent that appreciable air gaps that otherwise might inhibit cutting process continuity can be tolerated between plates. The use of divergent nozzles with high velocity cutting jets seems to aid this transfer action further. Another effect is that plate thickness need not be limited to 1/2 inch. Highly alloyed steels, including stainless, can now be stack cut. The extreme care required in preparing the stack has been lessened under certain conditions.

Regardless of procedure employed, the economy of a stack cutting operation must be carefully compared with the total costs involved, including such items as material preparations, stack makeup, clamping devices and increased skill and care requirements.

MATERIALS CUT

For most mild steel cutting, standard oxygen cutting equipment is satisfactory. For highly alloyed and stainless steel cutting, it may be necessary to use a special process such as flux injection or powder cutting (described in other sections of this chapter), or some of the newer arc cutting processes described in Chapter 43, "Arc Cutting." The cutting process and type of operation (manual or mechanized) selected depend on the material that is being cut and the ultimate use of the product.

Table 42.3—Data for manual and machine cutting of clean mild steel (not preheated)

Thickness of Steel, In.	Diameter of Cutting Orifice, In.	Cutting Speed, In. per Min.	Gas Consumptions, Cu Ft per Hour			
			Cutting Oxygen	Acetylene	Natural Gas	Propane
1/8	0.020–0.040	16–32	15–45	3–9	9–25	3–10
1/4	0.030–0.060	16–26	30–55	3–9	9–25	5–12
3/8	0.030–0.060	15–24	40–70	6–12	10–25	5–15
1/2	0.040–0.060	12–23	55–85	6–12	15–30	5–15
3/4	0.045–0.060	12–21	100–150	7–14	15–30	6–18
1	0.045–0.060	9–18	110–160	7–14	18–35	6–18
1 1/2	0.060–0.080	6–14	110–175	8–16	18–35	8–20
2	0.060–0.080	6–13	130–190	8–16	20–40	8–20
3	0.065–0.085	4–11	190–300	9–20	20–40	9–22
4	0.080–0.090	4–10	240–360	9–20	20–40	9–24
5	0.080–0.095	4–8	270–360	10–24	25–50	10–25
6	0.095–0.105	3–7	260–500	10–24	25–50	10–30
8	0.095–0.110	3–5	460–620	15–30	30–55	15–32
10	0.095–0.110	2–4	580–700	15–35	35–70	15–35
12	0.110–0.130	2–4	720–850	20–40	45–95	20–45

Preheat oxygen consumptions: Preheat oxygen for acetylene = 1.1 to 1.25 × acetylene flow (cu ft per hr); preheat oxygen for natural gas = 1.5 to 2.5 × natural gas flow (cu ft per hr); preheat oxygen for propane = 3.5 to 5 × propane flow (cu ft per hr).

Operating notes: Higher gas flows and lower speeds are generally associated with manual cutting, whereas lower gas flows and higher speeds apply to machine cutting. When cutting heavily scaled or rusted plate, use high gas flows and low speeds. Maximum indicated speeds apply to straight line cutting; for intricate shape cutting and best quality, lower speeds will be required.

The oxygen cutting speeds given in Table 42.3 contain a great many variables. The flow and cutting speed data given are to be considered only as a guide for determining more precise settings for particular jobs. When completely new material is being cut, a few trial cuts will be necessary to obtain the most efficient operating conditions. The flows and speeds indicated in Table 42.3 cover a fairly wide range and include most common practices using conventional equipment.

High pressure divergent nozzles will provide slightly faster cutting speeds with narrower kerf widths and produce equivalent high quality work. Cutting oxygen head pressures up to 500 psi, with attendant cutting speed increases, have been used with good results. Extreme care must be exercised to preserve the original cutting orifice contour or the tip efficiency will be drastically reduced. Only tip cleaning devices recommended by the tip manufacturer should be used.

It should be noted that the chart ends at 12 in., which is the maximum thickness normally encountered for shape cutting in production shops. The division has been made arbitrarily. The cutting of steel plate over 12 in. thick is considered heavy cutting. The characteristics of heavy cutting are given in another section of this chapter.

OXIDATION-RESISTANT MATERIALS

The absence of alloying materials in pure iron exposes all the iron to oxidation by the oxygen cutting jet. As the amount and number of alloying materials increase, the oxidation rate decreases from that of pure iron. The oxidation of the iron in the alloy liberates a considerable amount of heat and produces iron oxides, which have melting points near the melting point of iron. However,

the oxides of many of the alloying materials have a melting point far higher than that of iron. These oxides, which produce refractory material, may shield the material in the kerf to such an extent that fresh iron is not continuously exposed to the oxygen stream. Because of these factors, the rate of cutting is reduced as the alloying elements in the iron, which produce high melting point refractory oxides, increase. For those ferrous metals with high alloy content, such as cast iron and stainless steel, variations in the normal oxygen cutting methods must be used.

Cutting Methods

There are at least six methods of cutting materials containing relatively large quantities of alloy materials, particularly alloying materials that, when oxidized, will produce refractory oxides. Chromium irons, stainless steels and cast irons are examples of these materials. Adequate safety precautions and measures should be taken to protect the operator and those in the immediate area from the exhaust products of the operation when cutting oxidation-resistant material, especially when using flux or powder.

Oscillatory Motion.—Refractory oxides may form when the cutting jet impinges on some materials. In these cases it becomes necessary to move the torch slightly to one side or the other so that new material can be heated to the ignition temperature and additional material oxidized and blown out of the kerf. If this oscillatory motion is accompanied by a progressive forward motion, continuous cutting can be accomplished. Where the cut has for its prime intention the severing of material, with no regard for quality, and where the time consumed in cutting is not a major factor, this is a reasonably satisfactory method (Fig. 42.13). This procedure does not require the use of auxiliary apparatus.

Combinations of this method with some of the methods described below have been used. These combined methods normally require special nozzles designed to obtain greater quantities of preheat gas, since the ability to make a progressive cut is greatly dependent upon heat transfer from the preheat flames to the material. In the cutting of cast iron, it is customary to use cutting nozzles that can supply greater quantities of preheat.

Waster Plate.—One of the earliest and best known methods of cutting these materials is to clamp a low-carbon steel plate along the upper surface of the material to be cut. On occasion, a welding bead of low-carbon steel is put along the line to be cut to obtain the same result. In these cases, the cut is started in the low-carbon steel material. The heat liberated by the oxidation of this material and the subsequent formation of a greater amount of iron oxide in the kerf makes it possible to accomplish progressive cutting. The thickness of the waster plate or weld bead must be in proportion to the thickness of the material being cut. This method has the disadvantage of either a large loss of plate or the necessity of applying the welding bead along the line of cut.

Wire Feed.—With suitable equipment, a short length of low-carbon steel wire can be fed into the preheat flames. Because of its shape, the end of the wire melts very quickly and the molten particles are rapidly oxidized and carried by the oxygen stream onto the plate being cut. The heat from the burning of these particles of wire rapidly brings the surface or face of the steel plate up to the ignition temperature and a progressive cut is readily made. This method can be

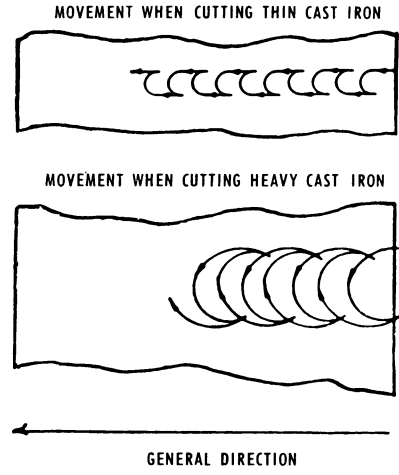


Fig. 42.13.—Typical cutting torch manipulation for cutting thin cast iron (top) and heavy cast iron (bottom).

used for starting cuts without stopping for preheating on carbon steels, a procedure known as a flying start. In the same way, oxygen cutting of hard-to-cut materials can be accomplished by continuously feeding iron wire into the cutting jet. To be successful, this method requires specially designed attachments on the cutting torch for continuous iron wire feed.

Heating.—It is known that many materials that are difficult or almost impossible to cut when cold can be cut with relative ease if they are heated to temperatures approaching the melting point of the material. Because of the temperature of the surrounding material, the heat liberated by the cutting reaction adds sufficient heat to the cutting zone to melt some of the refractory materials. These materials can then be washed from the kerf. This solution, although normally impractical, can be used in special cases.

Oxygen-Arc Cutting.—Another method that has been developed is the oxygen-arc cutting process, wherein an electric arc is struck between a hollow carbon or carbon steel electrode and the work. A stream of oxygen is passed through the hollow core of the electrode. This process is covered in detail in Chapter 43, "Arc Cutting."

Flux Cutting.—In 1945, the flux cutting process was introduced. This process was primarily intended for the cutting of stainless steels. The flux was designed to react with alloying materials, such as chromium and nickel, to produce compounds with melting points in the temperature range of the iron oxides produced in the cutting of carbon steels. In this way the cutting of stainless steels can be carried out in one continuous movement with no need for oscillation or the addition into the oxygen cutting stream of anything other than the flux. Special apparatus is required. By using the flux cutting method, cutting speeds approaching those for cutting equivalent thicknesses of carbon steel can be attained. The nozzle sizes will be larger and the cutting oxygen flow will be somewhat greater than are required for cutting an equivalent thickness of carbon steel.

Table 42.4.—Powder cutting data for stainless steel

Steel Thickness, In.	Diameter of Cutting Oxygen Orifice, In.	Oxygen Pressure, Psi.	Cutting Speed, In. per Min.	Gas Consumption, Cu Ft per Hr		Powder Flow, Oz. per Min.	Steel Thickness, In.
				Oxygen	Acetylene		
1/2	0.040	50	14	125	15	4	1/2
1	0.060	50	12	225	23	4	1
2	0.060	50	10	300	23	4	2
3	0.080	50	9	550	32	5	3
4	0.100	50	8	675	38	6	4
5	0.120	60	7	800	45	7	5
6	0.140	60	6	900	63	8	6
8	0.140	70	4	1000	63	8	8
10	0.160	75	3.5	1100	75	8	10
12	0.160	75	3	1200	75	8	12

Table 42.5—Data for heavy cutting

Thickness of Steel, In.	Oxygen Flow, Cu Ft per Hr	Diameter of Cutting Orifice, In.	Cutting Oxygen Pressure at Torch, Psi
12	1000–1500	0.147–0.221	26–56
16	1300–2000	0.1935–0.290	25–49
20	1600–2500	0.200–0.221	25–48
24	1900–3000	0.221–0.332	22–48
28	2200–3500	0.230–0.400	18–44
32	2500–4000	0.250–0.450	16–40
36	2900–4500	0.290–0.500	12–38
40	3400–5000	0.330–0.550	10–33
44	3800–5500	0.375–0.550	9–29
48	4500–6000	0.422–0.600	7–27

Powder Cutting.—In 1944 the powder cutting process was introduced for the cutting of most hard-to-cut metals. The powder process is a general term used to describe a technique for supplementing an oxy-fuel gas torch with a stream of powdered material. This material accelerates and propagates the oxidation reaction and the melting and spalling action of hard-to-cut materials. Powder operations may be performed with conventional cutting torches and nozzles. The powder is introduced into the reaction zone either through the nozzle or by means of single or multiple jets external to the nozzle or tip (Fig. 42.14). When the former method is used, the gas-conveyed powder is introduced into the cutting stream prior to its discharge from the nozzle. When the powder is introduced externally, the gas conveying the powder imparts sufficient velocity to the powder particles to carry them through the preheat envelope into the cutting oxygen stream. The short time in the preheat envelope is sufficient to produce the desired reaction in the cutting zone.

Some of the powders used are intended to react chemically with the refractory oxides produced by the oxygen jet. The resultant slags of lower melting points remain fluid and are washed out of the reaction zone. Unoxidized metallic surfaces are thus exposed and presented to the oxygen jet. Metallic powders such as iron powders may be employed. These powders burn and thus liberate additional heat in the reaction zone; this keeps the refractory oxides molten. The additional quantity of iron oxide produced results in the formation of a slag matrix, which carries the refractory oxides out of the reaction zone. The cutting of some materials may require mixtures of metallic powders such as iron and aluminum. This requirement exists where greater quantities of heat are needed to keep the oxidation melting and spalling reactions proceeding at the desired rate.

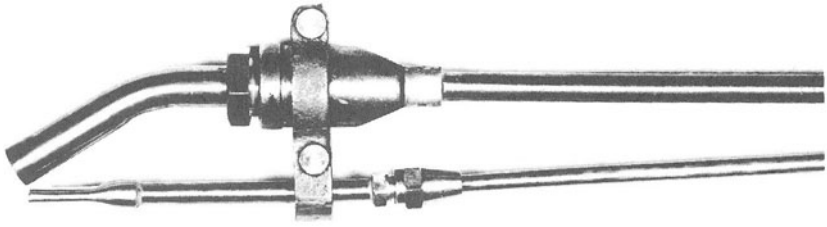


Fig. 42.14.—Close-up of a typical washing tip with an iron powder nozzle.

Operations on hard-to-cut materials, usually proceed at slower rates of speed with the same or slightly greater oxygen flow rates than are required for cutting equivalent thicknesses of ordinary carbon steel plate. Table 42.4 contains powder cutting data for AISI 302 steel. In this process, powdered iron or mixtures of powdered iron and other powdered materials are introduced into the reaction zone.

Powdered iron begins to burn when introduced into the cutting zone, thereby liberating a tremendous amount of heat in addition to that supplied by the normal preheat flames. This heat tends to melt at least some of the oxides that may be formed on the cut surface. Two other effects occur simultaneously. The principal one is that the iron oxides produce a matrix of iron oxide which is sufficient to flush away the refractory oxides that are formed. The second effect is that the presence of the iron powder or the burning oxides in the cutting stream, coupled with the kinetic energy of the resulting stream, increases the mass velocity of the cutting jet. This results in a combination of erosion and, in effect, shot blasting of the cut surface, thereby continuously exposing a fresh surface to the cutting stream. Cutting of difficult-to-cut materials by the powder method can be accomplished at the same speeds as oxygen cutting of carbon steel of equivalent thickness. However, the cutting oxygen flow is slightly higher with the powder process.

Equipment for Cutting Oxidation-Resistant Materials

Powder and flux cutting require several pieces of apparatus in addition to the torches and tips. Flux cutting employs a standard torch and tip, whereas powder cutting may employ a standard torch and tip with an auxiliary attachment. A powder dispenser and a gas supply to the dispenser are required for the powder process. The gas used for powder dispensing may be compressed air, nitrogen or other inert gas, or a special gas mixture. An additional hose for transporting the powder from the dispenser to the torch is also required.

Flux Cutting Equipment.— With the flux process a flux feed unit is required. The cutting oxygen is passed through the feed unit and this transports the flux to the torch. No auxiliary fluxhose or attachment is required.

In the flux cutting process a flux is held in a dispenser, which is a pressure vessel for use at the cutting oxygen pressures normally employed. The cutting oxygen flow through the dispenser is adjusted by means of a regulator. The flux, at rates of flow prescribed by the manufacturer, is transported by the cutting oxygen from the dispenser through a hose to the cutting torch. This torch utilizes three hoses. One hose supplies the preheat oxygen, the second, acetylene or other fuel gas in the conventional manner, and the third, the flux and cutting oxygen. The preheat gases are mixed as in standard oxyacetylene or oxy-fuel

gas devices. The preheat gases are delivered to the tip and burn at the exit face of the tip through a multiplicity of orifices. The cutting oxygen is turned on in the conventional way by depressing a lever, which opens the cutting oxygen valve. The lever is arranged so that depressing it also opens the valve in the flux line. The flux is in the cutting oxygen stream, so that a mixture of oxygen and flux issues from the tip.

Powder Cutting.—Dispensers for powder for the powder cutting process are of two general types. In each case, the dispenser includes a pressure vessel that operates at relatively low pressure.

One type of dispenser is a vibratory device in which the quantity of powder being dispensed from the hopper is governed by a vibrator. Varying amounts of powder can be obtained by changing the amplitude of vibration. The powder discharged from the vibrating device is dropped into a funnel-like arrangement. This funnel is within a sealed chamber. The powder conveying gas enters at this point, entrains the powder that has been dropped into the funnel and carries it through the hose to the torch. The size of the hose between the dispenser and the torch is important in order to entrain the powder with sufficient gas velocity but at the same time keep the ratio of conveying gas to powder as low as possible. The vibratory type of dispenser is generally used where uniform and accurate powder flow is required, such as in precision cutting, when shape cutting is to be done on materials such as stainless steel or when it is necessary to maintain high-quality, sharp top edges and other characteristics of conventional cutting.

The other type of dispenser, more in general use, is a completely pneumatic device and comprises a pressure vessel operating at relatively low pressure. In the bottom of this vessel is an ejector or fluidizing unit. The conveying gas is brought into the dispenser in a way serving to fluidize the powder so that it will flow regularly and easily into the ejector unit, where it will be picked up by the portion of the gas stream that serves as the transporting medium. The size of the connecting hose or conduit is important in that an effort is made to maintain a low transporting gas-to-powder ratio.

Whether a two- or three-hose machine cutting torch or a two-hose manual torch is used, an additional hose is required for powder. The special manual powder cutting torch brings the oxygen and acetylene or oxygen and fuel gas to the torch, mixes them and then discharges this mixed gas through a multiplicity of orifices in the cutting tip as in a conventional oxyacetylene torch. The powder valve is built as an integral part of the torch. The cutting oxygen lever that, when depressed, would normally turn on the cutting oxygen is so arranged that it also opens the powder valve in proper sequence. The powder entrained by the conveying gas is then brought through a separate conduit into a chamber forward of, and sealed off from, the preheat gas chamber in the torch head. This powder then enters a separate group of passages in a two-piece cutting tip and is discharged at the mouth of the tip in a conical pattern. The powder is discharged with sufficient velocity to cause it to enter and pass through the envelope of burning preheat gas and surround the cutting oxygen stream that issues from the central orifice in the tip. The tip passages conveying the powder are constructed from materials that can resist the abrasion of the gas borne particles. Similarly, the torch head, connecting tubing and all the other parts of the torch that are subject to abrasion by the powder must also be made of materials that will have relatively long life in this type of service.

Powder cutting adaptors are available for machine cutting or for adaptation of conventional two-hose manual cutting torches. Thus standard machine cutting or manual cutting torches may be used together with standard oxyacetylene or oxy-fuel gas cutting tips. In these cases, the powder valve is opened or closed by a completely separate motion from that required for opening the cutting oxygen valve. The gas powder mixture is carried from the downstream side of the powder valve to a powder cutting adaptor attached to the cutting tip. This adaptor surrounds the periphery of the exit end of the tip; the several powder passages cause the powder to issue in the form of a cone and at sufficient velocity to blow through the preheat envelope and impinge against the cutting oxygen stream. In a great many cases, particularly for manual cutting or straight line machine cutting, the powder cutting attachment is eliminated and a single tube is substituted. This tube discharges the powder-laden stream at an angle to the cutting oxygen jet at a velocity sufficient to drive it through the preheat envelope. This single tube attachment is applicable only where cutting is being done in one direction, for the powder tip must in all cases be at the leading or front edge of the cutting oxygen stream.

When the above methods are used for cutting oxidation-resistant metals, the quality of the cut surface is somewhat impaired. Dross adherence may occur. Carbon and iron pickup usually occurs in stainless steel and other nickel alloy materials, thus lowering the corrosion resistance and non-magnetic properties of the base metal. In order to retain the corrosion-resistant and non-magnetic properties of these materials, it is accepted practice to remove mechanically approximately ⅛ in. from the cut edge.

Fast-Starting Powder.—Ordinary cutting torches and nozzles may be equipped with external powder feed nozzles. Instantaneous starts can be accomplished with this equipment at the normal cutting speed by using a burst of powder when the leading edge of the cutting oxygen stream impinges against the piece being cut. After the cut has been initiated on carbon steel, the powder can be turned off, and the cut will progress in the conventional manner.

UNDERWATER CUTTING

Underwater cutting is used for salvage work and for any cutting that must be done below the water line on piers, dry docks and ships. The two methods most widely used are flame cutting and oxygen-arc cutting. The equipment and operating techniques of the latter are described in Chapter 43.

The technique for underwater cutting is not materially different from that used in cutting steel in open air. The torch used embodies the same features as a standard cutting torch, with the additional feature of supplying its own ambient gas atmosphere. In the underwater cutting torch, fuel gas (other than acetylene) and oxygen are mixed together and burned to produce the preheat flame, and a cutting jet is provided to supply the oxygen to cut the steel. The additional design requirement of the underwater torch is that provision must be made for maintaining an air bubble around the cutting tip. The air bubble is maintained by delivering compressed air to the torch; this compressed air is ejected around the tip, sheathing it in a bubble of air, or an artificially created atmosphere in which the tip can function normally. The air shield stabilizes the flame and at the same time displaces the water from the cutting area, permitting more efficient heating of the steel, since water is a far better conductor of heat than is air.

The underwater cutting torch is furnished with connections for three hoses to convey compressed air, fuel gas and oxygen. In addition, a combination shield and spacer device is attached at the end of the torch. The shield controls the formation of the air bubble and is also adjustable, so that the tip can be held at the correct distance from the work. This second feature is essential for underwater work where the torch is employed under adverse lighting conditions by operators wearing cumbersome diving suits that preclude the possibility of using a torch without a means of mechanically holding the torch at the optimum distance from the steel. Slots in the shield are provided to allow the burned gases to escape to the surface. A short torch is used to reduce the recoil accompanying the release of the gas jet against the surrounding water. Fig. 42.15 shows a cross-section of a typical torch.

As the cutting operations go deeper, the gas pressures must be increased to neutralize the added water pressure as well as the frictional losses in the longer hoses. Approximately ½ psi for each foot of depth should be added to the initial working pressures. Hydrogen and natural gas are the best all-purpose preheat gases since they can be forced to any depth that a diver can descend and still remain gaseous. Although most other gases normally associated with flame cutting can be used, they are usually restricted to shallower depths.

The oxy-fuel gas cutting torch experiences no great difficulty in progressively severing steel plate in thicknesses from ½ in. up to about 6 inches. Under ½ in., however, the constant quenching effect of the surrounding water lowers the efficiency of preheating to the extent that cutting speeds are substantially retarded. It is on this thin material that the oxygen-arc cuting process works well. Although the oxygen stream issuing from the electrode has no precise form for penetration, it washes the metal away under the intense heat of the arc. This feature also permits it to sever cast iron, brass and other nonferrous metals. There are, however, the ever-present hazards involved when handling high-amperage current.

Both processes have a definite application and each should be given careful consideration on specific jobs in order to use the diver's time effectively. For more details refer to "Underwater Cutting and Welding Manual" Navships 250-692-9 (1953).

HEAVY CUTTING

Heavy cutting is defined, for purposes of this chapter, as the oxygen cutting of steel over 12 in. thick and ranging upward to 94 in. or more. The art of heavy cutting was given a tremendous boost by the mandatory use of oxygen cut steels caused by the demand for rapid production of heavy steel items, especially heavy forgings, during World War II. The development of equipment for heavy cutting during the war period was followed in the late 1940's by controlled studies of the process. These events have resulted in putting heavy cutting applications on an orderly and predictable basis.

Results of technical studies under controlled conditions, backed by more than twenty years of field use, have shown how to do heavy cutting on a repetitive basis. The most useful observation from this experience is that the basic reactions permitting oxygen cutting of heavy steel are the same as those for cutting of thinner sections. Thus, materials ranging in thickness from ¼ in. to 94 in. may be cut, with preheat and cutting oxygen flows increasing and cutting speeds decreasing as thicknesses increase.

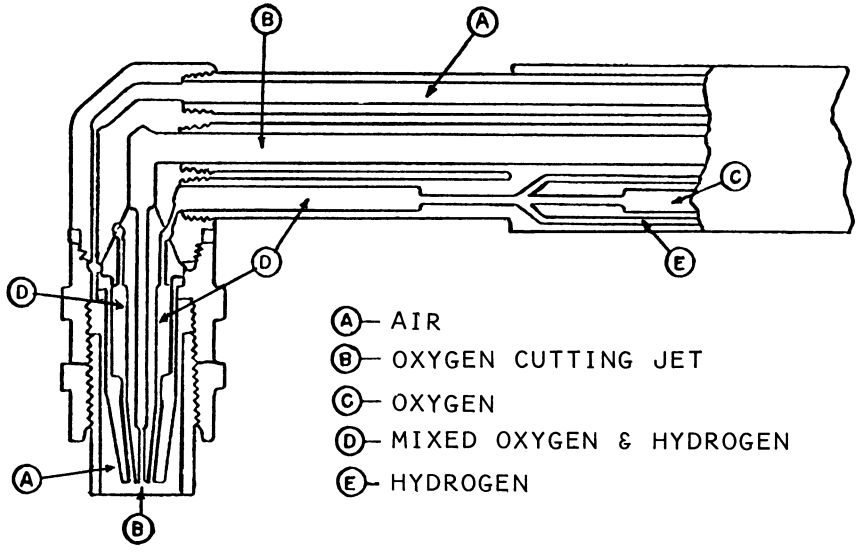


Fig. 42.15.—Operational functions of gases in underwater cutting torch.

For heavy cutting, the most important factor is oxygen flow. Nozzle size and operating pressure are involved only insofar as these values must provide the necessary flow required for the thickness being cut. Oxygen cutting pressures in the range of 7 to 50 psi, measured at the entry of the cutting torch, have been found adequate for the heaviest cutting attempted (up to 94 in.) provided that the nozzle size and equipment are properly selected. The oxygen flow at the torch entry is of paramount importance in comparing results of different cutting operations. Measurements of pressure at the regulator or at some point removed from the torch, without regard to restrictions nearer the nozzle, will lead to much confusion. Unknown restrictions cause variations in flow and unpredictable results when conditions are not exactly duplicated. By predicting performance on the basis of flow rather than pressure, heavy cutting data can be plotted as a continuous curve.

In terms of flow it is possible to arrive at an approximate demand constant that will be useful as a guide in selecting equipment suitable for a given job. These demand constants may vary, but in terms of thickness they usually fall within the approximate range of from 80 to 125 cubic feet of oxygen consumed per inch of thickness (80T to 125T, where T is thickness in inches). Table 42.5 gives the range of operating conditions that cover normal heavy cutting operations. Heavy cutting covers a wide variety of operations, such as ingot cropping, scrap cutting and riser cutting. It must therefore be understood that the data obtained from this table may not be entirely suitable for all heavy cutting operations, although these values have been used successfully.

They may be used as a guide in selecting the correct equipment and operating conditions. The actual values for most efficient operations of the specific cutting application involved are always best found by trial cuts.

When heavy cutting is performed with the torch in a horizontal position, the cutting oxygen pressure may have to be increased to aid in mechanical removal of the slag produced from the cutting reaction.

Recommendations as to the speed of travel are not included in Table 42.5 but speeds from 2 to 6 ipm are used in the range of thicknesses covered. A speed of 3 ipm is possible for thicknesses up to at least 36 inches. The correct speed is obtained by observing the operating conditions carefully and making suitable adjustments when actual cutting is in progress.

Because heavy pieces usually present an irregular, scale-covered surface, techniques of starting the cut differ from those usually used with thinner material where the edges are frequently square and clear of scale. The start of the reaction is made more slowly on the rougher edges, but the reaction, once started, is more marked and spectacular because of the greater volume of iron being oxdized per unit of time. Fig. 42.15 indicates correct and incorrect starting conditions. Fig. 42.15A shows the desirable starting position with the flow of molten metal extending down the face of the material rather than lying on the top. This flow of molten metal permits the cutting reaction to proceed down the face of the material to the bottom as the oxygen is turned on and forward motion is started. Fig. 42.16B, C, D, E, and F show problems occurring from incorrect procedures.

When the cut proceeds properly, with correct oxygen flow and forward speeds, the reaction will proceed to the end of the cut, without leaving a skipped corner. Fig. 42.17 illustrates various correct and incorrect terminating conditions and proper drag conditions. Conditions producing a drop cut are depicted in Fig. 42.17A.

In general, the conditions required for successful heavy cutting on a production basis are:

1. An adequate gas supply sufficient to complete the cut. This is necessary as a lost cut on heavy materials is extremely difficult, if not impossible, to restart at the lost cut surface.
2. Equipment of sufficient size structurally (to maintain rigidity and to carry the equipment needed) and of sufficient capacity to handle the range of speeds and gas flows required.
3. Skilled personnel trained in proper heavy cutting techniques.

The first item is important to ensure completion of the job without interruption due to insufficient gas capacity. Not only must the gas source be adequate, but the pipe lines, station drops and regulating equipment must be of a size suitable for the gas flows to be handled. Table 42.5 shows that oxygen flows for heavy cutting are in the range normally supplied only by pipe line with well-engineered facilities. Design of the gas supply should emphasize lack of restrictions so that full flow is maintained at the cutting nozzle at all times.

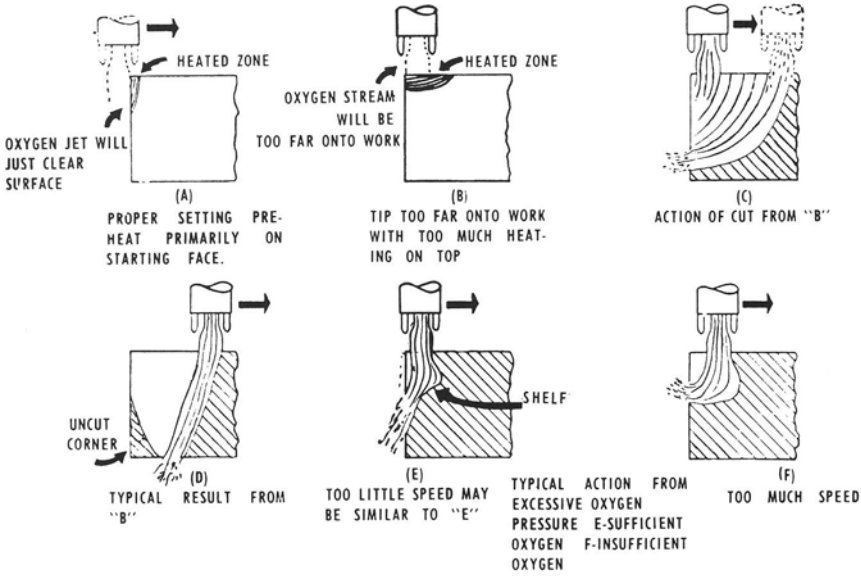


Fig. 42.16.—Typical conditions for heavy cutting.

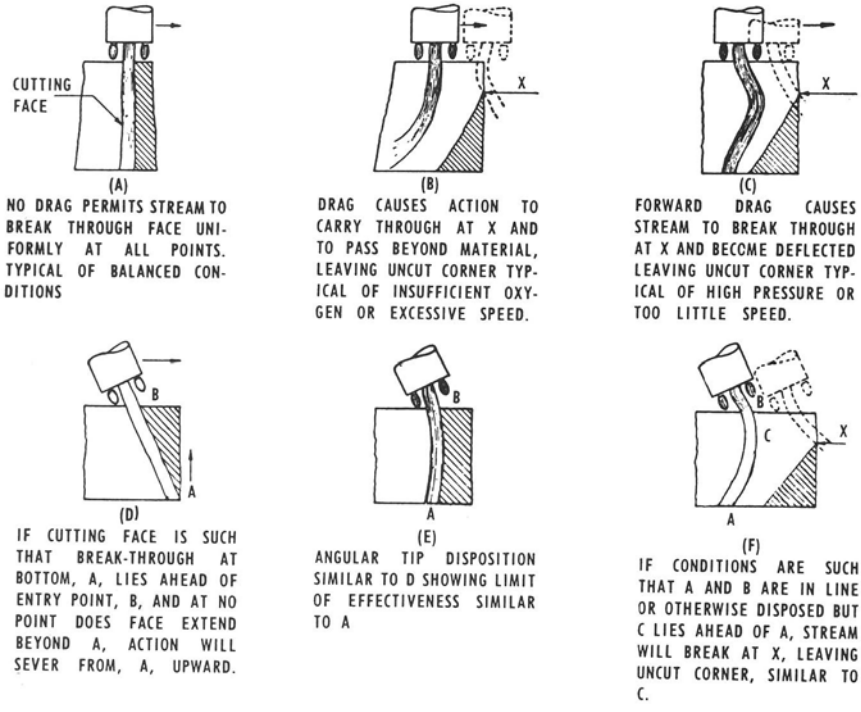


Fig. 42.17.—Terminating conditions for heavy cutting.

The cutting equipment and machines must also be selected for the particular job under consideration. The machines used to carry the cutting torches must be strong and rigid enough to carry the load of the cutting torches and the supply hoses, and should be properly counterbalanced where necessary. These precautions are essential for the safety of operating personnel and to maintain continuity in the cutting operation. The machines must be capable of maintaining a uniform speed and be geared to provide a minimum constant speed down to 1 ipm or less. Speed must also be readily adjustable so that it can be varied when cutting operations warrant.

Torches must be constructed with a minimum of internal gas flow restrictions. For cutting materials up to about 20 in. thick, torches with attached valves can be used satisfactorily, but for heavier work valveless torches are preferred. These permit locating control valves away from the heat of the cutting operation. Torch gas capacity for very heavy cutting should be a minimum of 6000 cfh at a maximum torch entry pressure of 20 psi for cutting oxygen and 300 cfh for the fuel gas; preheat oxygen capacity depends on the type of fuel gas employed.

Cutting nozzles designed specifically to provide preheat flames suitable for heavy cutting are essential for success. Preheat flames must be relatively large, or complete penetration will not be obtained and excessive drag will occur. No attempt should be made to obtain zero drag since this may tend to promote shelving; a drag commensurate with the thickness being cut should be sought.

The flame adjustment for heavy cutting should be a very long, slightly carburized flame so that much of the heat energy release takes place down in the kerf. Fuel gases that have a high heat release in the secondary portion of the flame usually produce the best results.

Trained personnel are essential for successful heavy cutting. They should be thoroughly familiar with the equipment and its control and should have no hesitancy about attempting heavy cutting operations. The cutting machine operators should be trained to be painstaking and exact in their work and to make accurate setups and alignments. A misalignment of a fraction of an inch, which would be of no consequence in thin sections, could become so exaggerated when dealing with thick sections that an expensive piece of steel could be ruined. Cuts up to 94 in. deep have been made in forging and scrap cutting operations.

The well-trained cutting machine operator, when starting a cut, knows that many variations in cutting conditions can be encountered; he also knows that proper and immediate adjustments to compensate for altering conditions will ensure consistently successful cuts. Finally, the cutting machine operator should wear proper clothing and protective devices at all times. (Refer to Section 1, Chapter 9, Sixth Edition of the *Handbook*.)

CUTTING AT ELEVATED TEMPERATURES

Continuing demands for greater production in the steel industry have increased the use of improved equipment for oxygen cutting of steels at rolling mill temperatures of 1500 to 2000°F (816 to 1093°C). Hot cutting is used to advantage directly in the rolling line, where the flexibility and low capital

cost of the process have encouraged its use in place of mechanical shears, saws and other severing devices. It is also finding application in cutting billets produced by continuous casting processes. Even the relatively slower speed of the oxygen cutting process is compensated for by multiple torches or other means, whereas the currently available, low-cost oxygen and natural gas in steel mills have made operating costs of oxygen cutting in the rolling mill competitive with shear and saw costs.

To permit the inherently greater speeds of oxygen cutting at elevated temperatures, gas flows considerably greater than those used for cold cutting must be supplied. Cutting equipment (machines, torches and regulators) must be of sufficient capacity and size to handle these larger gas flows, as well as the severe thermal and operating shocks such equipment is subjected to under mill operating conditions. Torches must be selected for large gas flows, which must also be remotely controlled. All equipment, including the machine, hose, etc., should either be protected from or capable of exposure to the heat from the high-temperature material. Water cooling of the torch itself is generally necessary. Adequate safeguards to protect the operating personnel from intense heat, flying slag and scale must be provided during a hot cutting operation.

Oxygen cutting at elevated temperatures follows the same general principles that apply to cold cutting except for the great increase in the speed of reaction and, therefore, cutting speeds.

Very high cutting speeds can be obtained in the oxygen cutting of steels at elevated temperatures with some variations in the flatness and squareness of the cut faces. Choice of the most desirable cutting speed to be used for any given cutting application will depend on a proper balance of gas costs, quality of cut desired and requirements of the mill cycle being serviced by the cutting operation. Since elevated temperature cutting of steel permits a much wider range in cutting speeds, it also permits a wider choice of quality of cut surface—from very rough to very smooth. It is possible to make cuts on steel at elevated temperatures that are equivalent in finish and dimensional tolerance to quality cuts on cold material of the same thickness; however faster cutting speeds are used.

Whenever cut surface requirements are not rigid, the cutting speeds realized at elevated temperatures are much greater than those obtained on cold material. For many applications, rough cuts are not of major importance, and the advantages to be gained by increased cutting speed make very high speed cutting at elevated temperatures advantageous.

Both standing starts and flying starts are possible with elevated temperature cutting. However, a very heavy preheat, additional heat in the form of a leading auxiliary preheat or the introduction of a steel rod or iron powder at the point of flame impingement on the steel may be required to accomplish flying starts.

Carbon and other alloying elements in steels have a marked effect on cutting speeds, but very little investigative work has been reported. In one study it was found that maximum cutting speeds are obtainable in steels having about 0.75% carbon. Since the effects of alloying elements on oxygen cutting are insufficiently known, no specific statements can be made.

Metallurgically, hot cutting results in a cut surface free of carbon enrichment, and with scarcely perceptible hardness gradient; the thermal gradients produced are not of sufficient magnitude to cause pronounced carbon migration toward the cut surface. The cut edge shows evidence of a slight decarburization, mainly in the areas immediately under the preheat flames. Photomicrographs show that grain growth along the cut surface is not appreciable. Hot cutting with the correct procedure results in perfectly sound material with normal structure and no indication of thermal checking or other undesirable features.

Kerf widths obtained for quality cuts of elevated temperatures can be almost identical with those obtained in cold cutting, provided proper cutting nozzles are used. Quality cuts at elevated temperatures can be made with preheat controlled to a degree such that meltdown of the upper edge is only slightly more pronounced than in cold cutting. The intensive preheat used in making lower quality cuts at elevated temperatures results in a noticeable meltdown of the top edge. At temperatures encountered in hot cutting, it should be noted that the tenacity of slag and scale is increased and may cause difficulty in later forming operations if the cut face is irregular.

EQUIPMENT

There are two basic types of oxygen cutting equipment, manual and machine equipment. The manual equipment is used primarily in scrap cutting, cutting risers off castings and other cutting operations that do not require a high degree of accuracy. Machine cutting equipment is utilized where a large volume of cutting is performed, such as in steel fabricating shops. Oxygen cutting equipment varies in appearance, but both types operate on the same principle.

MANUAL EQUIPMENT

For manual cutting, a torch that can be manipulated readily is preferred. Manual oxygen cutting torches are available in various sizes. Torch selection generally depends on the thickness of the steel to be cut. Tips used in manual cutting equipment are of varied design, depending on the type of work to be done. For example, for cutting rusty or scaly steel, a tip furnishing a great amount of preheat would be selected. Such a tip can easily be installed in a standard cutting torch.

There are two types of torches: the tip mixing type, in which the fuel and preheat oxygen for the heating flames are mixed in the tip; and the premixed type, in which the mixing takes place in the head or at some location upstream of the head (for example, in the body of the torch). If both the oxygen and fuel gas are under appreciable pressure, the torch is designated as a positive pressure type (Fig. 42.18). When the fuel gas is at a lower pressure, generally a fraction of a pound per square inch, and supplied to the flames through the aid of an injector, the torch is designated a low-pressure or injector torch (Fig. 42.19).

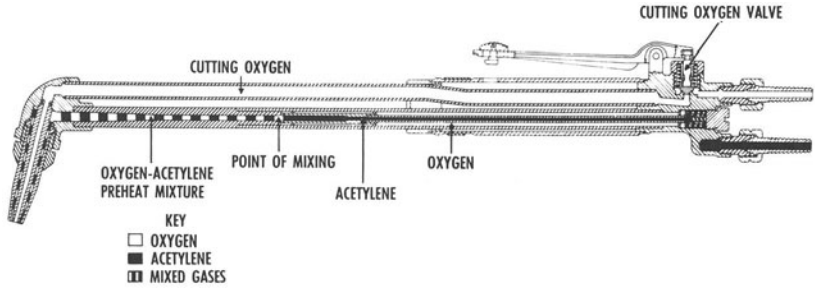


Fig. 42.18.—Schematic diagram of a positive pressure oxygen cutting torch.

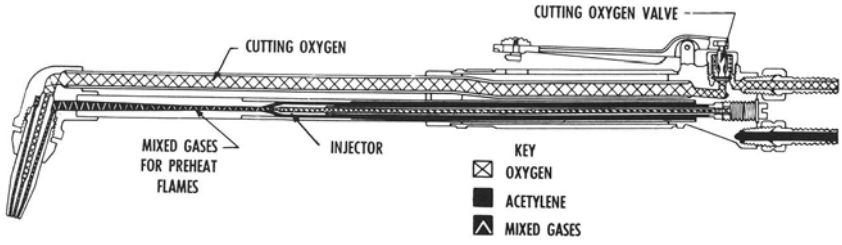


Fig. 42.19.—Typical premixed injector-type oxygen cutting torch.

The torch is connected to the gas supply by hose lines of sufficient size to conduct the volume of gases necessary for the cutting operation without excessive pressure drop. The hose lines are in turn connected to the outlet of the two pressure regulators (one for the fuel gas and one for the oxygen), which in turn are connected to the respective gas supplies, which may be a pipe line, a manifold or a cylinder.

MACHINE EQUIPMENT

Oxygen shape cutting machines are either portable or stationary. Portable machines are usually moved to the work, whereas the stationary machines are fixed in location and the work is moved to the machine.

The basic characteristics of stationary machine oxygen cutting are: a machine designed for the job, an operator station with complete electrical controls, a gas system to provide adequate quantities of oxygen and fuel gas and a materials handling system. Given a combination of these factors, machine oxygen cutting can be done with complete predictability.

Stationary oxygen cutting machines are usually classified in respect to the maximum width of the plate that can be cut, such as 60, 80, 120, 144 inches. Since most oxygen cutting machines run on tracks, the cutting length can be extended indefinitely.

An operator's station with consolidated controls for all the gases and the torch and machine movements is desirable and is usually designed as a part of the machine

Portable

Portable machines are used predominantly for straight line cutting, although they can be adapted for circular and some even for shape cutting. Portable machines usually consist of a motor-driven carriage with an adjustable mounting for the torch. In most cases the machine travels on a track, which performs the function of guiding the torch along the line of the cut, and which can be extended indefinitely. The speed control in these machines is adjustable over a wide range and controlled by a governor to maintain a uniform speed of travel. The degree of precision in following the line of cut depends upon the track or guide and the fit between such a guide and the driving wheels of the machine. Portable machines are of various weights and sizes, depending on the type of work to be done. The smallest machine weighs only a few pounds and is limited to carrying light torches for cutting thin material. The larger portable cutting machines are heavier and more rugged and can carry heavy torches and auxiliary equipment. The intermediate range machines are the ones generally used for miscellaneous straight line cutting and possibly circle cutting in the plate and general fabricating shop. The heavy-duty machines are used in fabrication shops, shipyards, steel mills and other areas where very thick steel sections are to be cut.

Stationary

The stationary type of cutting machine is designed to remain in a single location with the work being moved to the machine. These machines run on tracks with structures that either span the work with a gantry-type bridge or reach over the work with a cantilever device (Fig. 42.20). Stationary oxygen cutting machines may be classified into two main types:

1. Straight line cutting machines for plate edge preparation; these are often referred to as oxygen planners and are considerably heavier and of more rugged construction than the small portable machines.
2. Shape cutting machines which are capable of cutting any type of shape.

Straight line oxygen cutting machines usually span the plates, with either torch assemblies between the rails for edge preparation or several single torches for cutting steel strips in varying widths. Some types of oxygen cutting machines have lighter construction bridges that carry cross cutting carriages. With three such bridges, it is possible to cut all four sides of a plate at the same time. Torch assemblies used in the oxygen cutting machines for plate edge preparation are usually of the three-torch type, with wheeled carriages riding on the plate surface or with some other sensing means for maintaining a constant distance between torch tip and plate. The torch assemblies are gen-

erally arranged so that the torches can be angled with respect to each other for cutting bevels. Three-torch assemblies are capable of cutting two bevels and the root face in one operation.

Shape cutting machines are of two basic designs, one a pantograph and the other a cross-carriage mechanism. In both types of machines the basic element is a floating bar with a torch or torches located on one end and a tracing or driving device on the other. The differences in design are in the portions of the machine that carry this bar.

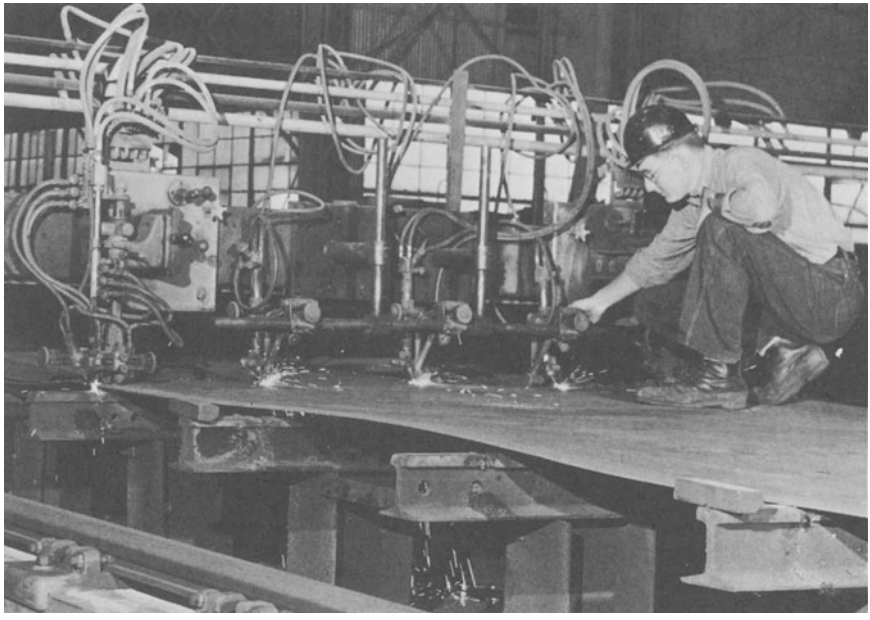


Fig. 42.20.—Typical gantry-type oxygen cutting machine.

In the pantograph-type machine, the bar is held by two arms that fold open and shut. The entire pantograph assembly is mounted on a carriage riding on rails which can be of any desired length.

In the cross-carriage mechanism, the carriage also rides on rails. The bar holding the torches can easily move at right angles to the longitudinal carriage on which it rides. Both designs can cut regular or irregular shapes of nearly any complexity and size. Shape cutting machines can mount numerous torches, depending on the size of the machine. Ten or more torches may be used in normal operations. In multiple-torch operations as many identical shapes can be cut simultaneously as there are torches (Fig. 42.21).

TRACING DEVICES

As indicated in the previous section, the usual type of oxygen shape cutting machine employs a bar with torches on one end a tracing device on the other end. On some machines this bar is driven at cutting speeds by a small wheel riding on the tracing table. A suitable tracing device is combined with the driving wheel to steer the torch bar around a template or drawing of the part to be cut. Both the pantograph and rectilinear machines use the same tracing and drive principles. A small wheel or magnetic tracer is employed to drive the machine. The tracing device and arm may be manually guided around the outline of a drawing, may follow a vertical strip pinched between two drive rollers or trunnions or may be a magnetic tracer which adheres to and follows the outline of a steel template. An electronic tracing device may also be used, here a photocell follows the outline of a drawing and steers the driving wheel. Traction for driving the machine comes solely from the tracing wheel. The most recent designs for rectilinear type machines utilize a sine-cosine relationship. The carriage and the cross-arm, each with its own driving motor, are driven in the desired direction, but the speed of movement of the tracing arm remains at the constant preselected value. This construction allows the manufacture of an oxygen cutting machine as heavy as necessary to carry all modern control equipment. It is possible to feed information to the electric drive motors of the carriage and cross-arm from any desired source. Adaptations of these machines are arranged to use pilot machines, which have a photocell tracing means and may follow reduced scale drawings. The most recently developed control devices for cross-carriage machines consist of calculated profile programs, placed on either punched or magnetic tapes. These tapes, in turn, control the shape cutting by suitable impulses to the cutting machine drive motors.

MATERIALS HANDLING SYSTEMS

Materials handling facilities are required for efficient operation of both portable and stationary oxygen cutting machines. These generally consist of an overhead crane and a multipoint table to support the work. Some of the more specialized machines can use roller table conveyors. The work-holding table, in any event, should be constructed to hold the work with the least possible interference with the cutting operation and should be designed to permit proper disposition of scrap pieces.

GAS SYSTEM

A gas system must be engineered to supply adequate quantities of oxygen and fuel gas for the maximum number and size of torches to be used. The manifolds, pipe lines, regulators and hoses, as well as the source of gas supply, must all be of sufficient capacity.

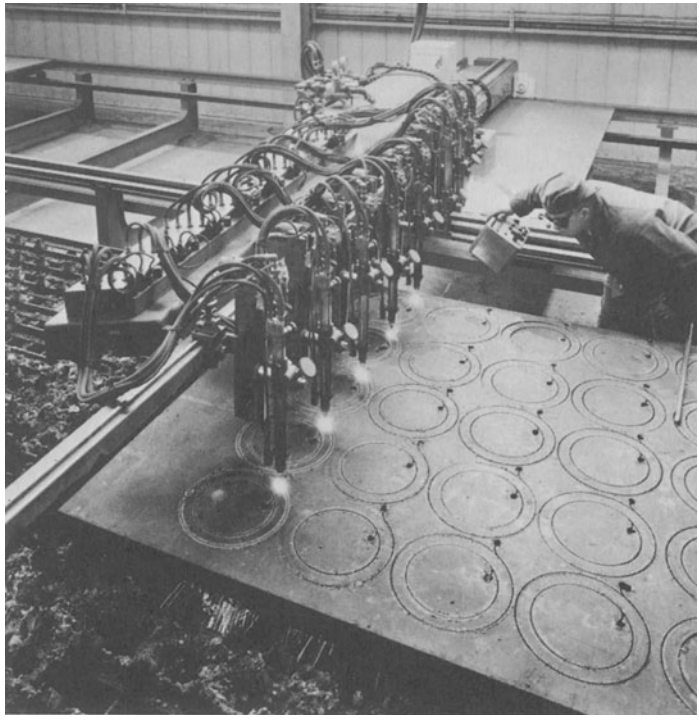


Fig. 42.21.—Multiple torch plate cutting procedure showing five torches in simultaneous operations.

APPLICATIONS

MULTIPLE-PIECE PRODUCTION

In shape cutting, multiple-torch units are frequently used for multiple-piece production and for plate edge preparation where more than one torch at a time is needed to produce the proper edge configuration. In multiple-piece production, it is possible to produce any number of pieces at one time, with additional torches on the same bar being guided around the same shape.

SHIPBUILDING

Ship plate cutting, because of lofting developments, has resulted in the development of very large automatic cutting machines for oxygen cutting several large plates simultaneously. This may be done from reduced 1:10 or 1:100 scale template drawings. Oxygen cutting is also used in many areas other than the plate fabrication shop. These applications include the use of manual oxygen cutting torches to change parts, to remove tack welds and to back-gouge welds.

STEEL MILLS

The adaptability of the oxygen cutting process to steel mill operations has resulted in a number of special applications.

Specially designed oxygen cutting machines for cutting steel billets and blooms in rolling mills have been devised. These are usually heavy, rugged, straight line cutting machines capable of cutting across the bars at rolling mill temperatures, thereby replacing mechanical or hydraulic shears. Blooms and bars up to 60 in. wide or more can be cut by a properly designed oxygen cutting machine. The main advantage of oxygen cutting machines is that they may be of lighter construction than shears and are less apt to break down because they are not subject to shock. In addition, because of their construction, the capital cost and maintenance of oxygen cutting machines is much less than that of shears. The major disadvantage of oxygen cutting machines for such steel mill applications is the relatively slow speed as compared to shears.

There are also heavy-duty machines for cutting heavy buttons that result from steel mill operations and machines for cutting such items as heavy forgings. Other machines are employed to cut finished beam sections to size and to trim off the cropped ends, as well as cutting Tee sections and other special shapes that cannot readily be sheared.

STEEL WAREHOUSE

In the steel warehouse, where it facilitates quick shipment of any desired size and shape of plate to the customer, oxygen cutting has become a vital part of the housing.

CONSTRUCTION

Oxygen cutting is an accepted tool in all the major construction industries using steel as the basic material. The facility with which it can economically cut steel of various thickness and intricate shapes has made oxygen cutting a major process in the production of steel plate shapes.

SCRAPPING AND SALVAGE

Oxygen cutting has proven to be the most economical process for the salvage and scrap industries. Without the use of oxygen cutting to demolish structures, ships and equipment, it would be difficult to dismantle such structures economically. Oxygen cutting permits the ready reduction of steel scrap to suitable size for shipment to steel mills for future steel production. Many salvage operations, especially underwater work, can only be accomplished by oxygen cutting to remove debris and damaged sections, allowing repair work to be undertaken.

EMERGENCY WORK

Oxygen cutting is an essential tool for emergency work. Many police and fire departments, as well as other rescue teams, have oxygen cutting equipment available. The oxygen and fuel gas cylinders are in a self-contained, readily portable unit.

AUXILIARY PROCESSES

Auxiliary processes include scarfing, gouging, grooving, washing, piercing and lancing. The chemistry of these reactions is the same as that described in the preceding section concerning oxygen cutting. Basically, the metal is heated to its ignition temperature and then high-purity oxygen is supplied to cause rapid oxidation and melting of the metal.

SCARFING

Scarfing or deseaming covers those operations involving the surface conditioning of steel blooms, slabs and billets preparatory to finish rolling in the steel mill. It has largely replaced chipping with the pneumatic hammer for the removal of cracks, seams, scabs and crows-feet from steel stock.

Scarfing has decided advantages over chipping as a means of removal of these defects. It is much faster than chipping. It also results in reduced floor space requirements for steel conditioning operations. Scarfing makes it possible to salvage many steel stocks too badly checked to warrant chipping. Contrary to supposition, scarfing does not cover up defects but actually exposes small cracks and imperfections which other methods may not reveal.

Another important application of hot manual scarfing is the removal of tears and scabs resulting from forging and pressing operations, thus eliminating the need for cooling and reheating cycles common to chipping operations.

Manual Scarfing Technique

The technique of scarfing is as follows: A spot on the surface is heated to the ignition temperature. During the preheating, which also loosens the surface scale and exposes clean metal, the tip is held at an angle of approximately 75° to the work, with the tip of the preheating flame almost touching the metal surface. The preheated area should be as extensive as possible to assure rapid starting and to prevent excessive digging at the beginning of the scarf. When the steel under the preheat flames has reached the proper temperature, the nozzle is rapidly drawn backward about an inch and the angle between the torch and work is reduced. The scarfing oxygen orifice is thus positioned so that the oxygen stream will impinge upon the preheated area when the oxygen valve is opened. The operator then depresses the scarfing (cutting) oxygen valve and simultaneously moves the torch forward at uniform constant speed.

Most manual scarfing torches are equipped with a rod feed starting device. Automatic rod starting results in instantaneous starts without the need for prolonged preheat or manipulation of the angle of impingement of the preheat flames on the workpiece. In general, the rod starting devices are arranged

so that, when the scarfing oxygen lever on the torch is initially depressed, approximately 3/8 to 5/8 in. of 3/16 in. diameter steel rod is fed down in front of the preheat flames and the scarfing oxygen orifice. As the scarfing lever is depressed still further, the scarfing oxygen valve is opened, thereby causing the heated portion of the rod to oxidize immediately. The scarfing oxygen stream impinges the burning steel of the rod on the surface of the material to be scarfed. The pattern of the impingement of the oxidizing metal approximates that of the scarfing oxygen stream thus producing a start which has essentially the same width as the remainder of the scarfed path. The oxidization of this small amount of steel rod liberates heat sufficient to permit instantaneous starts to be obtained. Under normal circumstances the scarfing oxygen lever is depressed in one continuous motion, upon completion of which the forward movement of the torch is started.

After the scarfing operation has commenced, the forward motion of the torch should be continued without interruption or hesitation. During forward motion, it is possible to alter the angle of the nozzle to the steel surface or to vary the forward speed in order to control the width and depth of the scarf.

When an entire surface is to be scarfed and a series of adjacent passes are required, the first pass is usually made nearest to the worker. Subsequent passes should then be made on the far side of the previous scarf, allowing sufficient overlap to remove defects. When the tip is angled slightly away from the worker or toward the right of the direction of travel (when travel is from right to left), the slag will be washed to the far side of the scarf. Succeeding passes of the torch will remove the slag remaining from the preceding scarf without leaving excessive fins on the sides of the scarf.

If the tip is held directly in line with the direction of forward motion, a deep, narrow scarf results. The slag removed from the scarf may be blown to both sides, and may form parallel fins on the surface, depending upon the carbon content of the steel. Fins are then removed by other cleaning methods.

After successive passes of the torch a properly scarfed surface is covered by a light, flaky oxide coating that may be removed by a wire brush, leaving a bright clean, finished surface. If any defects remain, they will be clearly visible and can readily be marked for additional treatment. The finish will be superior to that of steel cleaned by chipping.

Mechanical Scarfing

It is posible to mechanize the scarfing process in its simplest form by mounting the scarfing torch on a machine that permits control of the motion between the torch and the workpiece.

In practice, mechanized scarfing is performed with a nozzle that forms a continuous sheetlike stream of oxygen for the scarfing reaction. The scarfing nozzles are mounted on scarfing machines that are designed to fit into the production rolling line. The majority of the scarfing on semifinished materials is done in the production line at rolling temperature, normally 2000°F (1043°C).

Hot scarfing speeds may vary from 50 to 250 linear feet per minute so that steel can be conditioned without interrupting the rolling process. The modern scarfing machines can condition the four surfaces on billets, blooms and slabs over a wide size range. Where entire surfaces are being removed, the surface is usually removed to a depth calculated to result in the elimination of all or the greatest possible proportion of surface defects. For direct rolling to final product size, an initial scarfing depth should be selected to approach 100% surface conditioned yield in the final rolled product. Where the rolling cycle is interrupted, economics may dictate a depth of surface removal designed to result in a minimum amount of manual spot scarfing on the product before reheating for further rolling. Metal loss is a prime consideration when specifying depth of removal, particularly on high-grade steel.

GOUGING

Gouging is used extensively to remove deep defects in steel revealed by scarfing, and by radiographic, magnetic particle, ultrasonic and other inspection methods. Other applications include the removal of tack welds or defective welds, defects in steel casting owing to blowholes or sand inclusions, welds in temporary brackets or supports, flanges from piping and heads and old tubes from boilers. It is also used in demolition work and in the preparation of plate edges for welding.

Manual gouging provides a rapid method of metal removal. Speeds from 1 to 7 linear feet per minute have been obtained. Depending upon the skill of the worker, it is possible to control the accuracy of the gouge to a tolerance of about 1/16 in. in both width and depth. The equipment is readily portable and can be used for the removal of otherwise inaccessible defects. The process is relatively quiet and maintenance costs are less than for mechanical processes that require repeated sharpening of tools.

Gouging Technique

Oxygen gouging is a modified oxy-fuel gas cutting process for producing a fully controlled groove or gouge. Small orifices in the end of the nozzle supply mixed oxygen and fuel gas for the flames to preheat the steel surface to its ignition temperature. The torch should remain stationary until the ignition temperature has been reached. The gouge is slowly started by gradually depressing the cutting-oxygen valve and at the same time retracting the torch a short distance. The nozzle is then turned in a smooth downward arc until the angle between the nozzle and the work is reduced to the correct operating angle. The nozzle is then moved forward along the line of cut.

Progressive Gouging.—A standard manual torch is used in oxygen gouging. The gouging tip is designed to deliver a high volume flow of oxygen at relatively low velocity. The correct tip or nozzle is first selected depending on the size of the desired gouge. The choice may be based upon the experience of the individual or the data provided in Table 42.6. The oxygen pressure is then regulated to give the desired width and depth of groove. The data in Table 42.6 apply for average conditions and for best results tests may be necessary in order to select optimum operating conditions.

Table 42.6—Operating data for gouging equipment

Tip Dia., In.	Oxygen Regulator Pressure, Psi*	Consumption, Cu Ft Per Hr			Approximate Speed, Ft per Min	Approximate Width, In.	Gouge Depth, In.
		Acetylene	Preheat O_2	Gouging (Cutting) O_2			
0.130	65	35–38	35–38	78–82	1.0–1.2	5/16	1/8–3/16
0.130	70	35–38	35–38	88–92	1.4–1.6	5/16	5/32–7/32
0.130	75	35–38	35–38	98–102	1.5–1.8	5/16	3/16–1/4
0.190	80	50–55	50–55	170–175	1.6–1.9	3/8	3/16–1/4
0.190	85	50–55	50–55	188–192	1.8–2.0	7/16	7/32–9/32
0.190	90	50–55	50–55	205–210	1.9–2.2	7/16	1/4–3/8
0.250	90	55–60	55–60	278–282	1.9–2.2	1/2	3/16–1/4
0.250	95	55–60	55–60	308–312	2.3–2.6	1/2	1/4–3/8
0.250	100	55–60	55–60	328–332	2.5–2.8	1/2	5/16–7/16

* Pressure measured at the regulator; acetylene pressure 10 psi in all cases. Tips can also operate on low-pressure acetylene with appropriate torches.

In starting the gouge, the torch is held with the end of the tip or nozzle at an angle of approximately 30 to 45° to the workpiece (Fig. 42.22A), so that the tips of the inner cones of the preheat flames just touch the work. The preheat flames are then directed to the area where the gouge is to be started, until the surface reaches the ignition temperature. The angle between the tip and the surface is then reduced to between 15 and 20° and the tip is immediately withdrawn so that the inner cones of the preheat flames are from 1/4 to 1/2 in. behind the preheated area (Fig. 42.22A). The oxygen control lever is also gradually depressed and the torch is advanced as soon as the reaction starts. The gouge progresses slowly while the angle of the end of the tip is gradually reduced to the final operating position of 5 to 25° (Fig. 42.22B). The proper angle will be readily discernable. If the tip is not lowered far enough some of the slag tends to flow backward into the gouge toward the operator; if it is lowered too far, however, the gouge will become shallow and will soon be lost. Best results are obtained when the torch is held with the tip clear of the bottom of the groove.

About 2 feet per minute is the approximate torch travel speed for making a clean gouge 3/8 in. wide and 1/4 in. deep in cold steel plate.

When it is necessary to change the direction of the gouge, the angle of the nozzle in relation to the work should remain unchanged while the torch is rotated to the new direction. Too sharp a turn should be avoided to prevent the outside wall from being cut into as a result of the molten slag action. It is advisable to use lower oxygen pressures than those indicated in Table 42.6 when not gouging in a straight line.

The depth of the gouge is a function of the speed of progression and the angle between the oxygen stream and the work. To cut a deep gouge, the angle of the torch is increased in relation to the gouge and the speed is correspondingly decreased. To make a shallow gouge, the procedure is reversed. Gouges can be made as deep as they are wide or slightly deeper. Furthermore, successive passes can be made to reach the bottom of a defect that may be as much as 2 to 3 in. below the surface.

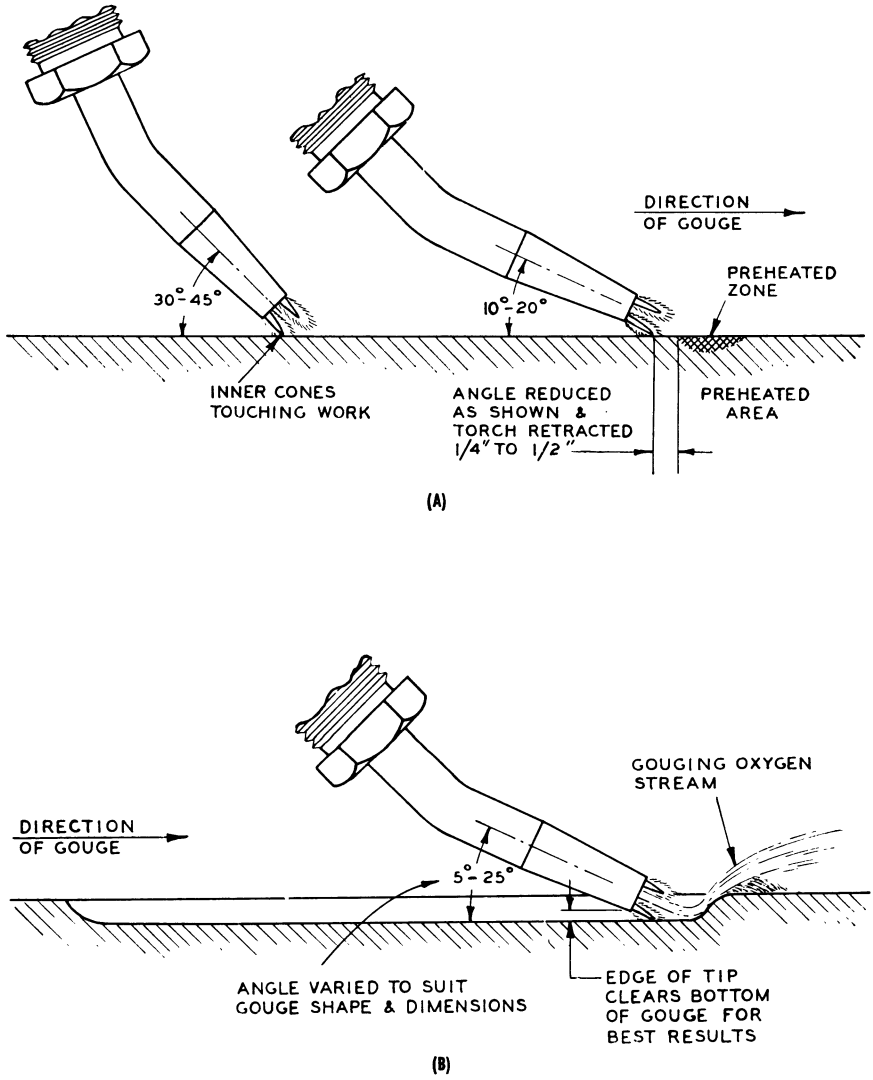


Fig. 42.22.—(A) Schematic showing nozzle angle for preheating (left) and for start of gouging operations (right). (B) Schematic diagram of oxygen cutting torch held at a proper angle for gouging.

The contour of the gouge is dependent upon the characteristics of the tip used and the operating conditions. If the oxygen pressure is too low, the gouging action will be very shallow and slow. Too high an oxygen pressure requires rapid tip movement to prevent a deeper gouge than is desired, and to prevent piercing of the plate.

Gouging operations can be mechanized by mechanically moving the tip relative to the work. Gouges are obtained smoother and more accurate than can be cut with manual operations. Gouging speeds are from two to five times faster than cutting speeds and therefore require machines with higher driving speeds.

Backstep Gouging.—The backstep method was developed to facilitate removal of defective welds and imperfections in the base metal. The nozzle is held in a similar position to that used in the progressive method during preheat. After the starting point has been heated to the ignition temperature, the oxygen valve is opened and the tip is moved to the line of gouge but in a backward instead of a forward direction for 3/4 in. while the angle between the tip and the plate is gradually increased. The oxygen valve is then closed and the torch moved forward along the proposed line of gouge for approximately 1 1/4 inches. A puddle of molten metal can be maintained with the preheat flames to facilitate rapid start of the next gouge. The oxygen valve is again opened and the torch drawn backward until the gouge made by the preceding pass has been reached. This intermittent sequence and the rocking motion produced by inclining the torch is repeated along the entire length of the defective section of the weld.

Spot Gouging.—Single weld defects are removed by spot gouging. The defect is first outlined on the surface of the weld and a starting point a little to the rear of the defect is selected. The exact location depends upon how deep the defect is judged to be. The gouge is then started in the usual manner, but instead of reducing the angle of the tip, it is increased gradually so that the oxygen jet is directed downward until the gouge has penetrated to the depth of the defect. With a little experience any defects can be readily observed as dark streaks through the red color of the reaction zone. The torch should be held so that the tips of the inner cones of the flames are about 1/16 in. above the plate surface at all times during the operation. The resulting gouge is narrow and U-shaped and can be filled with weld metal without difficulty.

GROOVING

Grooving is similar to gouging. A straight nozzle is generally used rather than a bent one and the torch is usually mounted on a tractor-type cutting machine, which produces a more uniform groove. This process is similar to scarfing and gouging except that a deeper, narrower groove can be obtained.

Grooving Technique

Grooving is used to prepare the edges of heavy plate for welding. The objective of this edge preparation is to obtain a contour similar to a "J." When two pieces of plate prepared in this manner are placed together, the resulting groove is in the shape of a "U." J-grooving can be done by three different methods:

machine planing; thermal cutting, with which it has been possible to produce J-grooves in plate up to 1 1/2 in. thick in two passes by following a bevel cut with a gouging pass; and by a recently developed J-grooving method. This latter method utilizes an oxy-fuel gas flame applied in a single pass to plates between 1 1/2 in. and 4 in. thick and to plates of greater thickness in a dual pass combination. With single-pass J-grooving, the desired "J" groove contour is produced repeatedly. The nose width and the groove radius are maintained to specified dimensions (Fig. 42.23).

J-grooving may be applied to either horizontal or vertical plate and to curved sections. An adequate installation is required to produce successful and repetitive single pass J-grooves. Proper operating techniques and conditions are also required. Variables that must be controlled include processing speeds, cutting oxygen and preheat gas flows, and nozzle angle and distance settings.

The basic components of a J-grooving installation are a J-grooving nozzle, an adequate gas and oxygen supply, a nozzle positioning device, a plate follower, and a machine tractor to act as a motivating force (Fig. 42.24).

The four variables encountered when positioning "J" grooving nozzles are: (1) the impinging angle (θ) Fig. 42.25A; (2) the lateral angle (ϕ) Fig. 42.25B; (3) the slot angle (ψ) Fig. 42.25C; (4) the slot distance (a) Fig. 42.25C.

Operating conditions and variables for 1 1/2 to 4 in. thick plates shown in Table 42.7 will produce J-grooves with a 3/16 to 1/4 in. nose, a 3/8 to 3/4 in. groove radius and a 5 to 7 1/2° bevel angle. The larger dimensions are for the thicker plates.

At the start of the J-grooving pass, there is a short distance before the groove actually assumes its final depth and contour. Therefore, it is necessary to use a starting tab lightly tack welded to the edge of the plate and long enough to ensure that a full-depth groove is being made before the plate itself is reached. Typical lengths vary between 8 and 12 in.; the shorter tabs for the thinner plates and the longer tabs for the thicker plates.

Using the data presented in Table 42.7 it is possible to estimate J-grooving costs and to predict the subsequent welding requirements. Calculations based on known gas flows, processing speeds and J-groove cross-sectional areas are shown in Table 42.8. Total gas costs can be determined by applying current price schedules to the gas consumptions. As shown in Table 42.8, the weld area is twice the J-groove area and is formed when two J-grooves are placed in welding position to form a U-groove.

Single pass J-grooves are limited to plates having a maximum 4 in. thickness, but thicker plates can be J-grooved by utilizing a two-pass technique in which a standard J-grooving pass is followed by a cutting operation to remove excess metal along the lower edge of the plate as shown in Fig. 42.26.

In J-grooving it is essential that plate edges be perpendicular to the plate faces since the resulting bevel angle is always relative to the face of the plate edge.

J-grooving can also be done on top edges of plates in a vertical position. However, the effect of gravity for slag removal is lost and it becomes necessary to compensate for this loss by employing an air jet to blow away the molten slag.

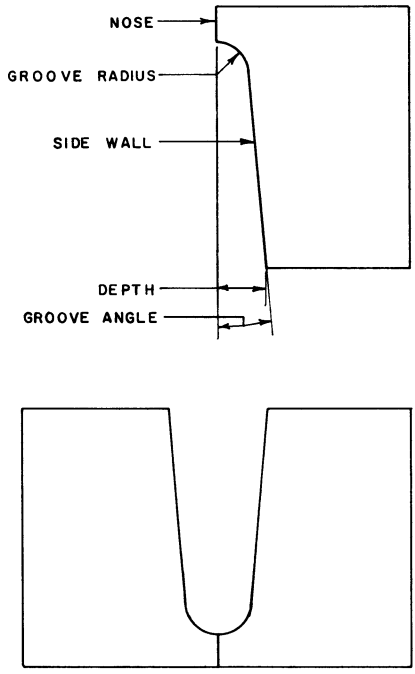


Fig. 42.23.—Characteristics of a single-pass oxy-fuel gas flame cut J-groove.

Single-pass J-grooving can also be applied to the preparation of circular pressure-vessel drum ends and end caps. Standard conditions are maintained except that the nozzle remains in a fixed position while the workpiece is rotated at a circumferential speed equal to the recommended carriage speed.

Heat-affected depths and hardnesses are no greater than are encountered in oxygen cutting. Single-pass J-grooving with an oxy-fuel gas flame can be performed on any steel that can be oxygen cut.

WASHING

The technique used in washing is almost identical to that employed in scarfing and gouging. It is usually applied to castings where risers, pads, gates or fins are cut down and blended with the remainder of the surface.

Pad Washing—In foundries, risers and gates are generally cut off reasonably close to the surface of the finished casting. The cutting may be accomplished by abrasive wheels, saws or by a thermal cutting process. It is generally the intricacy of the shape of the casting or the method used in removing a riser or gate that determines if cutting down to the surface level is possible. Any excess metal remaining on the riser pad may be washed down by successive passes and

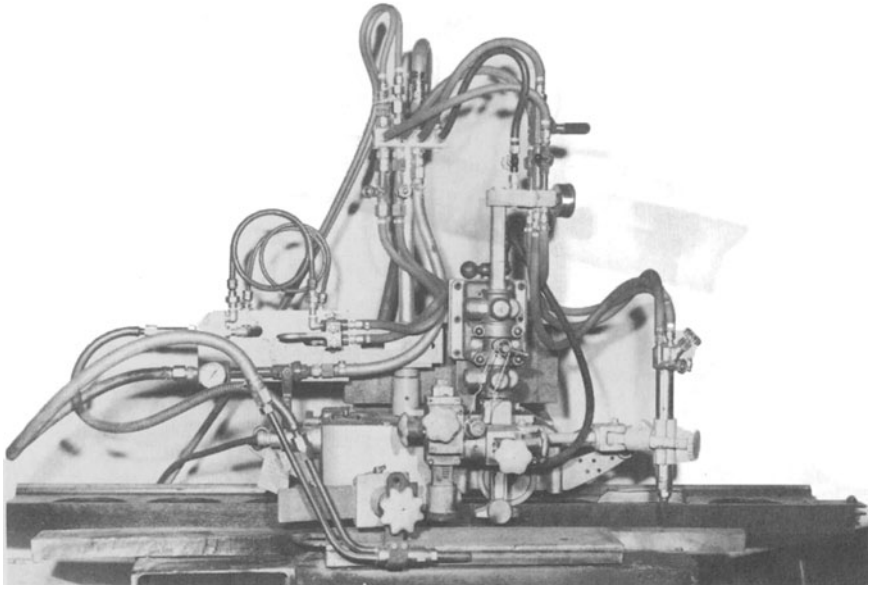
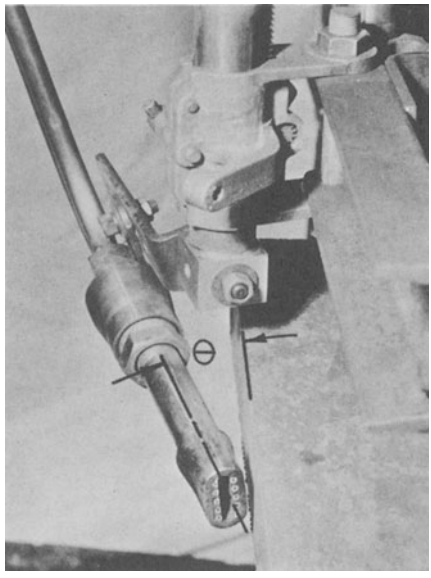


Fig. 42.24.—Single-pass oxy-fuel gas flame J-grooving installation for horizontal plate.

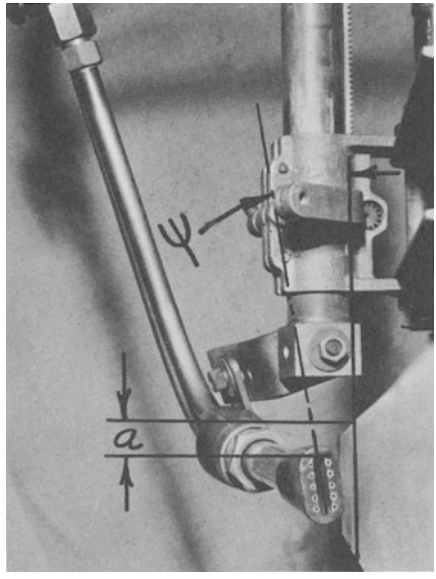
blended in with the cast surfaces. The number of passes required to accomplish this blending is dependent upon the height and contact area of the riser pad or gate above the finished surface desired. On castings of reasonable size, successive washing passes will usually remove approximately 1/8 in. of metal per pass to a width of about 3/4 inches. Passes of greater depth or width are generally not practical because of the danger of cutting into or below the finished surface desired. Grinding of the washed surface is unnecessary when pad washing is skillfully performed.

Fin Washing.—Fin washing is similar to gouging or scarfing, but its purpose is to remove the fins on castings. The fin can usually be washed down to the surface of the casting with a single pass. The technique is essentially the same as that previously described for scarfing, except that a tip with a smaller oxygen orifice can be used at slower speeds. Washing may be accomplished with large bore sizes at speeds higher than those normally used for gouging.

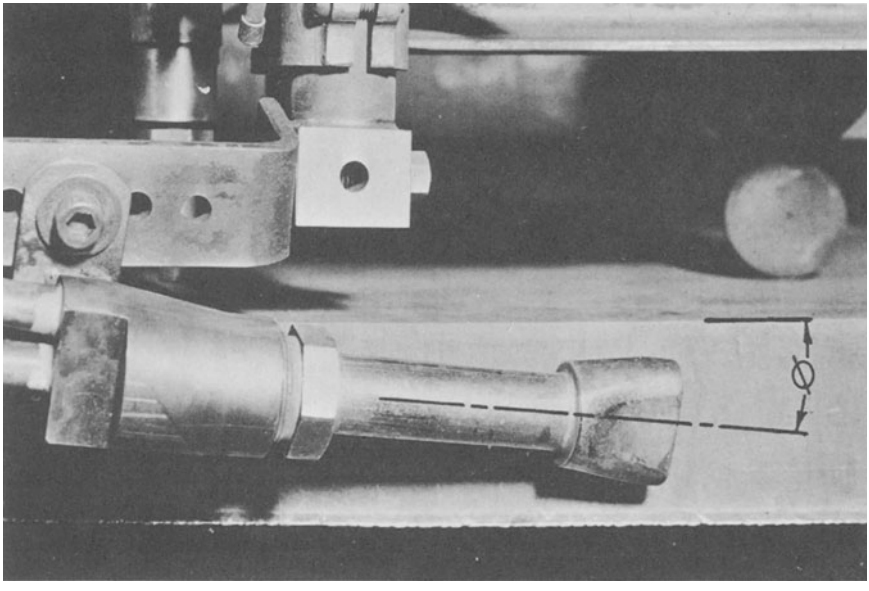
Rivet Washing.—Rivets may be removed by means of the cutting torch. In rivet washing, the rivet is removed by using the cutting torch to consume the rivet head by a washing action. The torch is repeatedly manipulated until the entire rivet head has been oxidized, after which the rivet is punched out. This applies where the rivet has not been deformed. The slag resulting from the washing action is blown away by the force of the cutting stream (Fig. 42.27).



A—Impinging angle



B—Lateral angle



C—Slot angle and slot distance

Fig. 42.25.—Variable encountered when positioning J-grooving nozzles.

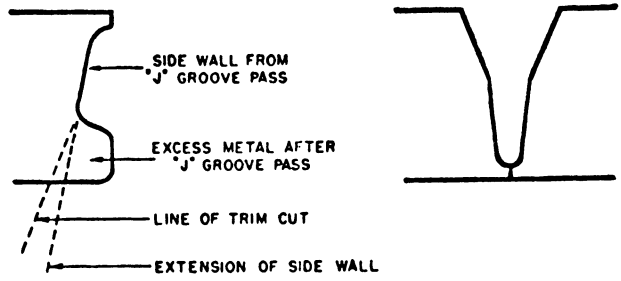


Fig. 42.26.—Two-pass technique of J-grooving followed by oxygen cutting.

The technique can be acquired readily by practice. An experienced person can achieve results wherein the plate remains undamaged and unmarked by the washing action of the oxygen stream. Since the shank of the rivet is merely punched out, the diameter of the hole in the plate remains unchanged. The rivet washing process has wide application when the plates and their existing rivet holes are to be used again.

PIERCING

Piercing is a general term covering operations where holes are to be formed in base material. If the hole is to be finished to a given diameter, the size of the cutting oxygen orifice in the nozzle must be selected with care. The diameter of the preheat circle should also be considered. The oxygen cutting bore in the nozzle is generally held at a right angle to the surface in which the hole is to be pierced. The end of the inner cones of the preheat flames should be positioned just clear of the surface of the material. After the preheated area has been brought up to the oxygen ignition temperature, the cutting oxygen valve lever is depressed slowly. Full oxygen flow through the cutting bore should not occur until the hole has been pierced completely through the plate, or the required depth and diameter have been obtained.

When a hole of large dimensions is being pierced, the tip of the nozzle is held in one position until the required depth is obtained. The nozzle may then be moved in order to obtain the required diameter or shape. It is often advantageous to incline the nozzle at a slight angle and manipulate the torch slightly as the oxygen is turned on. This permits the slag to be blown clear of the tip face.

Rivet Piercing.—In addition to rivet washing, rivets can be entirely removed by piercing. Care should be taken not to damage the holes in the plates through which the rivet passes during cutting out of the shank. This technique is usually performed when the rivet shank cannot be removed by punching because of poor alignment of the original holes in the mating plates. This is a highly skilled operation and great care must be exercised if it is to be successful.

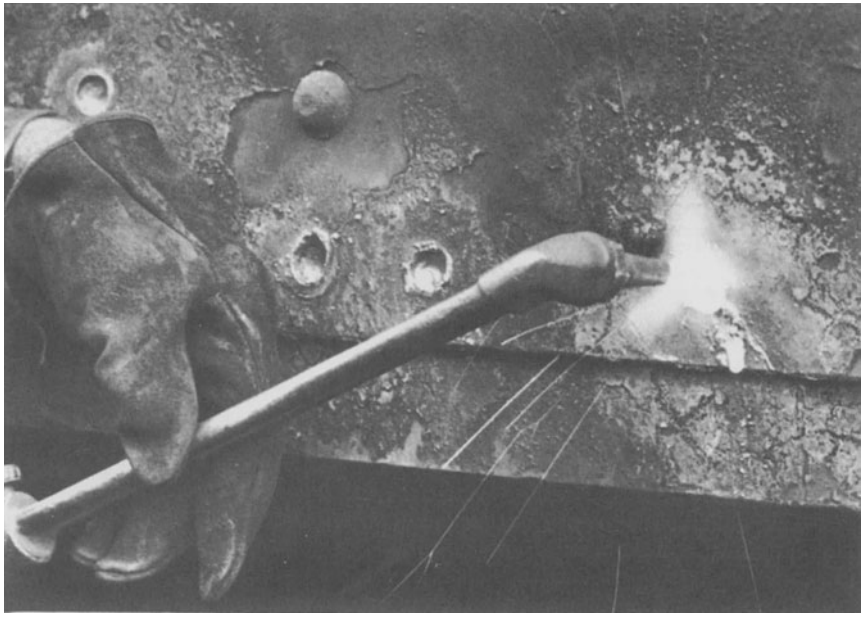


Fig. 42.27.—Typical oxyacetylene rivet washing operation.

Billet Centering—Billet centering is a form of piercing in which a large-size cutting tip is used. It is used extensively in the production of seamless tubing to form a center for the piercing mandrel. The center of the billet end is heated to the ignition temperature and the cutting oxygen is turned on. The size and shape of the hole depend upon the oxygen orifice size, the oxygen pressure, the duration of oxygen flow and the material temperature. Small holes (1 in. deep, with a 1 in. mouth diameter) in hot steel may require only 1 or 2 seconds of preheat time and an application of the cutting oxygen for perhaps half a second. Larger holes (2 or 3 in. deep with a 2 in. mouth diameter) on cold material may require 7 to 10 seconds or slightly more of preheat time plus a 7 to 10 second burst of cutting oxygen. Nozzles and tips used for this work usually have a large number of preheat flames spaced around the oxygen orifice. Portable and stationary billet centering machines are used in production operations. In order to prevent the sparks and slag from blowing back, billet centering may also be carried out with a conventional cutting or scarfiing torch of a greater length than standard torches. Billet centering operations performed on hot steel, or where good control is desired over the depth, diameter and shape of the center require automatic timing devices.

LANCING

Conventional lancing is employed when a very long or deep hole is pierced through a fairly thick metallic body (Fig. 42.28). The conventional consumable lance is a piece of reasonably clean steel pipe from 1/8 to 1 in. in diameter.

Oxygen is fed to this lance by means of a hose and the flow is regulated by an oxygen valve. In lancing operations a cutting or welding torch, electric arc or any available means of supplying heat is used to preheat the surface of the material to be lanced. If a cutting torch is used as the preheating medium, the cutting oxygen is turned on in the manner described for piercing. As soon as the pierce begins, however, the oxygen is turned on through the lance pipe, and the end of the lance pipe is brought over the area where the hole is being pierced. As the hole is pierced through the material, some of the steel lance pipe is consumed. A rotary motion is usually imparted to the lance pipe in order to produce a hole larger than the diameter of the lance pipe, thus permitting the slag to be blown out of the hole as the lancing progresses. Some difficulty may be experienced in restarting a deep lance hole once the operation has been stopped. Steel wool padding may be used at the bottom of the hole to reinitiate the reaction. It is always desirable to employ a lance pipe long enough to permit complete piercing of the material in one continuous operation.

AUXILIARY POWDER PROCESSES

The powder process described on pages 42.28-42.31 may also be adapted for scarfing, gouging, washing, lancing, etc. When the powder-laden oxygen stream comes into contact with the preheat flames and the reaction zone, it reacts to cause oxidation, melting and spalling. The circumstances and techniques involved are virtually identical to such conventional operating as oxygen cutting, scarfing and gouging.

Table 42.7—Operating conditions for single-pass oxy-fuel gas J-grooving

Plate Thickness, in.	Cutting Oxygen Flow, cfh	J-Grooving Speed, ipm	Impinging Angle θ, deg	Lateral Angle ϕ, deg	Slot Angle Angle ψ, deg	Slot Distance a, in.
1 1/2	1650	44	15	4	2	7/16
2	1450	24	18	4	4	1/2
2 1/2	4300	40	18	4	4	6/5
3	5000	27	15	2	4	1/2
3 1/2	5000	27	15	2	4	1/2
4	7000	27	18	2	8	1

Table 42.8—Gas consumptions and weld areas for single-pass oxy-fuel gas J-grooving

Plate Thickness, in.	Groove Cross Section Area, sq in.	Total Gas Consumption, cu ft per linear ft of J-groove					
		Oxygen	Acetylene	Oxygen	Propane	Oxygen	Natural Gas
1 1/2	0.375	7.9	0.35	8.2	0.22	7.9	0.27
2	0.650	13.4	1.26	14.0	0.66	13.2	1.00
2 1/2	0.900	22.1	1.26	22.9	0.66	*22.6	1.00
3	1.35	38.6	1.56	40.5	1.13	38.9	2.13
3 1/2	1.65	38.6	1.56	40.5	1.13	38.9	2.13
4	2.20	53.5	1.56	55.3	1.13	54.7	2.13

* Weld area—2 X groove area.

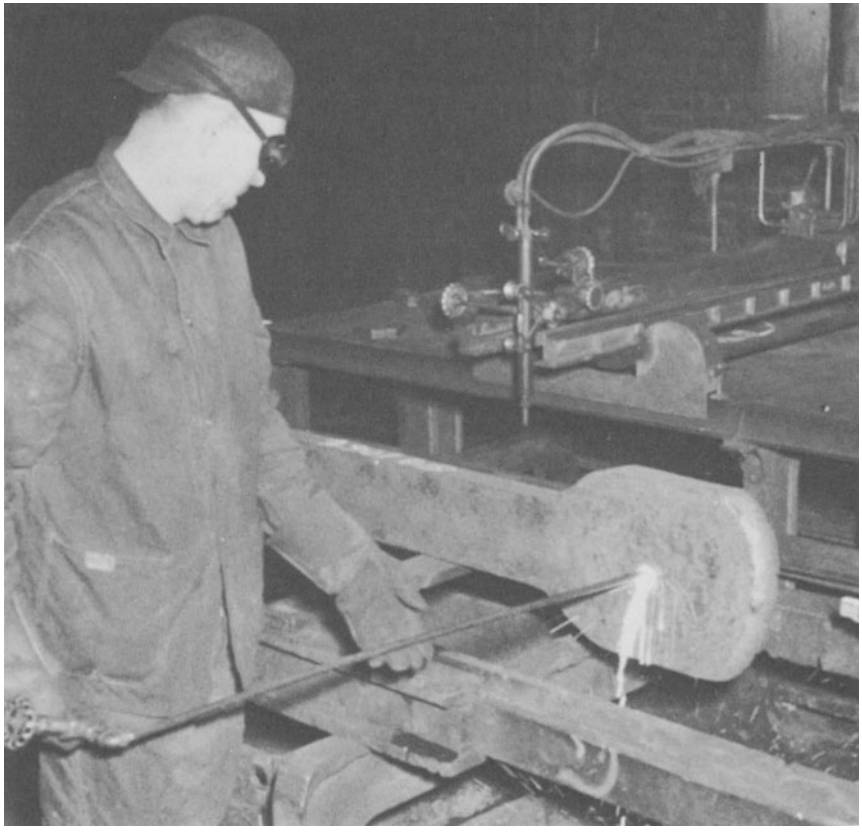


Fig. 42.28.—Lancing a starting hole in the main rod of a locomotive drawbar forging.

Powder Scarfing.—A conventional scarfing torch and nozzle with an external tip may be employed in powder scarfing operations or the torch and nozzle may be designed so that the powder is introduced into the cutting oxygen jet inside the scarfing nozzle.

The opening of the powder valve should precede the opening of the scarfing oxygen valve. Since the starting is instantaneous, no starting rod is necessary, nor is there a need for preheat dwell time. The powder scarfing technique is identical to the technique used for the scarfing of plain carbon steels, except that the distance between the end of the nozzle and the reaction zone must be greater than that ordinarily employed for carbon steel scarfing. Thus, sufficient time is allowed for the powder to be preheated and burned as it impinges upon the surface of the material to be scarfed. Scarfing speeds on cold stainless steel, for example, are generally about one half the speed required for carbon steel. Oxygen consumption is therefore higher, and the width of the scarf is usually about two thirds that obtained on carbon steel (Fig. 42.29).

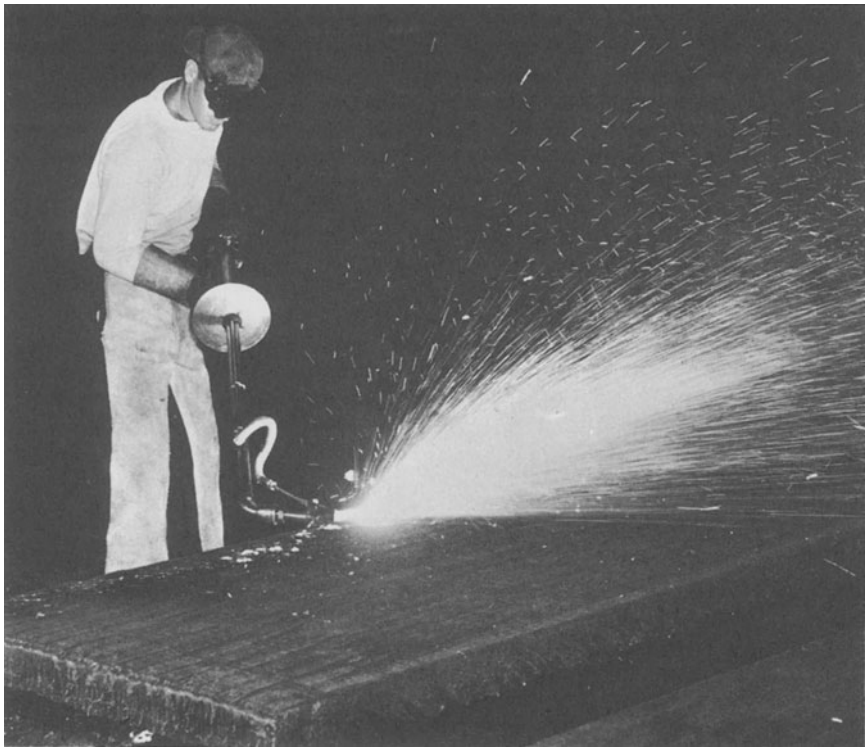


Fig. 42.29.—Stainless steel billet being scarfed with a manual powder scarfing torch.

Powder Gouging and Washing.—Powder can also be introduced by means of an external feed for pad or fin washing or gouging of materials such as cast iron and stainless steel (Fig. 42.30). Powder washing is particularly valuable in the preparation and reworking of carbon steel castings where washouts in the mold have occurred and the resultant areas are laden with molding sand These castings would be difficult, if not impossible, to recondition or reclaim with oxygen cutting or any other conventional cutting means. This washing or gouging is carried out in essentially the same manner as in the conventional process, except that slightly reduced speeds of operation can be expected.

Powder Lancing.—Materials such as concrete, cast or pig iron, and ladle spills resist lancing by ordinary means. They can be lanced, however, by mixing the oxygen with iron powder or mixtures of iron with aluminum or other metallic powders. The powder lancing technique is identical to conventional lancing, except that deeper holes can be cut at much faster speeds. Materials that are highly resistant to other cutting methods can be lanced by means of this technique, and with less consumption of the steel lance pipe. If the end of the lance pipe is heated to the ignition temperature before the mixture of oxygen and powder is turned on, it is possible to restart a lance hole at any time.



Fig. 42.30.—Powder washing technique as applied to casting pads.

EFFECTS OF AUXILIARY OXYGEN PROCESSES ON MATERIAL

Chemical

The chemical effects produced by the auxiliary oxygen processes are similar to those resulting from oxygen cutting when equivalent operations are performed. For a discussion of these effects, reference should be made to the section on effects earlier in this chapter.

The chemical effects, in general, are slight and hardly noticeable and do not interfere with subsequent operations such as welding. When billets and slabs are scarfed in a steel mill, reheating for rolling purposes produces more pronounced oxidation and scaling of the scarfed surface than the surface chemical effects produced by the scarfing process itself.

Metallurgical

The effect of oxygen cutting on the metallurgy of steel is discussed earlier in this chapter. The same considerations apply to the auxiliary oxygen processes. The metal being removed is elevated to a temperature approaching its melting point; consequently, heat is transferred to the steel immediately adja-

cent to the melting zone which is thus heated above its critical temperature. However, most of the auxiliary cutting processes produce a larger area of metal removal than that of oxygen cutting and a greater heat-affected area is produced. The mass of metal at a distance from the operation may not be affected appreciably. These conditions represent typical hardening conditions for the metal in the vicinity of the melting zone with a large temperature gradient from the melting zone to the cooler mass of metal. Stresses of varying degrees are introduced into the part because of this hardening effect and the expansion and contraction of the metal.

Proper precautions are necessary to prevent checking and cracking of the steel surfaces, especially when large billets or castings are being scarfed.

To determine whether special precautions are needed to prevent checking and cracking, the analysis of the steel should be known. Knowledge of the analysis makes it possible to predict the likelihood of checking and cracking by determining the hardenability of the steel. The considerations discussed earlier in this chapter are equally valid for the auxiliary oxygen processes.

The conventional auxiliary oxygen processes (without powder) may be employed on almost all types of carbon and alloy steel. The corrosion-resistant and austenitic stainless steels, cast iron, nonferrous and refractory materials require the use of the powder processes. High carbon and alloy steels must be preheated sufficiently to reduce cooling stresses and also to minimize the percentage of martensitic transformation in the affected area. Preheating is essential when alloys containing nickel or chromium are processed. Where billets are scarfed in steel mills during rolling operations, scarfing is often performed by machine in the roll line at rolling temperatures usually between 1800 and 2000°F (982 and 1093°C). When scarfing is not performed during the rolling cycle, preheating temperatures from 400 to 900°F (204 to 482°C) have been found adequate for many steels. Many steels may be scarfed cold without danger of cooling cracks. In practice, however, it is preferable to determine the required preheating temperature by experience with the particular type of steel being used.

Some borderline steels require preheating in winter but not in summer. Regardless of the nature of the alloy, a preheat of the material decidedly improves the operational ability of any of the auxiliary oxygen cutting processes.

STEEL ALLOYING ELEMENTS

The auxiliary oxygen cutting processes may be used on all grades of steel with the exception of those steels whose chemical analysis would tend to result in fissuring and cracking.

Corrosion-resistant and heat-resistant steel alloys usually contain nickel, copper, cobalt, chromium or aluminum. Such alloys are not readily shaped by the auxiliary oxygen processes unless a chemical flux or iron enriched powder is introduced into the oxygen stream. These compounds either remove the refractory slag or aid in the melting of the slag.

High-carbon steels can be scarfed without difficulty if they are preheated. Steels with carbon contents as high as 1.36% have been scarfed successfully. Scarfing of high-carbon steels containing nickel or chromium up to 3% is a standard commercial practice. Manganese as an alloying element is not detrimental. Steels with a manganese content as high as 10.5% are processed easily.

High-manganese steel with high sulfur content does not prove troublesome. Silicon in the amount usually found in steel does not appear to be detrimental.

QUALITY OF SURFACES

The desired contour of the surface depends to a large degree on the purpose for which the material is intended. Surfaces that have been gouged for the removal of defects prior to rewelding require a smooth, fairly accurate groove. It is necessary to gouge out the defect with a minimum removal of adjacent sound metal. A narrow, deep groove is usually the ultimate aim. Other work such as pad washing, fin washing and scarfing requires the removal of metal in wide, shallow passes. Ridges or fins may be formed between the various passes. If such ridges are present, they should be of minimum height. The shaping of a large shaft to fit a wobbler plate in the drive mechanism of a steel mill roll assembly, or a J-groove in the edge of a plate are examples indicating the variety of end results obtainable with the auxiliary oxygen processes.

By proper selection of equipment and technique, all contour requirements can be obtained. Different types of contours used in the various auxiliary operations are sketched in Fig. 42.31. Typical gouging operations on arc welds are depicted in Fig. 42.32. The dotted lines show the metal removed by gouging. It should be noted that the U-grooves shown in Fig 42.32A and C are produced by oxygen gouging, as is the Vee-groove with a rounded bottom (Fig. 42.32B). A wide range of widths and a variety of shapes of grooves can be produced by a skilled worker using suitable apparatus.

EQUIPMENT USED

Manual Scarfing, Gouging and Washing

A scarfing torch (Fig. 42.33) differs from a conventional cutting torch in four principal respects:

1. The torch is usually 36 to 72 in. long. The operator is permitted to work in an almost erect position, permitting easy handling of work at floor level.
2. The oxygen flow requirements for scarfing may greatly exceed those of normal cutting.
3. Most scarfing nozzles are larger in diameter and size of oxygen bore than the normal cutting nozzle.
4. Most scarfing torches are equipped with a rod feed device for obtaining faster starts. Torch head angles usually range from 65 to 90 degrees.

The amount of preheat required is usually equal to that needed for cutting with a very large cutting tip. Where no rod feed is used and relatively rapid preheating is required, it is invariably necessary to increase the preheat capacity of the nozzle. A tip suitable for surface removal by means of manual scarfing

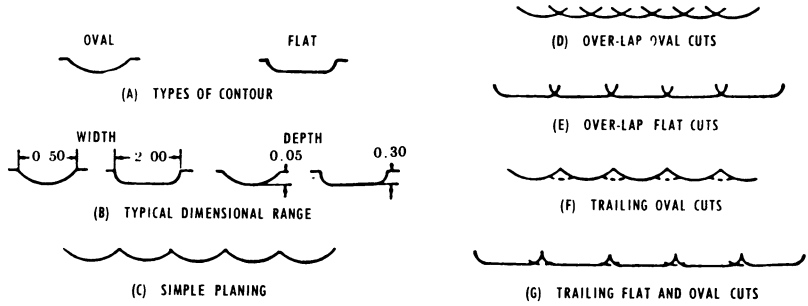


Fig. 42.31.—Typical surface configurations possible with the auxiliary oxygen cutting processes.

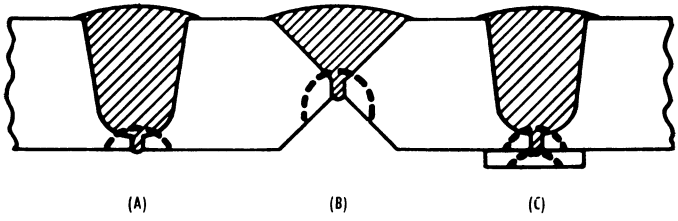


Fig. 42.32.—Typical gouging operations that may be applied to arc welds.

is desired; it is customary to use a nozzle with a very large outlet bore, thereby producing a scarf on each pass 20 to 50 times as wide as it is deep. A slotted nozzle orifice must be oriented with respect to the surface being removed. For this reason most manual scarfing is done with a round bore.

Gouging or grooving is usually performed with a conventional manual cutting torch. The head angle ranges from zero to 90° depending upon the application.

Pad, fin and rivet washing are performed be means of conventional cutting torches. A convenient head angle, providing the best control over the process, is employed. The torch length, preheat and oxygen capacity are the same as are required for manual cutting.

The most important consideration in the use of manual scarfing, gouging and washing is the selection of an appropriate tip for a particular application. For surface scarfing operations the tip is designed to remove metal from a wide area, but a shallow depth. Other tips are available for making a narrow groove, and can produce a cut of considerable depth when the correct technique is used. Such a tip would be used to remove deeply located defects in welds. Porosity in castings can be removed similarly, and the minimum amount of metal is removed in order to reduce the amount of welding necessary to correct the defect. Tips for various fuel gases are available.

Conventional cutting torches with convenient head angles are used for piercing. The nozzles used are generally standard cutting nozzles. The size of the orifice chosen depends on the skill of the individual operator and the depth of the hole.



Fig. 42.33.—Typical manual scarfing torch.



Fig. 42.34.—Washing torch with an iron powder nozzle.

Billet centering may require the use of a torch that is longer than the conventional cutting torch, in order to prevent the slag and sparks from being blown back.

Oxygen lancing can be carried out by either screwing a piece of steel pipe into a suitable adaptor for the oxygen supply bore or by means of a collecting and sealing device for the lance which eliminates the need for pipe with a threaded end.

The torches used for powder cutting are usually specially designed for the purpose (Fig. 42.34). The powder valve may be a separate part of the torch or it may be integrated with the cutting-oxygen valve. In the latter case, by depressing the cutting valve lever, the powder and oxygen are opened in a preselected sequence. The conduit carrying the powder from the powder valve to the torch head or to the powder attachment may be built into the torch. Torches are available with various nozzle head angles. Powder cutting attachments are also available for use on standard cutting torches, necessitating separate operation of the cutting-oxygen valve and the powder valve. The powder tube is usually attached to the outside of the torch handle. This arrangement permits the use of a conventional torch for powder cutting or scarfing.

A recently developed powder lance utilizes a collecting and sealing device integral with a handle upon which are located separately operable but interlocked oxygen and powder valves. Unthreaded pipe can be used. The powder and oxygen enter the lance pipe close to the handle.

In general, most of the equipment used in these processes is identical to that employed in cutting operations. Regulators, hoses, valves, fitting, etc., should be of sufficient capacity to handle the gas flows required for the particular process. Obstructions in gas supply systems should be avoided and nozzles designed for specific fuel gases should be used.

Mechanical Scarfiing and Grooving

Fixed-position scarfing machines mounted directly in the roll line of the steel mill are used today mainly for scarfing blooms and billets with cross sections of 4 to 14 in. on a side, slabs up to 84 in. wide and 18 in. thick, and rounds of commonly rolled sizes (Fig. 42.35).

Surface removal on slabs 76 in. wide to a depth of 1/16 in. on all four sides is possible at speeds of approximately 100 feet per minute with modern equipment. Shallower removal may be acomplished at even higher speeds. These machines perform the same function as manual scarfing torches, but on a larger scale and in an automated manner.

The stationary type scarfing machines are built so that they can be retracted or lifted from the roll line. This permits repairs and maintenance without interrupting the schedule of the mill.

The scarfing units are mounted singly or in groups on one, two or four moveable carrier plates which allow them to be moved into position on the steel. They are adjusted by electric, hydraulic or pneumatic controls for steel sections of various sizes. The units are free-floating and follow the axis of the bloom or slab. The water-cooled scarfing units consist of individual nozzles, block-type tips or slotted segments. The gases fed to the nozzles or segments are controlled either by individual shut-off valves or by large-bore selector-valve manifolds. The entire machine is operated by controls located in the pulpit near the rolling line in a position that provides good visibility for the operators.

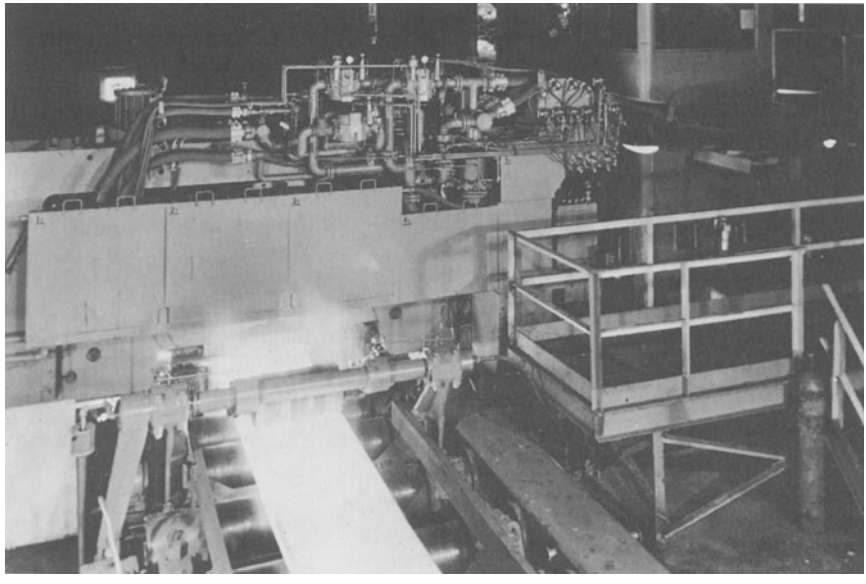


Fig. 42.35.—Machine scarfing of steel slabs in a typical steel mill application.

Another consideration is the provision of adequate facilities for handling the large volume of slag and fumes produced during the scarfing process. Special slag targets equipped with water sprays to break up the slag and flush it away to a settling pit are provided. Fume hoods and exhaust fans are connected to a conveniently located stack. Many of the more modern scarfing machine installations include means for collecting the smoke solids from the exhaust fumes.

The oxygen consumption in mechanical scarfing is among the highest in steel mill work. For an installation capable of handling 200 tons of steel per hour, some 6 tons of surface may be removed. About 7 tons of fumes and slag result, and approximately 20,000 to 25,000 cu ft of oxygen and about 1000 cu ft of fuel gas are required. Short-duty cycles for these machines result in momentary oxygen demands that may exceed 500,000 cu ft per hour. The oxygen supply and gas-handling equipment should be engineered to supply these demands.

The oxygen consumption in terms of the weight of metal removed depends upon a number of factors. These include the speed of scarfing, depth of scarf, carbon content, analysis of the steel and temperature of the steel. An approximate figure for oxygen consumption in cold scarfing ranges from 2 to 6 cu ft per pound of metal removed. For hot scarfing in the vicinity of 2000°F (1093°C), this index is approximately 1.5 to 2 cu ft of oxygen per pound of metal removed. In cold scarfing a large percentage of the metal removed is oxidized, whereas in hot scarfing the resultant slag has an exceptionally high iron content. This slag has been found to contain as much as 45% free iron, indicating that melting is an important phase of the action. This accounts, in part, for the fact that alloy steels may often be scarfed hot, whereas at ordinary temperatures they cannot be scarfed satisfactorily.

Stainless steel billets, blooms and slabs may also be scarfed mechanically with essentially the same equipment used for scarfing carbon steel. Iron powder is dispensed and distributed pneumatically through special equipment and is introduced into the scarfing reaction in a manner similar to that employed in manual scarfing. Mechanized stainless steel scarfing is usually performed on cold steel. Surface removal can be varied from depth of less than 1/16 to over ¼ inch. The speed of scarfing varies up to approximately 40 feet per minute.

Industrial Applications

The steel industries are major users of the auxiliary oxygen processes. Since their introduction, the processes, particularly the scarfing process, have been used extensively to replace grinding and chipping. Because of more stringent buyer specifications regarding surface finish, mechanical scarfing of large tonnages is being performed today. In the future, an even greater percentage of total steel tonnage produced will be scarfed.

The heavy machine tool industries, foundries, shipyards and railroads also use these processes for plate edge preparation and the removal of defects in weldments and castings. These industries use gouging for the correction of spot defects, and they use the cutting torch for rivet washing and removal of damaged riveted steel plates.

Fabrication shops use the auxiliary processes for making initial cuts on large plates and rolled sections. Depending on the surface requirements, the cut produced by these processes may or may not be satisfactory for use as produced. Their uses, particularly the powder processes, have yet to be explored fully.

Salvage industries use the manual gouging and rivet washing processes. Among other principal users of the auxiliary oxygen processes are foundries, where the processes are being used for the removal of riser pads, thus eliminating costly grinding operations.

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CHAPTER 43

ARC CUTTING

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CHAPTER 43

ARC CUTTING

FUNDAMENTALS OF PROCESS

DEFINITION AND GENERAL DESCRIPTION

Arc cutting is defined as a group of cutting processes wherein the severing or removing of metals is effected by melting with the heat of an arc between an electrode and the base metal.

Arc cutting, with or without the use of compressed gas, is based on the conversion of electrical energy into heat within the confines of an electric arc maintained between the material being cut and the electrode. This localized conversion, with a practical degree of control, is utilized for arc cutting by a number of methods.

Carbon-Arc Cutting

Carbon-arc cutting, without compressed gas, is the oldest of these methods. It employs the heat generated by the arc to melt metal progressively to produce a cut. The material is removed from the cut by gravity and/or the force of the arc. This method has almost entirely been replaced by better methods.

Shielded Metal-Arc Cutting

Shielded metal-arc cutting, without compressed gas, employs covered electrodes which permit manipulation of the arc to accomplish a cut. Material is removed from the cut by gravity and/or the force of the arc. This method has also been replaced to a great extent by more efficient methods.

Oxygen-Arc Cutting

Oxygen-arc cutting is a method of cutting, piercing and gouging metals using an electric arc and a stream of oxygen. The oxygen-arc cutting electrode consists of a ferrous metal tube covered with a mineral type, nonconductive coating. The function of the metal tube is to conduct current for maintaining the arc. In addition, the bore of the tube is used to convey and direct oxygen at the area of incandescence on the metal being cut. The mineral type coating not only provides a sleeve of insulating material for the electrode but also acts as an arc stabilizer and provides fluxes for making the products of combustion more fluid.

Air Carbon-Arc Cutting

Air carbon-arc cutting is a method for cutting or gouging metal by melting with an electric arc and blowing away the molten metal with a high velocity jet of compressed air, parallel and external to the electrode. Because this process does not depend on oxidation, it works on metals which do not readily oxidize.

A special holder is used to clamp a carbon-graphite electrode in such a position that air emitted from orifices in the electrode holder is directed parallel to the electrode. The air then strikes the molten metal immediately behind the arc. The electrode holder also contains an air control valve and a cable which carries both the current and the air. This cable is connected to a welding machine as well as to a source of compressed air.

Gas Metal-Arc Cutting

Gas metal-arc cutting obtains heat from an electric arc formed between a continuously fed metal wire and the plate, usually in the presence of inert gas shielding. Arcing occurs between the forward side of the wire and the advancing kerf edge. A force within the kerf ejects the molten metal from the kerf in all cutting positions. The force is developed by a pressure gradient produced in the shielding gas by the pumping action of the arc and by the issuance of metal vapor from the electrode.

Gas Tungsten-Arc Cutting

Gas tungsten-arc cutting is similar to gas tungsten-arc welding in that the same basic circuit is employed and a shielding gas is used. A high velocity jet of gas issues through the same nozzle as the arc and ejects the melted metal, thereby producing a cut.

Plasma-Arc Cutting

Plasma-arc cutting employs an extremely high-temperature, high velocity constricted arc between an electrode contained within the torch and the piece to be cut. The arc is concentrated upon a small area of the base plate where its intense heat melts the metal which is continuously removed by the jet-like action of a gas stream issuing from the torch.

CARBON-ARC CUTTING

Today carbon-arc cutting is used in lieu of a more modern cutting method by small shops, garages, home owners of welding machines, etc. to minimize their investment in cutting and welding equipment.

Cutting with carbon-arc is performed with the heat of an arc between a carbon or graphite electrode and the base metal or the heat of an arc between two electrodes.

SHIELDED METAL-ARC CUTTING

PRINCIPLES OF OPERATION

Shielded metal-arc cutting is a progressive operation using covered metal electrodes. The preferred power source is direct current straight polarity (dcsp). The principal function of the electrode covering in cutting is to serve as electrical insulation, permitting insertion of the electrode into the gap of the cut without short circuiting the sides of the electrode, and to act as an arc stabilizer, thereby concentrating and intensifying the arc action. Effectiveness of this procedure in cutting heavy thicknesses is a function of manipulation of the E6010, E6012 and E6020 electrode types which are usually employed. Electrodes with coverings specially made for cutting are also available.

EQUIPMENT

The power source for metal-arc cutting should be a dc welding machine, but an ac power source may also be used. For shielded metal-arc cutting in air, the standard electrode holders are applicable. Heavy duty type holders should be used with $\frac{3}{16}$ in. dia. and larger electrodes. For metal-arc cutting under water, specially constructed, fully insulated electrode holders are mandatory. A straight polarity power source must be used to protect the holder and the metal parts of the diver's outfit from electrolytic corrosion.

APPLICATIONS

Shielded metal-arc cutting is used for cutting risers and gates in nonferrous foundries and to cut nonferrous scrap for remelting. Shielded metal-arc cutting electrodes with special coverings designed to accelerate the cutting rate are also available. The cut produced by shielded metal-arc cutting is less ragged than that of the carbon-arc cutting process. Generally it does not provide satisfactory preparation for welding without considerable trimming by chipping or grinding. Shielded metal-arc cutting employing covered electrodes processed with water-proofing has had some application as an emergency procedure for underwater cutting.

OXYGEN-ARC CUTTING

PRINCIPLES OF OPERATION

Metals are severed in oxygen-arc cutting by a combination of melting, oxidizing, diluting, fluxing and mechanical ejection. Mild steel is cut by raising the temperature of the material to its kindling point in the presence of oxygen. The combustion reaction that occurs is self-sustaining, liberating sufficient heat to maintain or exceed the kindling temperature on all sides of the cut. The necessary preheat is provided by an electric arc at the point of impingement of the oxygen on the surface of the steel. For oxidation-resistant metals, the cutting mechanism is more of a melting action. In these instances, the covering on the electrode is an aid in helping the molten metal flow from the cut. This function of the covering is similar to that of the powdered flux or powdered metal injected into the oxyacetylene flame in the flux cutting or powder cutting of stainless steels (see Chapter 42).

A schematic illustration of the process is shown in Fig. 43.1.

EFFECT ON MATERIALS CUT

Metallurgical

The oxygen-arc method of cutting produces metallurgical effects in the heat-affected zone comparable to those that occur in shielded metal-arc welding. The power input approaches that of shielded metal-arc welding, but the heat penetration is generally not as deep in oxygen-arc cutting because of the faster speed of travel (Table 43.1). This produces a somewhat more pronounced quench effect. Metals that do not require a postheat treatment after welding may be severed by this process without detrimental effect. Grades of austenitic stainless steels that are sensitive to corrosion attack when subjected to shielded metal-arc welding will be sensitized along the cut when severed by this process.

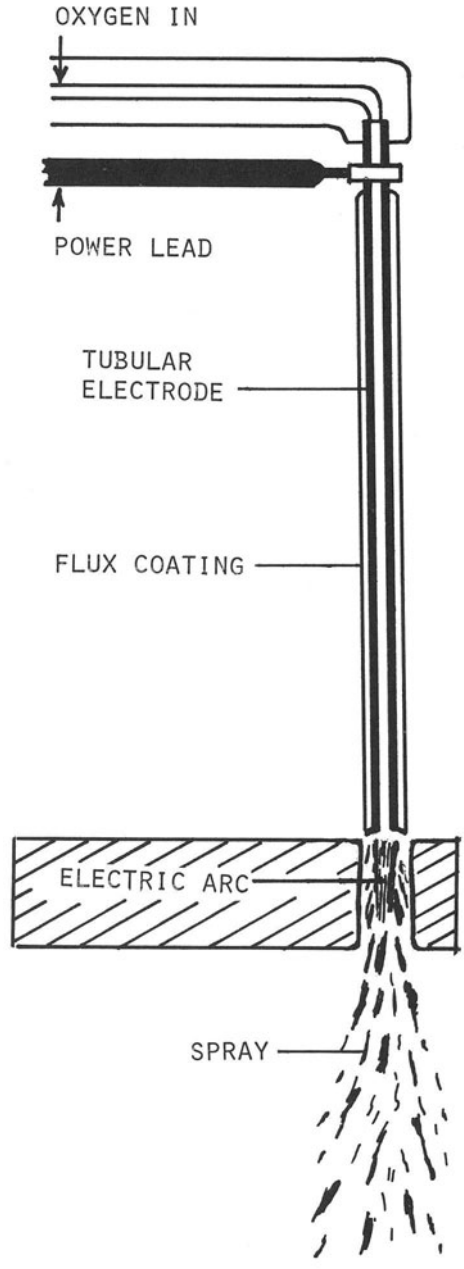


Fig. 43.1—Schematic of oxygen-arc electrode in operation.

Physical

The physical effects of oxygen-arc cutting are similar to those obtained in oxyacetylene cutting. Cast iron and medium-carbon, low-alloy steels are apt to develop cracks on the face of the cut. The extent and frequency of cracking depend on the composition and hardenability of the steel.

Heat penetration is shallow, consequently, warpage is practically nonexistent.

Generally, the surfaces of the cut are rougher than oxyacetylene cuts. The amount of chipping or grinding needed to prepare the cut for fabrication depends on the material and intended application.

Machinability

The machinability of low-carbon, mild steel and nonhardenable metals is not affected by the oxygen-arc cutting process. In cast iron and hardenable steels, the heat effects of the cutting operation will generally produce hardening to such a degree that the heat-affected zone will be unmachinable.

EQUIPMENT

Oxygen-arc cutting may be performed using either ac or dc power sources of sufficient capacity. However, dcsp is preferred for rapid cutting. The electrode holder used for oxygen-arc cutting is of special design; it must convey not only electric current to the electrode but also oxygen to the arc. This is accomplished by bringing oxygen to the electrode holder and passing it through the bore of the electrode to the arc.

For cutting in air, a fully insulated electrode holder is desirable. When used for underwater cutting, a fully insulated holder equipped with a suitable flashback arrester is required.

Tubular steel electrodes are available in 3/16 and 5/16 in. diam sizes, 18 in. long, with bore diameter approximately 1/16 inches. The extruded covering is comparable to a mild steel electrode of AWS classification E6013. Underwater electrodes are steel tubes with a waterproof coating, or a hollow carborundum electrode.

CUTTING TECHNIQUES

In the oxygen-arc method of cutting, piercing and gouging, the coating is kept in contact with the base metal at all times. The coating insulates the core from the work and automatically maintains the proper length of arc.

The start of cutting and piercing operations is the same. The tip of the electrode is tapped on the work at the desired location as though striking an arc for welding, and the arc is maintained for a moment while the oxygen valve is opened. Piercing action begins immediately and the electrode is pushed into and through the plate as the hole is formed. The coating insulates the electrode core from shorting against the sides of the hole.

In cutting, the electrode is dragged along the plate surface at the speed of forward travel dictated by the progress of the cut. The inclination of the electrode and the speed of motion are adjusted to give the most efficient and highest quality cut.

Template-guided cutting is common. The electrode is pressed against the template; it is insulated from it by the coating. For straight line cuts, any straight edge (metallic or not) may be clamped along the line to be cut. The cut is accomplished by holding the electrode against the guide and the plate at the same time. Circular openings in partially fabricated tanks have been cut by using the circumference of a suitably sized pipe as the guiding template.

The speed of cut varies with the thickness and composition of the plate, the oxygen pressure and the current. The approximate relation between the voltage and amperage in oxygen-arc cutting is shown in Fig. 43.2. It will be noted that the total oxygen pressure has little effect on the arc voltage.

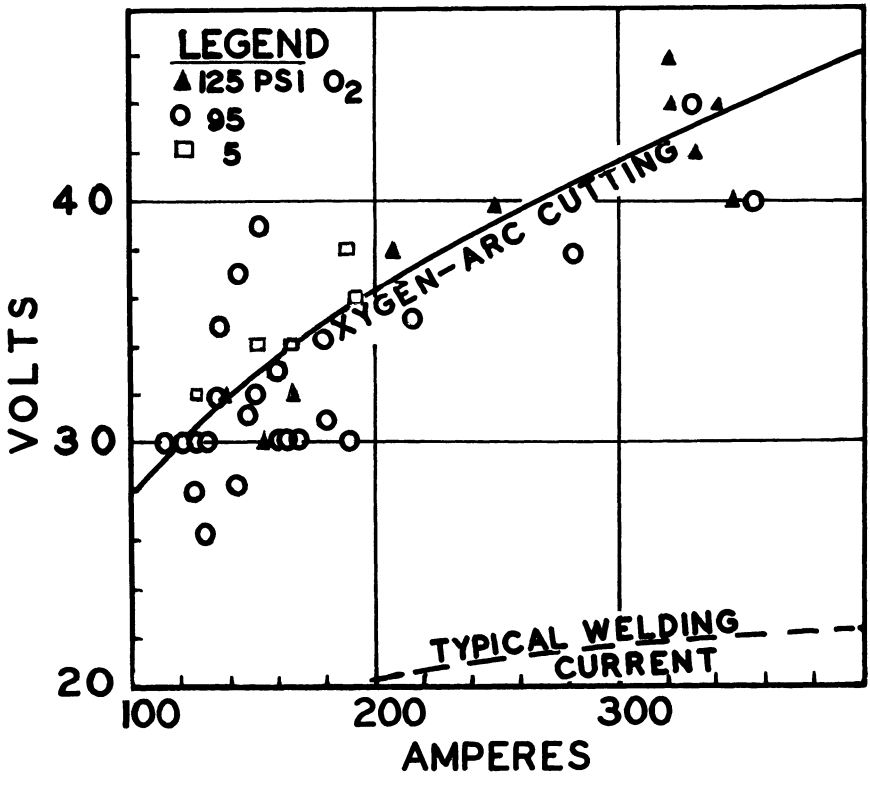


Fig. 43.2.—Typical voltage-amperage relationship in oxygen-arc cutting.

When cutting in air (up to 3 in. of mild steel or ½ in. of certain nonferrous alloys), the technique is to drag the electrode along the intended line of cut while applying slight pressure. In underwater cutting, regardless of the thickness of the metal being cut, positive pressure must be maintained against the metal being cut.

Gouging is performed by striking the arc, releasing the oxygen stream, and inclining the rod until it is almost parallel to the plate surface and pointed away from the operator along the line of the prospective gouge. The arc and oxygen bite into the plate and pile up a pool of slag and oxides beyond the tip of the rod. The rod is pushed rapidly over the surface of the plate into the pool of oxidized metal.

APPLICATIONS

Oxygen-arc cutting electrodes were developed primarily for use in underwater cutting and were later applied for cutting in air. In both applications they can cut ferrous and nonferrous metals in practically any thickness and position. Fig. 43.3 illustrates the use of the process for cutting a hollow chrome-nickel shaft with a 4½ in. wall.

Oxygen-arc cutting is used effectively by foundries and scrap yards for cutting mild and low alloy steels, stainless steel, cast iron and nonferrous metals in all positions. The usefulness of the process varies with the thickness and composition of the material being cut.

The edges of metal cut by the oxygen-arc torch are somewhat uneven and usually require a light surface preparation to make them suitable for welding.

AIR CARBON-ARC CUTTING

PRINCIPLES OF OPERATION

Air carbon-arc cutting is essentially a progressive melting of material which is blown away by high velocity jets of compressed air. Power requirements are higher per diameter of electrode than is usually employed in normal arc welding and speed of travel is much faster. Base metal melting is much less than in oxygen cutting. The process is primarily physical rather than chemical; hence it can be used on most metals.



Fig. 43.3.—Cutting a chrome nickel hollow shaft with a 4½ in. wall.

Table 43.1—Oxygen-arc cutting speeds for various metals

Metal	Thickness, in.	Cutting speed, ipm
Mild Steel	1.0	30.0
Cast Iron*	1.0	3.7
Bronze	1.0	3.3
Monel	1.0	2.7
Aluminum*	1.0	7.0
Stainless Steel Type 347*	1.0	2.6
Inconel	1.0	1.6

* Interpolated data based on tests

Table 43.2—Recommended current ranges for various carbon-arc cutting electrodes

Electrode (in.)	5/32	3/16	1/4	5/16	3/8	1/2	5/8	3/4	1
Min. Amps	90	150	200	250	350	600	800	1200	1800
Max. Amps	150	200	400	450	600	1000	1200	1600	2200

EFFECT ON MATERIALS CUT

Metallurgical

The chemical changes that result from this cutting process are similar to those produced by the arc welding process. A very thin hardened zone may occur in some metals but subsequent welding remelts this zone and reduces the hardness level. Copper contamination (from copper-plated electrodes) has not been observed in the base material. Tests on ELC stainless, cut by this process and mechanical processes, show no appreciable difference in corrosion resistance.

Distortion

As previously stated, heat penetration is shallower with this process than with oxygen cutting. Accordingly, the volume of metal adjacent to the cut which is subjected to a high rise in temperature is also less than in oxygen cutting. Warpage is, in part, a function of the volume of material raised to a higher temperature than that of the rest of the base metal. As a result, distortion with this process is less than with oxygen cutting.

Machinability

The machinability of low-carbon and nonhardenable steel is not affected by this cutting process. In cast iron and high-carbon steels this process will generally cause appreciable hardening of the heat-affected metal. It is possible for a cutting tool to get under this zone to remove the hardened surface.

Table 43.3—Electrode recommendations for air carbon-arc cutting

Material	Electrode	Current	Polarity
Steel	dc	dc	Reverse
	ac	ac	
Stainless	dc	dc	Reverse
	ac	ac	
Iron (Cast, Ductile & Malleable)	dc	dc (high amp)	Reverse
	ac	ac or dc	Straight
Copper Alloys	ac	ac or dc	Straight
	dc	dc	Reverse
Nickel Alloys	ac	ac or dc	Straight

Table 43.4—Data for making single U-grooves with the air carbon-arc process (Direct current reverse polarity)

Electrode Diameter inches	Groove Depth inches	Current amps	Travel Speed in/min
5/16	1/8	400	65
	3/16	400	45
	1/4	425	36
	3/8	450	33
3/8	1/8	500	65
	3/16	500	57
	1/4	500	46
	3/8	500	25
	1/2	500	17
1/2	1/8	800	72
	1/4	800	57
	3/8	800	35
	1/2	800	24
	5/8	800	20
	3/4	800	17
5/8	1/8	1100	72
	1/4	1100	50
	3/8	1100	30
	1/2	1100	28
	5/8	1100	22
	3/4	1100	17
	1	1100	2 passes @ 21

Note: These data for the following conditions:
Electrode stickout — 3½ inches
Torch to work angle — 45°
Air pressure — 100 psi
Arc volts — 40
Deeper grooves with each size electrode can be made by successive passes with combination of settings

EQUIPMENT

An ordinary welding power source is usually used. Care should be taken to select one able to produce the current needed. Table 43.2 may be used as a guide for amperage selection.

The application will determine the power requirement for each job. Note that the welding machine must have sufficient reserve power available above the maximum current that is expected to be used during actual operations, unless it carries a 100% duty cycle rating.

Direct current reverse polarity (dcrp) is used for most applications. However an electrode for alternating current is also available. On some materials dcsp is preferred. Table 43.3 indicates the most suitable electrode, current and polarity for various materials, in order of preference.

Air Supply

Ordinary compressed air as supplied by a shop air line or compressor is suitable. Most applications require 80 to 100 psi air pressure although pressures as low as 40 psi may be used with light duty torches and shortened electrode stick-out. Pressures as high as 125 psi have been used with heavy duty torches. However, they are not required for efficient operation. Air supply hoses for manual torches should have a minimum inside diameter of ¼ inch. For the voltage-controlled automatic torch a minimum inside diameter of ½ in. is required. Although the actual air pressure (within 80 to 100 psi range) is not critical, it is important that a sufficient volume of air is supplied to ensure a clean, slag-free surface after gouging.

Electrodes

The electrode used in the air-carbon-arc cutting process is composed of a special mixture of carbon and graphite. This electrode is usually copper-coated to increase its life, provide a uniform groove, increase the current-carrying capacity and reduce radiated heat.

Electrodes are also available with male and female joints for continuous production use and for mechanized torches. Except for mechanized torches, most of the jointed electrodes are used in foundry applications.

The composition of the electrode has an important effect on the results obtained with the air carbon-arc cutting process. It is important that the effect of and difference between carbon and graphite electrodes be understood.

Carbon is amorphous while graphite is crystalline. There is some difference in density; carbon is hard while graphite is soft. Carbon has high resistance to abrasion or erosion, while graphite has low resistance. Graphite has a higher oxidizing temperature, a lower rate of oxidation and lower electrical and thermal conductivity. In the air carbon-arc process it is desirable to have an electrode which is hard and has a high resistance to erosion. On the other hand, a high oxidizing temperature and a low rate of oxidation are advantageous, while high electrical conductivity and low thermal conductivity are desired. This means that the best electrode for the process contains a combination of carbon and graphite. Proper blending of the two materials gives the properties required.

CUTTING TECHNIQUES

The electrode holder is used by positioning the electrode at a leading angle and striking an arc between the end of the electrode and the material to be cut or gouged. The air blast is directed immediately behind the point of arcing and the electrode is pushed forward at a rapid rate with the air jet on continuously. The depth and contour of the groove produced are controlled by the electrode angle, travel speed and current. Grooves up to 1 in. deep may be made in a single pass; however, the deeper the groove, the greater the operator experience required. A steep angle and slow speed produce a narrow, deep groove. A flat angle and fast speed produce a wide, shallow groove. The width of the groove is determined primarily by the size of the electrode used. The groove width is usually slightly wider than the electrode diameter if the electrode is moved in the forward direction only. A wider groove may be made with a small electrode by oscillating or weaving the electrode as in welding. Gouging or cutting may be done in all positions. In overhead work care should be taken that the torch is held at a sufficient angle to avoid molten metal dropping on the operator.

In through-cutting, the electrode is held at a steeper angle than in gouging, and the arc is directed at a point approximately 1/16 in. below the bottom of the material being cut. For material thicker than 1/2 in., two or more passes may be required. The air jets should be parallel to the plate surface at all times to prevent dross.

To remove excess metal such as pads, bosses, riser stubs and surfacing, a washing or weaving motion is recommended. Care should be taken to keep the air behind the electrode. The smoothness of the cut surface is determined by how steady the electrode is held.

Travel speed depends on the size of the electrode, type of material, amperage and air pressure. Proper speed produces a good, clean cut and is recognized by a smooth hissing sound. Too slow a speed causes an intermittent gouging action. Table 43.4 shows the operating conditions for voltage controlled automatic equipment. Groove depth tolerances of ± 0.025 in. are possible with this equipment.

APPLICATIONS

The most extensive use of this process is in foundries. It is used to remove defects from castings, and it has found applications as a method for washing off excess metal, such as pads remaining when gates and risers are cut from castings. In some instances the air carbon-arc cutting process has replaced swing grinding and chipping operations.

Special heavy duty electrode holders are available for pad washing applications. Holders providing air outlets on both sides of the electrode are also available for fin removal in the internal areas of complicated castings, as well as for the removal of excess metal in casting conditioning. The 1/2, 5/8 and 3/4 in. diameter electrodes are those most commonly used for foundry work.

When this process was first introduced, it could only be operated on dcrp. However, when the dcrp electrode is used on cast iron a tenacious slag is produced which restricts the gouging or cutting operation. An ac electrode has been developed with performance found to be much better than the original dc electrode on reverse polarity. The ac electrode operating on either ac or dcsp blows the slag out of the groove. A cleaner surface is produced and more rapid cutting speed is possible.

A short-arc, high-amperage technique has given excellent results using dc electrodes with dcrp current, without the refractory slag condition occurring. This technique consists of using the maximum current per electrode diameter and maintaining an arc about $\frac{1}{16}$ in. long.

The second large application of the air carbon-arc process is in metal fabrication. The process was originally developed for removing stainless steel welds from naval armor. It was later used to remove welding defects as well as to clean out the roots of welds and widen grooves that had been pulled together by welding. In many plants the process is also being used for preparing plates for welding. In this technique, the plates are butted squarely together and the cutting electrode is run down the joint. The resulting U-groove, from a design standpoint, is quite preferable to the V-groove previously used in these instances, since it not only makes the root more accessible but also reduces the amount of deposited metal required. With the air carbon-arc cutting process, it is possible to prepare a U-groove on both plates simultaneously after fitting up (see Fig. 43.4).

In manual work the quality of the groove produced is dependent upon the skill of the operator. Many plants prefer to use semiautomatic or fully automatic electrode holders for this reason (Fig. 43.5).

The broadest use of the air carbon-arc cutting process has been in maintenance. It is useful for veeing out cracks for rewelding, for washing off surfaces or for cutting many materials which cannot be cut with the oxygen cutting processes. In this field the small size manual electrode holders have had application (Fig. 43.6).

The air carbon-arc cutting process is used by railroads for maintaining rolling stock, structures and track work, as well as to clear wreckage from the right-of-way. Its ability to cut almost any metal and its low heat input requirements make it a good emergency tool.

Contractors can use this process to remove hardsurfacing and stainless steel welds, as well as to prepare cast iron and manganese steel for repair welding. With this process it is also possible to cut pilings without removing backfill, as well as to cut steel plates imbedded in concrete.

In refineries it may be used for cutting stainless steel pipe; cutting out or patching tank bottoms in coke and pipe stills; removing stainless steel liners from mild steel tanks; removing boiler and heat exchanger tubes as well as for repairing defects in nonferrous and stainless steel castings (Fig. 43.7). This process may also be used to prepare the surface of eroded and corroded areas for rebuilding by welding. This latter application is useful in the power plant turbine maintenance field.

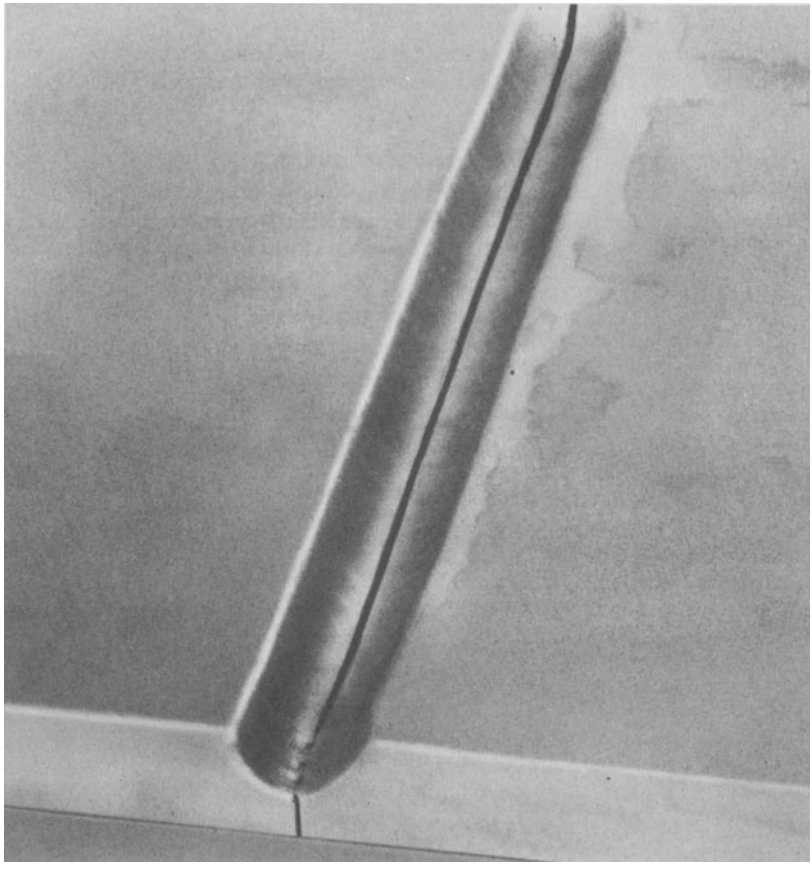


Fig. 43.4.—Plates prepared for welding by gouging with semiautomatic air carbon-arc process.

GAS METAL-ARC CUTTING

PRINCIPLES OF OPERATION

Gas metal-arc cutting was developed soon after the commercial introduction of the gas metal arc welding process. Apparently arc cutting was first accomplished accidentally during welding operations. It was found that if the electrodes were to penetrate through the plate while welding, cutting could be accomplished. Once started, this cutting arc is not difficult to maintain. Conventional gas metal arc welding equipment can be used for cutting although some modifications have been made in the equipment designed especially for cutting operations.

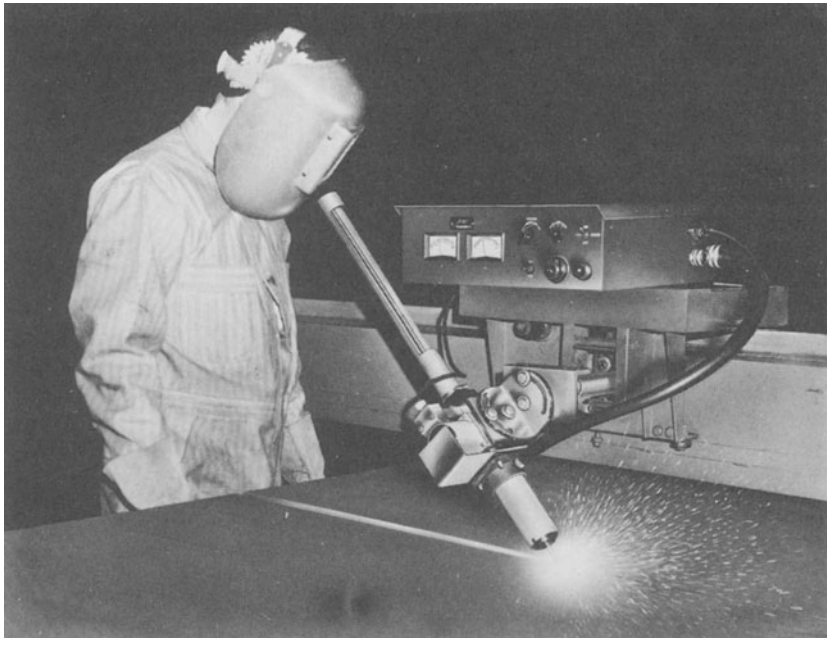


Fig. 43.5.—Typical fully automatic air carbon-arc cutting equipment.

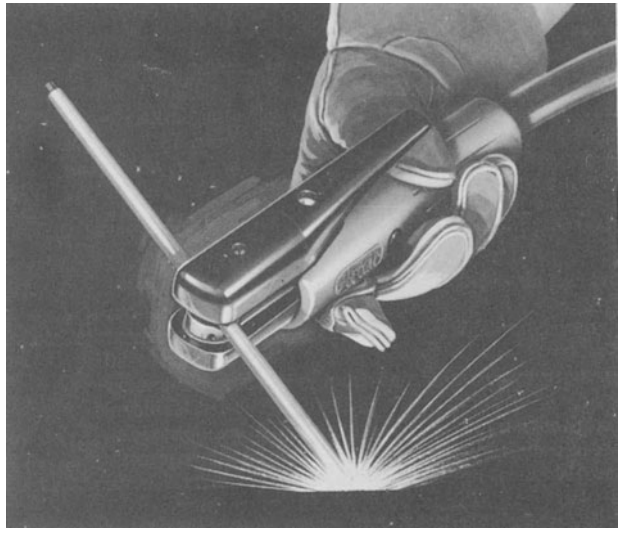


Fig. 43.6.—Typical manual air carbon-arc torch with carbon electrode.



Fig. 43.7.—Foundry application of air carbon-arc cutting process for removal of casting defects as well as for conditioning of castings

Ultra-slow motion pictures of the gas metal arc cutting process show that the electrode extends through the plate thickness and the arc plasma oscillates in the vertical direction within the kerf. Oscillograms taken during the cutting process show that the current never falls to zero and that the arc is continually ignited.

EFFECT ON MATERIALS CUT

Metallurgical

Metallographic examination of the cross section of cuts made in both aluminum and stainless steel show a very narrow heat-affected zone (about 0.010 in. maximum). The condition of this zone is sound and free of defects.

Distortion

When cuts are made at the highest speeds, there is very little warpage in plates above ⅜ inch. To eliminate warpage in sheet stock it can be stacked to a total thickness of at least ⅜ inch.

Machinability

Since aluminum and austenitic stainless steels are not quench-hardened, the hardness of the cut surface is not above that of the base metal and its machinability is not altered.

Surface Condition

The molten material, consisting of melted plate and the electrode, leaves the bottom of the kerf in a fashion that minimizes the possibility of plate contamination. Drag lines are formed by step-wise melting which occurs as the arc oscillates during cutting. An adjustment in wire feed speed is made to supply just enough wire to penetrate the plate (Fig. 43.8). Somewhat smoother surfaces are obtained at higher cutting speeds.

EQUIPMENT

Constant potential direct current or alternating current power is required for gas metal arc cutting. The cutting voltage ranges from about 20 to 40 volts; current values up to 2000 amperes may be required. The wire feeding equipment must be capable of producing high wire feed speeds and handling $\frac{3}{32}$ in. or larger wire. When using a looped, nonconsumable electrode the shape or cross section may be round or rectangular, but the feed rate must be very high (10,000 ft per minute).

CUTTING TECHNIQUES

The most important variables of this cutting process are the voltage and the wire feed speed. Fig. 43.9 shows the effect of cutting voltage on kerf width and illustrates the usable range of voltage of cutting ½ in. thick type 304 stainless steel at two speeds. Kerf width increases with voltage so that the narrowest kerfs are made at the lowest voltages. The wire being fed into the kerf in the operation of this arc cutting process is analogous to the oxygen jet issuing from an oxyacetylene cutting tip. An adjustment in wire feed speed is made to supply just enough wire to penetrate the plate. Additional wire is only wasted as it is not melted by the arc. The cutting speed in gas metal arc cutting is analogous to wire feed speed in gas metal-arc welding, wherein the rate of wire feed controls current.

Although steel wire is usually used for the gas metal arc cutting process, its use is only promoted for economic reasons. Stainless steel and aluminum wire may also be used. An inert shielding gas is usually supplied to the cutting to protect the kerf walls from contamination. Kerf wall contamination is particularly noticeable with aluminum alloys, but is negligible in the cutting of stainless steel. This cutting process can be accomplished with a variety of shielding gases including air. The surface of the kerf may be contaminated by nitrides and oxides when cutting is done in air. The commercial processes use argon as the principal shielding gas whether aluminum, stainless steel, Monel or copper alloys are cut.

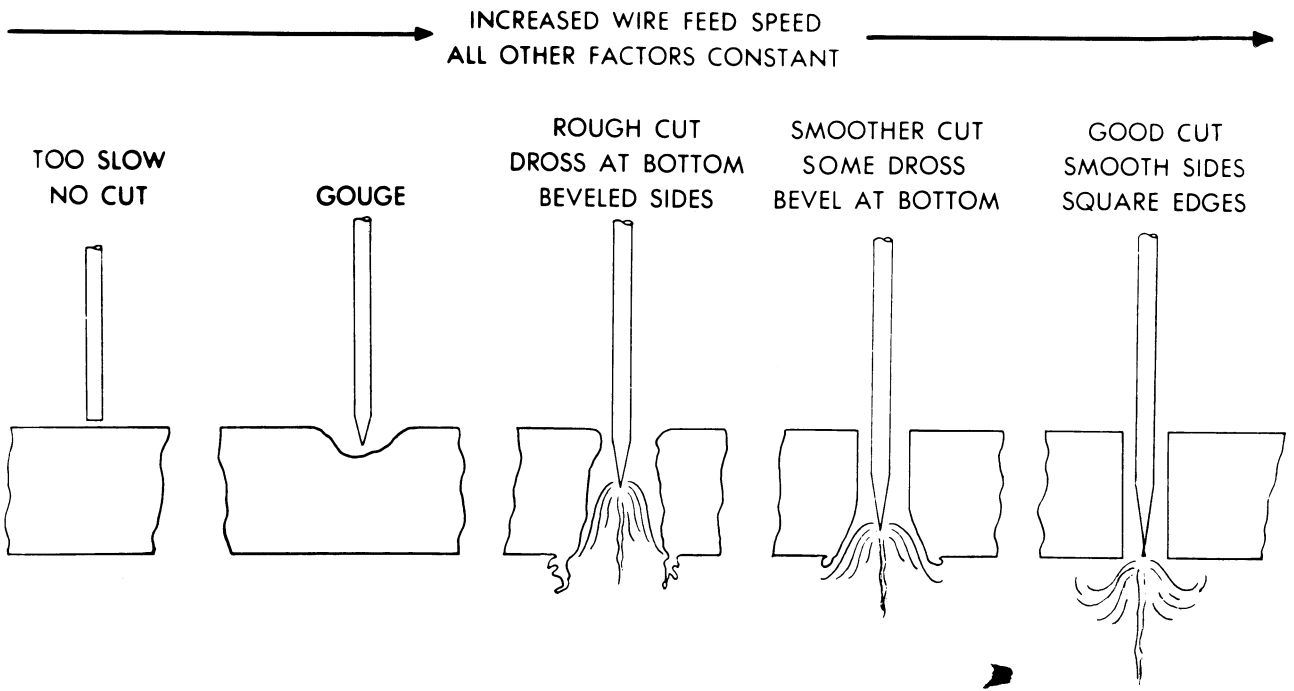


Fig. 43.8.—Effect of wire feed speed on gas metal-arc cutting.

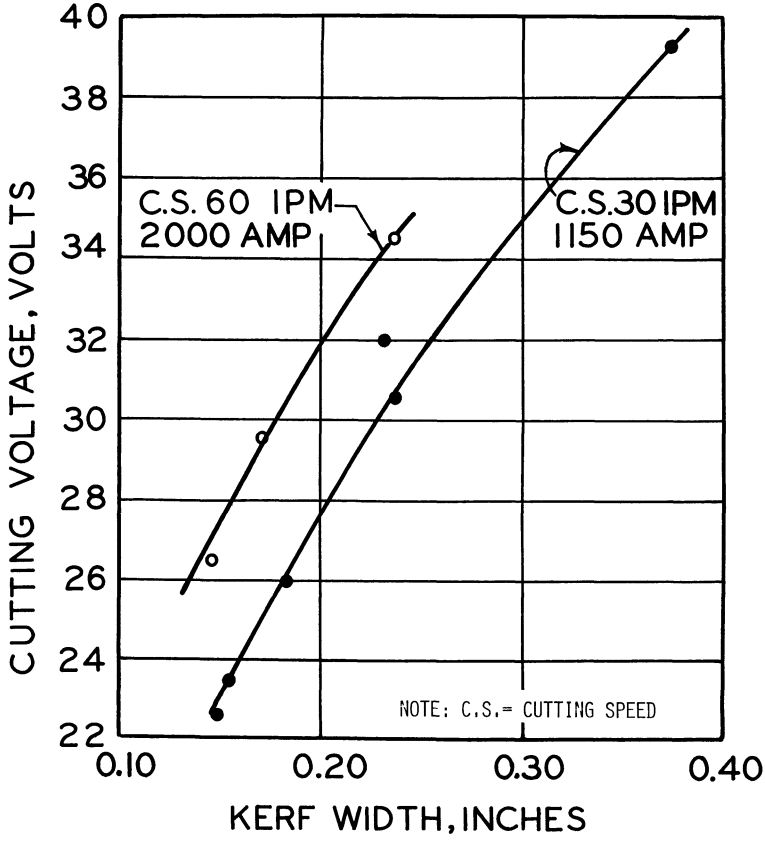


Fig. 43.9.—Effect of wire feed speed on gas metal-arc cutting.

In welding, the arc establishes itself between the tip or end of the wire and the upper surface of the plate. In cutting, the arc occurs between the leading side of the wire and the edge of the plate, extending along the entire depth of the kerf (Fig. 43.10). The cut edges usually require no further processing prior to welding.

OPERATING DATA

The data in Fig. 43.11 provide a guide for use in establishing the proper settings for a specific application. These data are intended as a starting point only for cutting square edges. For making bevel cuts, select conditions based on cutting a material equal in thickness to the dimension of the face of the bevel. Settings are given for several energy levels to permit their use with various equipment installations and job conditions. No differentiation is made between manual or machine cutting; parameters for both methods of cutting may be taken from this figure.

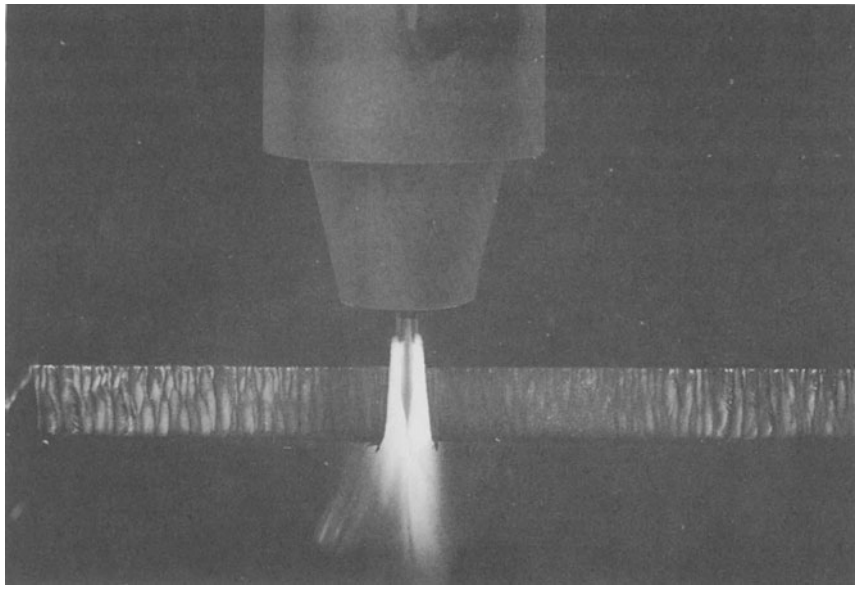


Fig. 43.10.—The cutting arc.

The currents and voltages indicated in Fig. 43.11 are arc values. Allowances must be made for voltage drops through the welding cables. The values given for aluminum can also be used as starting points for magnesium. The values shown for stainless steel can be used as starting data for other nickel and copper alloys.

SAFETY

Safety in Welding and Cutting-Standard Z49.1-1967 provides for adequate operator safety while gas metal-arc cutting. Since heavy fumes are generated an adequate exhaust system is necessary.

APPLICATIONS

Although this cutting method has gained little commercial acceptance, some fabricators like the unitized feature of this cutting method which permits them to cut and weld using the same equipment. The primary faults of the process are the high consumption of wire and the inability to cut heavy sections. Modern cutting machines are capable of controlled high cutting speeds required by this process. This eliminates a previous problem of contour cutting.

The high consumption of wire has been overcome by making a continuous loop from a suitable section, e.g., 0.01 sq. in. and applying dc power to it. The looped conductor has to be moved very rapidly in order to withstand the arc starting current and extinguishing voltage without failure when constant potential power sources are used. This method of cutting has been used to cut shapes

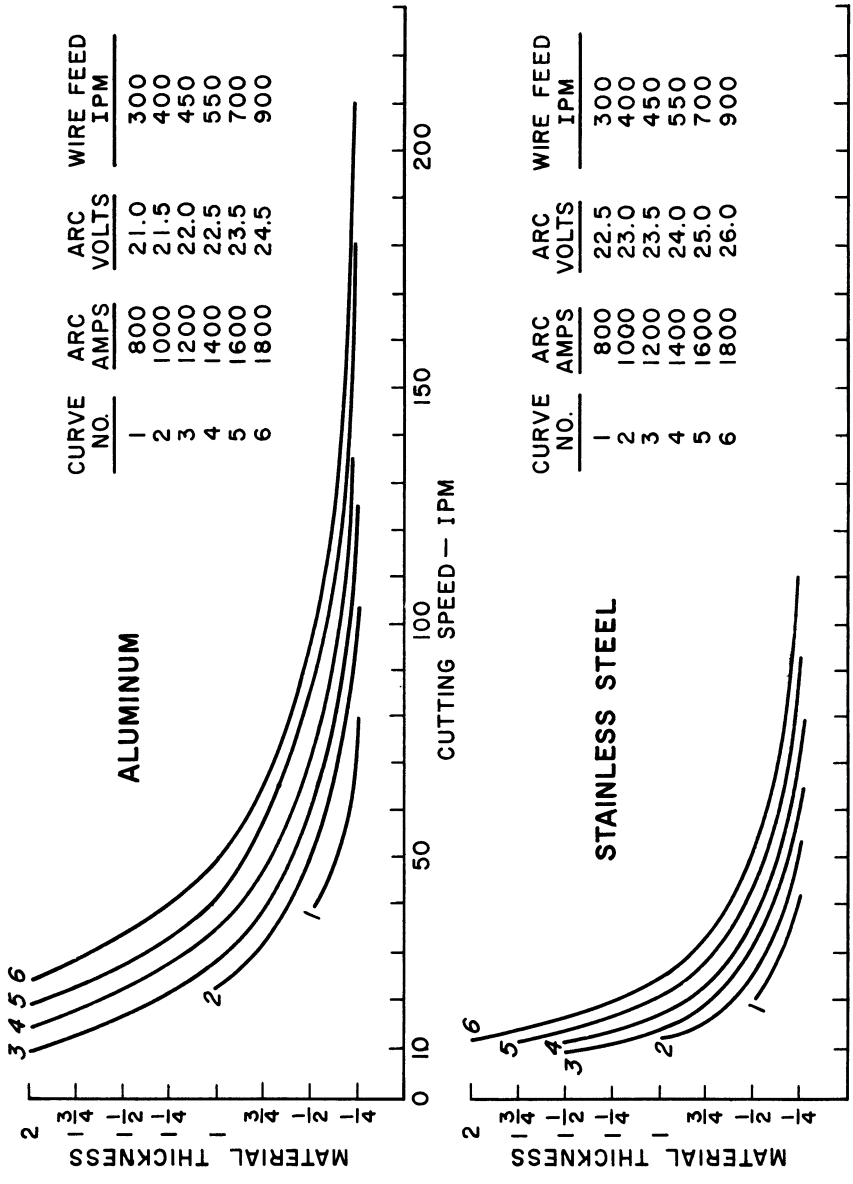


Fig. 43.11.—Operating date for gas metal-arc cutting.

in stainless steel honeycomb panels. Using ac power, the cutting speed for good quality cuts was lowered to 10 to 20 ipm, or about three times slower than required with dc power.

The maximum thickness practically cut with this method using wire sizes compatible with normal welding equipment (3/32 in.) is 1½ in. thick stainless and 3 in. thick aluminum.

GAS TUNGSTEN-ARC CUTTING

PRINCIPLES OF OPERATION

Gas tungsten-arc cutting with a nonconstricted arc can be used to sever nonferrous metals and stainless steel in thicknesses up to ½ in. using standard gas tungsten-arc welding equipment. Metals cut include aluminum, magnesium, copper, silicon-bronze, nickel, copper-nickel and various types of stainless steels. This method can be used for either manual or mechanized cutting. The same electric circuit is used for cutting as for welding. When cutting a plate of a given thickness, current higher than that used to weld a plate of equivalent thickness is used in conjunction with increased gas flow to melt through and sever the plate.

In practice, a 5/32 in. diameter 2% thoriated tungsten electrode is extended approximately ¼ in. beyond the end of a ⅜ in. diameter metallic or ceramic gas cup. A mixture of argon and hydrogen, usually with 65% argon, is delivered to the torch at a flow rate of 60 cfh. Best cutting results are obtained using dcsp, but alternating current with superimposed high frequency (achf) has produced satisfactory cuts on material up to ¼ in. thick.

Arc starting can be accomplished with either a high frequency spark or by scratching the electrode on the workpiece. An electrode-to-work distance of 1/16 to ⅛ in. is used, but this is not a critical factor. As the torch is moved over the plate, a small section of the plate is melted by the heat of the arc and the molten metal is blown away by the gas stream to form the kerf. At the end of the cut, the torch is raised from the workpiece to break the arc.

EFFECT ON MATERIALS CUT

Metallurgical

Because the material has to be melted, the edge of the cut has a heat-affected zone similar to that left by shielded metal-arc welding.

Distortion

The degree of distortion obtained from the process varies as to the thickness. The thinner materials exhibit more warpage.

Machinability

There is no loss of machinability on nonferrous or low carbon steel materials. A hard heat-affected zone may be expected on those materials that are hardenable.

Surface Condition

One side of the cut is usually dross-free, with dross adhering to the side of the workpiece away from the ground. The cut quality on the dross-free side is about the same as may be obtained with plasma-arc cutting.

EQUIPMENT

Standard gas tungsten-arc welding torches can be used for cutting. As shown in Table 43.5, cutting currents up to 600 amperes are utilized. Welding torches can be used for cutting at currents up to 175% of their nominal ratings because there is little reflected heat from the cutting operation. For example, a 300 ampere torch can be used for cutting with 500 amperes for short periods.

The best quality cuts have been obtained using ⅜ in. diameter gas cups. When smaller gas cups are used, lack of electrode centering may result in poor cut quality. For a given gas flow rate, larger diameter gas cups reduce the force available for removing molten metal and may reduce cut quality. In order to prolong the life of the gas cup, it is important to maintain an electrode extension of ¼ in. to reduce the heat load on the nozzle.

Power Supply

A dc power supply, either rectifier or motor generator, with a minimum open-circuit voltage of 70 volts is recommended for cutting. Cuts made with ac power have a plate thickness limitation of ¼ inch. The major difficulty encountered when using ac power is the loss of tungsten from the electrode at the high currents required.

Shielding

Good quality cuts can be made with an argon-hydrogen gas mixture containing 65 to 80% argon. Nitrogen can also be used, but the quality of cut is not as good as that produced with an argon-hydrogen mixture. Table 43.5 contains the conditions for gas tungsten-arc cutting. These cuts were made using a ⅜ in. diameter gas cup, a gas flow of 60 cfh and a 5/32 in. diameter electrode. Torch stand-off in each case was 1/16 inch.

Table 43.5—Conditions for gas tungsten-arc cutting

Material	Thickness in.	Travel Speed, ipm	Current, dcsp amps	Type of Gas
Stainless Steel	⅛	20	350	80% A + 20% H_2
Stainless Steel	¼	20	500	65% A + 35% H_2
Stainless Steel	½	15	600	65% A + 35% H_2
Aluminum	⅛	30	200	80% A + 20% H_2
Aluminum	¼	20	300	65% A + 35% H_2
Aluminum	½	20	450	65% A + 35% H_2

PLASMA-ARC CUTTING

PRINCIPLES OF OPERATION

Plasma-arc cutting employs an extremely high-temperature, high-velocity constricted arc between the electrode in the plasma torch and the piece to be cut. The arc is constricted by passing it through a nozzle with a small diameter orifice. The arc is thereby localized so that its energy is concentrated upon a small area on the base plate where its intense heat melts the metal. The gas, which is preheated by the arc, expands and is accelerated as it is forced through the constricting orifice. The metal which is melted is then continuously removed by the jet-like action of the gas stream to form a kerf. The combined heat and force of the arc stream produce a high-quality, sawlike cut. Where inert gases are used, the cutting process depends upon thermal action alone. When cutting such materials as mild steel and cast iron, increased cutting speeds can be achieved by using oxygen-bearing cutting gases. In this case, the chemical energy obtained by the combination of oxygen with the base material is added to the arc heat to permit higher cutting speeds. The process can be used to cut any metal.

The plasma cutting process is shown schematically in Fig. 43.12. The circuit is basically the same as is used for gas tungsten-arc welding with one exception: a lead is taken from the ground and passed through a resistor to the nozzle of the torch. A high frequency spark is used to complete the circuit between the electrode and the nozzle, thereby producing a pilot arc. This pilot arc is then used to initiate the main arc from the electrode to the workpiece.

EFFECT ON MATERIALS CUT

Metallurgical

The depth of the heat affected zone resulting from cutting depends on cutting speed or, conversely, the duration of time that a given portion of the cut face is exposed to the heat of the arc. The heat-affected zone on the plasma arc cut face of 1-in. stainless steel is only 0.003 to 0.005 in. deep. This measurement has been determined from micrographs of the grain structure at the edge of a cut plate. Since the cut edge passes through the critical 1200°F (649°C) temperature very rapidly at high cutting speeds, there is virtually no chance for chromium carbide to precipitate along the grain boundaries and reduce corrosion resistance.

Measurements of the magnetic properties of type 304 stainless steel have been made on uncut base metal and on plasma cut samples. These tests indicate that magnetic permeability is unaffected by plasma-arc cutting.

Machinability

In the cutting of hardenable materials it is expected that the heat-affected zone will exhibit hardnesses comparable to those obtained when arc welding the material, and the edges will therefore require some grinding or annealing if optimum machining conditions are desired.

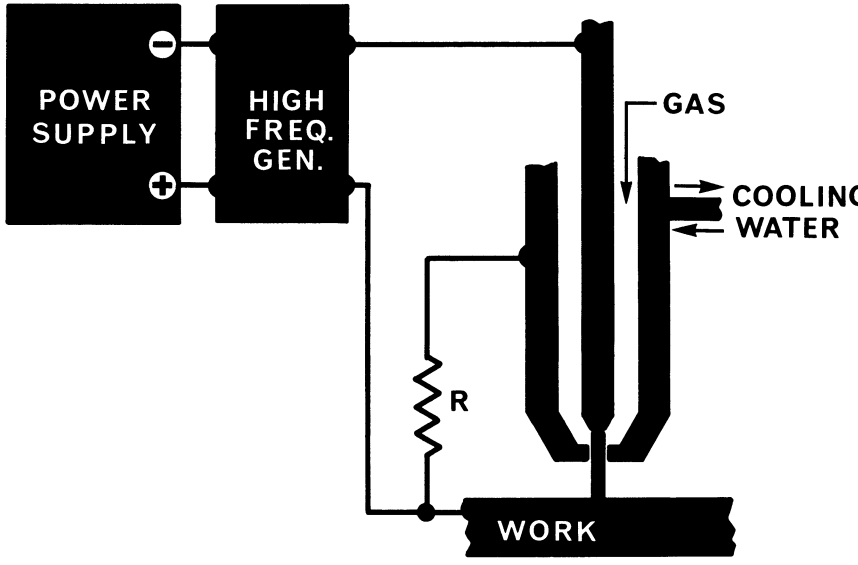


Fig. 43.12.—Plasma arc torch circuitry.

Cut Quality and Surafce Condition

An analysis of cut quality involves an examination of cut surface smoothness, kerf width, parallelness of cut faces, tendency for dross on form on the bottom edge of the cut and tendency for the top edges of the cut to be rounded. A perfect cut would be described as having perfectly smooth cut faces, a very narrow kerf to minimize loss of base metal, parallel cut faces, dross-free bottom edges and square top edges.

Plasma-arc cuts in plates up to about 4 in. thick have surface smoothnesses ranging between that produced by oxy-fuel gas cutting and band-saw cutting. The cut faces in thicker plates tend to be rougher, because of excessive melting caused by lower cutting speeds.

Kerf widths of plasma-arc cuts are 1½ to 2 times as wide as oxy-fuel gas cuts in plates up to 2 in. thick. For example, a typical kerf width for a plasma cut in 1 in. stainless steel is about 3/16 inch. Kerf width increases as plate thickness increases. A plasma-arc cut in 7 in. stainless steel made at 4 ipm produces a kerf width of 1⅛ inches.

The plasma jet tends to remove more metal from the upper part of the workpiece than from the lower part. This results in beveled cuts wider at the top than at the bottom. A typical included angle across a cut in 1 in. carbon steel is 4 to 6 degrees. The bevel angle increases as cutting speed is increased.

One side of the cut can be made square by angling the torch a few degrees off the vertical toward the side which is desired to be square. All the bevel is then on the "off" side which is presumably scrap. This method is not practicable, of course, in shape-cutting operations.

Essentially parallel kerf walls can be obtained by using a so-called "high quality" cutting procedure. This technique involves the use of multiport nozzles and programmed control of cutting current and gas to get a very high degree of arc construction.

The term "dross" refers to the material that melts during cutting but adheres to the bottom edge of the cut face. Plasma-arc cuts are generally dross-free if the proper cutting conditions and the appropriate cutting gas are used.

Top edge rounding will result from using excessive power for cutting a given plate thickness. It may also occur in high speed cutting of relatively thin material. Most plasma arc cuts have fairly square top edges.

EQUIPMENT

There are two types of electrode holders and automatic cutting controls. One type is designed for manual cutting where the torch is manually guided. The other type is for mechanized cutting where the torch is mounted on an automatic travel mechanism. A machine cutting torch is shown in Fig. 43.13.

Water cooling is used to prolong the operating life of the torch electrode and nozzle. Torch surfaces are insulated as completely as possible to prevent the operator from touching an electrically "hot" metallic surface.

Gas pressure regulators and flowmeters are required for controlling the flow of cutting gas. A contactor, usually built into the power supply, is necessary for turning the power on and off. A high-frequency unit initiates the pilot arc. For mechanized operation, a suitable travel carriage having the desired speed range is required. This travel carriage may be of the straight-line, circle-cutting or shape-cutting type.

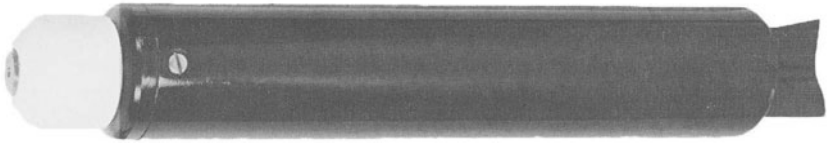


Fig. 43.13.—Typical plasma-arc cutting torch for automatic cutting operations.

Controls

The cutting controls contain relays and solenoid valves to control the flow of cutting gas, to operate the high-frequency power supply required for arc starting and to open and close the cutting power contactor. The controls also provide a flow switch to indicate an adequate flow of cooling water. The machine control provides a means of starting and stopping the carriage on which the torch is mounted. A remote control box provided with the machine cutting control enables the operator to start the mechanized cutting operation and to stop it in case of an emergency.

Nozzles

Arc-constricting nozzles are provided in a variety of diameters and shapes. The shape and diameter of the arc-constricting nozzle to be used depend on the application and the current to be used, with higher currents requiring larger diameter orifices. Both single port and multiport nozzles have been used for cutting. The multiport nozzles used with this process generally have the auxiliary ports arranged in a circle around a central orifice.

Power Supplies

Power supplies used for cutting have open-circuit voltages in the range of 120 to 400 volts. The open-circuit voltage is selected on the basis of the type of equipment to be used and the cutting application. The equipment manufacturer's recommendation should be followed when choosing a power supply. Dcsp is used, and the power supply must have a drooping volt-ampere output curve.

Heavy-duty cutting requires power supplies with 400 open-circuit volts. The high open-circuit voltage is required for severing thick plates and for piercing material as thick as 2 inches.

Cutting Gases

Mixtures of argon and hydrogen or nitrogen and hydrogen are generally used for cutting stainless steel, aluminum and other nonferrous metals. Nitrogen and oxygen, supplied separately to the torch and mixed in the torch nozzle, exhibit desirable properties for cutting carbon steel, cast iron and alloy steels such as 18% Ni maraging steel. Since the operating life of an electrode exposed to oxygen at plasma temperatures is relatively short, oxygen is injected into the plasma jet downstream of the electrode. Two methods of doing this are shown in Fig. 43.14.

CUTTING TECHNIQUES

Typical conditions for mechanized plasma arc cutting of stainless steel, aluminum and mild steel are given in Tables 43.6, 7 and 8. In mechanized operations, the torch standoff distance is set between ¼ in. and ⅝ in. from the work piece. The cutting current, gas type and rate of flow are set at values recommended by the manufacturer. These values are primarily determined by the type and thickness of the material being cut. After the operator presses a start button to initiate the cutting arc, the sequence of operations is regulated by the cutting control.

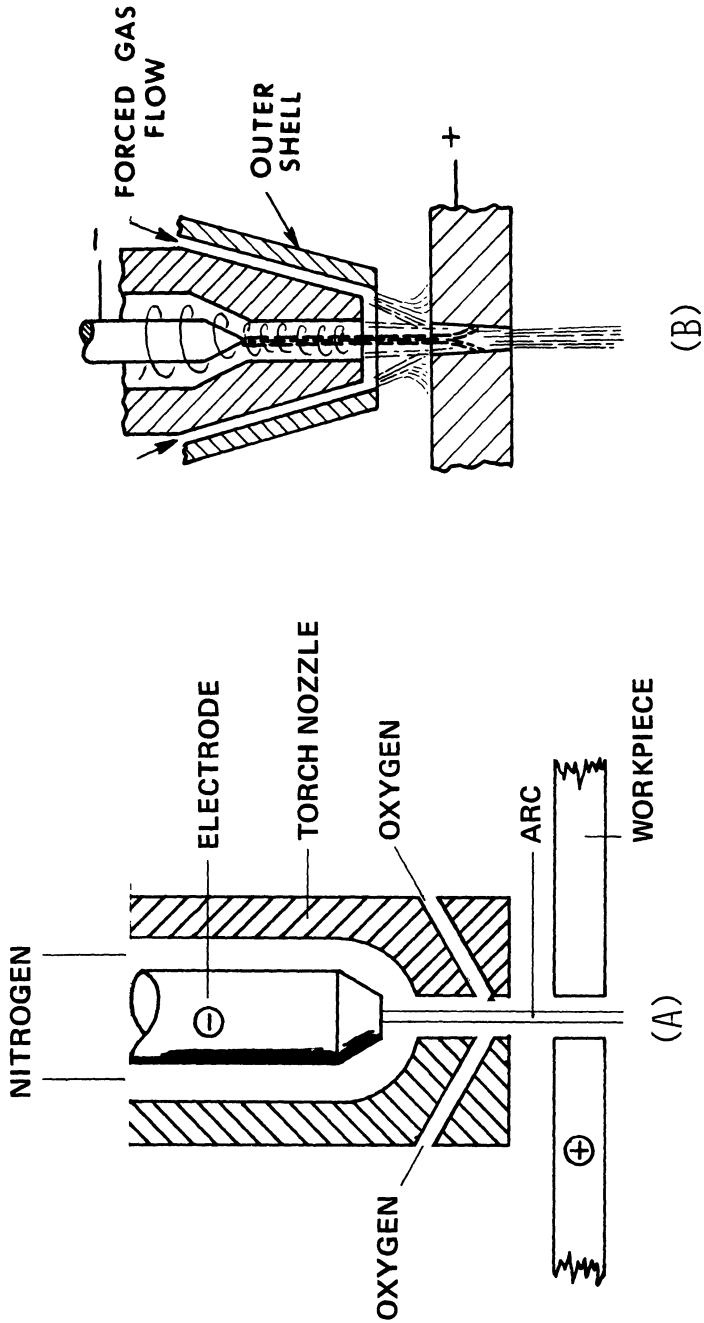


Fig. 43.14.—Two nozzles designed for cutting carbon steel using nitrogen and oxygen as the cutting gases. In design (a) oxygen is injected into the arc-constricting orifice. In design (b) oxygen (or air) is introduced through an outer shell to form a sheath surrounding the nitrogen plasma jet.

Table 43.6—Typical conditions for plasma arc cutting stainless steel

Thickness in.	Speed imp	Orifice Diameter in.	Current amps	Gas Flow cfh
¼	200	⅛	300	150 N_2
½	100	⅛	300	150 N_2
1	50	5/32	400	175 N_2
2	20	5/32	500	130 A-70 H_2
3	16	3/16	500	130 A-70 H_2
4	8	3/16	500	130 A-70 H_2

Table 43.7—Typical conditions for plasma arc cutting aluminum

Thickness in.	Speed imp	Orifice Diameter in.	Current amps	Gas Flow cfh
¼	300	⅛	300	80 A-40 H_2 or 130 N_2-30 H_2
½	200	⅛	300	65 A-35 H_2 or 140 N_2-60 H_2
1	90	5/32	400	65 A-35 H_2 or 140 N_2-60 H_2
2	20	5/32	400	65 A-35 H_2 or 140 N_2-60 H_2
3	15	3/16	450	130 A-70 H_2 or 140 N_2-60 H_2
4	12	3/16	450	130 A-70 H_2 or 140 N_2-60 H_2

Table 43.8—Typical conditions for plasma arc cutting carbon steel*

Thickness in.	Speed ipm	Orifice Dia. in.	Current amps	Nitrogen Flow, cfh	Oxygen Flow, cfh
¼	200	⅛	275	150	80
½	100	⅛	275	150	80
1	50	5/32	425	150	80
2	25	3/16	550	200	100

* Plasma arc cutting is generally considered uneconomical, compared to the oxy-fuel gas process, for cutting carbon steel thicker than 2 in.

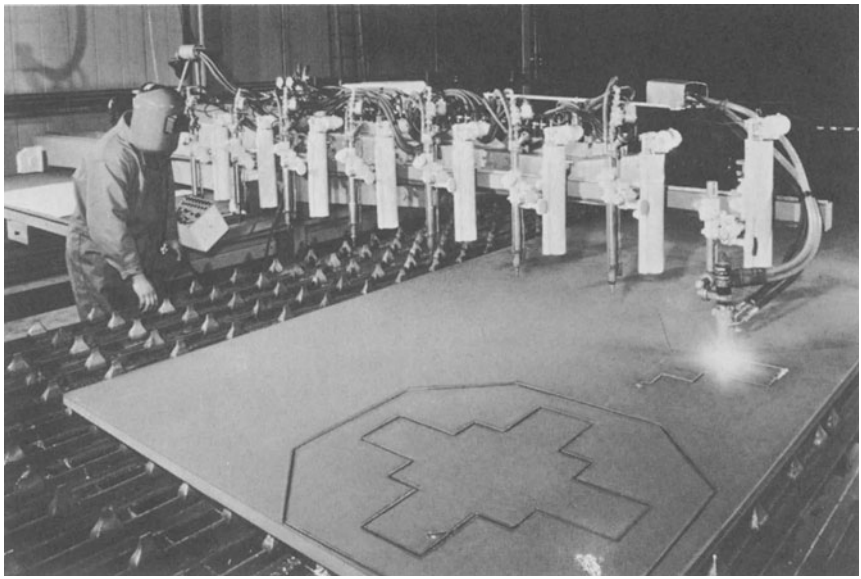


Fig. 43.15.—Automatic plasma-arc cutting of 1 in. thick stainless steel at 40 ipm. Plasma-arc cutting torch is mounted on a conventional oxyacetylene cutting machine.

For manual operation, the operator selects the gas flow rate and cutting current according to the table of conditions supplied by the manufacturer. The torch is held over the workpiece and the cutting arc is struck by pressing a button on the torch handle. The torch is then manually guided over the workpiece. At the end of the cut, the arc automatically extinguishes and the control automatically opens the contractor and closes the gas solenoid valves. The operator can extinguish the arc at any point by moving the torch away from the workpiece.

The metal nozzle of the torch must not be allowed to contact the workpiece being cut and thus become grounded. This would cause the arc to go directly from the electrode to the nozzle and result in serious nozzle damage. For manual cutting, the nozzle is insulated to prevent accidental contact with the workpiece.

SAFETY

Cutting operators and persons in the vicinity of the cutting operation must be protected from arc glare, spatter and fumes. Refer to the AWS publication A6.3-69, *Recommended Safe Practices for Plasma Arc Cutting,* for complete description of safety procedures.

APPLICATIONS

The plasma cutting process can be used in the general fabrication of all metals in many industries, such as shipyard, aircraft, chemical, nuclear and pressure vessel. It also finds application in the forging and casting industry, for removing risers and gates; in the extrusion industry for cutting the hot extrusions to length; in the continuous casting industry, for cutting plates to the desired shape; in gross-machining type applications for quickly removing large amounts of metal, and in the piping industry, for cutting any desired pipe contour. The process can be used in manual or mechanized operation and is especially adaptable to automation.

Fig. 43.15 shows the plasma arc cutting of 1 in. thick stainless steel at 40 ipm. The plasma arc torch is mounted in place of an oxygen cutting torch on an automatic shape cutting machine. Stack cutting of several sheets of $\frac{1}{16}$ to $\frac{1}{4}$ in. thickness can also be performed. In stack cutting operations, it is preferable to have the sheets clamped together to avoid movement during cutting.

The plasma cutting process also has application in the manufacture of automotive and railroad components as well as for the fabrication of structural shapes and equipment for heating and refrigeration.

As it is not necessary to start the cut at the edge of the plate, the process is particularly adaptable to the piercing and cutting of holes in large plates and vessels. The piercing and cutting of manholes in railroad tank cars is a typical example.

The process is also well adapted to gouging applications, including pad washing and scarfing.

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CHAPTER 44

SURFACING

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CHAPTER 44

SURFACING

FUNDAMENTALS OF PROCESS

DEFINITION AND GENERAL DESCRIPTION

Surfacing is defined as the deposition of filler metal on a metal surface to obtain desired properties or dimensions. It is usually employed to extend the life of a part which may not otherwise have all the properties necessary for an engineering application or to replace metal which has worn or corroded away. The overlay may contribute corrosion resistance, wear resistance, toughness or anti-friction properties exactly where they are needed most.

Where the overlay contributes abrasion resistance, it is generally referred to as hard facing. This term is employed also where a tough or nongalling overlay is used for impact resistance or low-friction qualities. "Hard" connotes durability rather than the more common denotation. Since added service life is the objective of hard facing, it is well to recognize that hardness is not always a valid index of wear resistance.

PRINCIPLES OF OPERATION

Surfacings are usually deposited by the arc or gas welding processes. Manual, semiautomatic or automatic techniques may be employed with either process. Suitable filler metals such as bare welding rods, covered electrodes, coiled strips, pastes and powders are available in great variety. Adhesion is by fusion or metallurgical bonding.

Thermal spraying, which is described in detail in Section 2 Chapter 29, is a spray coating technique that usually does not produce a fusion bond, and is not to be confused with other methods of surfacing that result in a metallurgical bond. It can be used to build up contours where metal has been worn away by friction. Because of microscopic porosity, spray coatings may have excellent resistance to metal-to-metal wear of lubricated surfaces. However, they tend to have poor resistance to abrasion.

Specifications for surfacing filler metals are difficult to develop as tests for quality and the more useful properties are not well standardized. Forty-five grades from six well-known types are included in AWS Specification A5.13, which was prepared by an AWS committee. Many useful grades are not yet covered because their identifying and behavior characteristics have not as yet been well defined. The work of the aforementioned committee is continuing, and additional grades will be added to the specification at intervals.

The important properties that may be provided by surfacing alloys are:

1. Hardness
   A. Gross or macrohardness
   B. Microhardness, or the hardness of individual constituents of a heterogeneous structure
   C. Hot hardness, or resistance to the weakening effect of temperature
   D. Creep resistance, which involves the effect of time at temperature on apparent hardness of statically loaded bodies

2. Abrasion resistance
   A. Under low-stress conditions
   B. Under high-stress grinding conditions
   C. Under gouging conditions associated with high compressive stresses of different abrasives and velocity

3. Impact resistance
   A. Resistance to plastic deformation under repeated impact (related to yield strength)
   B. Resistance to cracking under impact (related to both strength and ductility)
   C. Compressive strength
   D. Compressive ductility

4. Heat resistance
   A. Resistance to tempering
   B. Retention of strength when hot (includes hot hardness)
   C. Creep resistance (time factor added to B)
   D. Oxidation or hot gas corrosion resistance
   E. Resistance to thermal fatigue
5. Corrosion resistance
6. Frictional properties and welding tendencies
   A. Friction coefficients
   B. Galling tendency
   C. Surface films
   D. Lubricity
   E. Plasticity

The end result desired from surfacing is long or increased life of the working area. Since the conditions of wear are often varied and complex, it is difficult to establish a simple correlation between service and properties. The best approach is a careful analysis of service conditions and a logical application of pertinent physical, mechanical or wear test data. The usual alternative, an arbitrary ranking of alloys by reputation or by casual service tests, is not acceptable from an engineering viewpoint.

The engineering principles which should form the basis for the selection of surfacing filler metals have only been partially understood. When certain surfacing filler metals have been found acceptable for typical applications, they will be so designated in the section of this chapter. The following are the advantages of surfacing:

1. Addition of wear or corrosion resistance exactly where it is needed
2. Easy use of very hard compounds and wear-resistance alloys
3. Ready application in the field
4. Economical use of expensive alloy elements
5. A hard surface layer reinforced by a tough base
6. Economies to the user through:
   A. Longer service life
   B. Reduction of maintenance and replacement
   C. Reclamation of worn parts
   D. Use of lower cost base materials
   E. Reduced power consumption in service
   F. Sometimes greater efficiency of a part

Some important considerations in the use of surfacing in addition to the character of the filler and base metals are the geometry of the part, the cost of welding labor, the development of cracks or distortion from the thermal stresses of welding and the quality of deposit required.

The quality of the surfacing deposit may vary widely depending upon the application, the surfacing filler metal and the skill of the welder. Valve facing, for example, may require absolute perfection in the deposit of a Cr-Co-W alloy applied by oxyacetylene welding (Fig. 44.1). Careful quality control of the welding rods is necessary in manufacture, and a considerable training period is required of a welder before his work is acceptable. Corrosion resistant overlays are even more exacting, as the surface must not only be perfect (since a flaw can result in rapid local corrosive attack with possible catastrophic damage), but the deposit must be protected from excessive dilution or composition changes that would modify its response to corrosion. At the other extreme, hard facing of some earth-handling equipment in the field may be done by welders using loosely controlled filler metals. Overlays full of cracks and blowholes may result, but in spite of them increased life may result. This wide variation in acceptable quality complicates the development of surfacing filler metal specifications.

SURFACING METHODS

Surfacing can be achieved by a variety of methods and the surfacing filler metals are provided in several forms. Most of the methods involve fusion welding (that is the filler metal and sometimes the base metal melt in place and then resolidify to provide a continuous metallic matrix.) However, some techniques spray the metal on the surface where it clings by mechanical bonding. Combustion of gases or an electric arc then provides the heat for fusion. Undesired reactions of the molten metal with the atmosphere may be inhibited by a flux covering of the pool, by shielding with inert gases, or by including protective elements (e.g. deoxidizers) with the filler metal. A survey of the possibilities is provided by Table 44.1.

Gas welding usually tends to establish slower heating and cooling rates for the base metal, tends to facilitate greater precision of placement, involves little or no dilution of the overlay by the base metal, and can be done with portable and relatively inexpensive equipment. Arc welding is faster, generally less expensive overall, may be less demanding of skill and is more commonly used, but it imposes sharper thermal gradients that promote cracking. For small jobs and for field use the usual choice is between manual gas or arc welding based on the above factors.

For factory use, especially where surfacing is extensive, automatic methods are likely to be more economical even though large equipment outlays are required. The factors above may still be persuasive, but the special advantages of a variety of other methods merit consideration.

FILLER METAL FORMS

The surfacing filler metals are usually in the form of rods, filled tubes, strip, granules or powders. Fluxes may be in the central core portion of tubes, on the surface of covered electrodes, introduced as a granular blanket or mixed in an agglomeration with powdered filler metal.

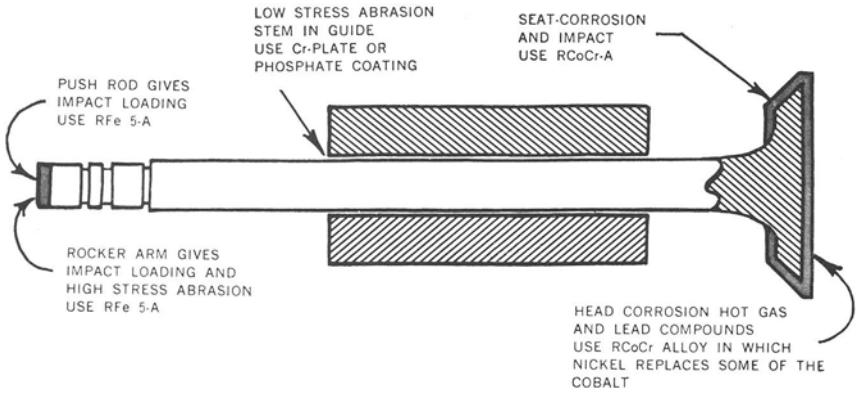


Fig. 44.1.—Typical surfaces that may be applied to engine valves subject to corrosion, impact and abrasion.

For gas welding, rods and powders are commonly used. Solid rods may be drawn wires (for ductile alloys) or castings. Tubular rods are composites. The usual sheath material is mild steel formed by special machines from strip and filled with alloying elements, perhaps supplemented with fluxing ingredients. An important composite type has granular tungsten carbide as the filling. All types of rods should be bare and clean for gas welding.

The tubular rod design can be produced in the form of continuous coils. Tubular wires, solid drawn wires, or drawn strips serve as the electrodes for semiautomatic and automatic arc surfacing. They are usually provided with a flux blanket or a gas shield at the arc, but some are adapted for bare arc welding. The tube design is quite versatile, and it provides the only way that brittle filler metals can be furnished for automatic arc welding. Where both forms are available for the same filler metal, the tubular product in some cases shows superior usability. A number of the stainless steels are available in tubular form, sometimes with their compositions adjusted to compensate for dilution from the base metal.

The powder form is also quite versatile. Practically any metal or alloy can be made available at relatively low cost. The character of the powder is important; each process requires a specific powder size range and shape for optimum results. The powder alloys are usually arc melted after precise formulation, and then atomized or cast and granulated. The alloy powders used with the bulk welding process may be simple mechanical mixtures as well as prefused alloys. Composition control of mechanical mixtures, usually by a metering device adjustable by the welder, is considered inherently less precise than that of arc furnace melting under metallurgical control.

Table 44.1—Surfacing methods and variations

Basic Process	Process Variations	Mode of Application	Hard Facing Alloy Form	Applicable Hard Facing Alloys	Cladding Alloy Form	Applicable Alloys For Corrosion Resistance	Remarks	AWS Handbook Chapter Reference
WELD FUSION PROCESSES								
Combustible gas	Oxy-fuel gas (rod)	Manual	Bare Cast or tube rod	Co, Ni, and Fe base, tungsten-carbide composites	*	*		Section II Chapter 21
		Automatic	Extra Long bare cast rod or tube wire	"	*	*		"
	Oxy-fuel gas (powder)	Manual	Powder	Co, Ni, and Fe base, tungsten-carbide composites	*	*		———
Bare Metal arc	None	Manual Semi-auto.	Bare solid or tube wire	Austenitic manganese steel	*	*		Section II Chap. 26, 29
Shielded Metal arc	Covered electrode	Manual	Flux-coated cast rod, wire or tube rod	Co, Ni, and Fe base, tungsten-carbide composites	Flux coated wire	S.S., Ni, Cu & Fe base		Section II Chap. 25, 29
	Flux cored electrode (self-shield.)	Semi-auto.	Flux-cored tube wire	Fe base	*	*		Section II Chap. 29
		Automatic	Flux-cored tube wire					
Gas Shielded arc	Gas Tungsten arc (tig)	Manual	Bare cast or tube rod	Co, Ni, and Fe base, tungsten-carbide composites	Bare solid wire or rod	S.S., Ni, Cu & Fe base		Section II Chap. 27, 29
		Automatic	Bare tube wire; Extra long bare cast rod; Tungsten-carbide powder with bare solid wire.	Co, Ni, and Fe base, tungsten-carbide composites	Bare solid wire	S.S., Ni, Cu & Fe base		"
Gas Shielded arc (cont'd.)	Gas Metal arc (MIG)	Semi-auto. Automatic	*	*	Bare solid wire	S.S., Ni, Cu & Fe base		Section II Chap. 27, 29
	Gas Metal arc-short circuiting	Semi-auto. Automatic	*	*		S.S., Ni, Cu & Fe base		"
	Gas Metal arc-auxiliary wire	Automatic	*	*	Bare solid wire	S.S., Ni, Cu & Fe base		Section II Chap. 29
	Magnetic flux (CO_2)	Semi-auto. Automatic	Bare solid wire & metal powder	Fe base	*	*	Alloy powder magnetically attached to wire entering arc	Section II Chap. 27, 29

Submerged arc	Single-wire	Semi-auto.	Bare solid or tube wire	Fe base	*	*	Limited use	Section II Chap. 28, 29
		Automatic	Bare tube or solid wire	Fe base	Bare solid or tube wire	S.S., Ni, Cu base	Limited use with Cu base alloys	Section V Chap. 94
	Multiwire	Automatic	Bare tube or solid wire	Fe base	Solid or tube wire	S.S., Ni, Cu base	"	Section V Chap. 94
	Series arc	Automatic	Solid wire	Fe base	Solid wire	S.S., Ni, Cu base	Used primarily for cladding large vessels	"
	Strip Electrode	Automatic	*	*	Bare strip	S.S., Ni base		Section V Chapter 94
	Strip Electrode — Aux. strip	Automatic	*	*	Bare strip	S.S., Ni base		"
	Bulk process	Automatic	Bare solid or tube wire with metal powder	Fe & Co base	Bare solid wire with metal powder	S.S. & Ni base		"
Plasma arc (transferred arc)	Plasma arc-powder	Automatic	Powder with or without tungsten-carbide granules	Fe, Co, Ni base, tungsten-carbide composites	Powder	S.S., Ni, Cu base	Used primarily for production hardfacing	Section III Chapter 53
	Plasma arc-hot wire	Automatic	Bare solid or tube wire	Fe base	Bare solid or tube wire	S.S., Ni, Cu & Fe base	Used primarily for cladding large vessels & related components	"
Carbon arc	Carbon Electrode	Manual	Bare rod	Fe base	*	*	Seldom used for surfacing	Section II Chapter 24
	Atomic-Hydrogen	Manual	Bare rod, Preplaced Powder	Co, Ni, Fe base tungsten-carbide composites	*	*	Used on limited applications	Section II Chap. 26, 29
COATING PROCESSES								
Combustible gas	Flame spray (metallizing)	Semi-auto.	Powder, rod	Fe, Co, Ni base tungsten-carbide composites, ceramics	Bare solid wire	S.S., Ni, Cu base Al, Zr, tin, etc.	Some hard facing alloys may be fused after spraying to produce a fused bond	Section III Chap. 42
		Automatic	Powder, rod	"	"	"		
	Detonation Gun plating	Automatic (proprietary)	Powder	Tungsten-carbide with selected matrices; selected oxides	*	*	Equipment not sold.	"
Plasma arc (nontransferred arc)	Plasma spray metallizing	Semi-auto. Automatic	Powder	Fe, Co, Ni base tungsten-carbide composites, ceramics	*	*		"

A number of fluxes are available for the submerged arc welding processes. Their use provides a blanket for the arc, whose heat melts the granules into a protective molten flux cover for the molten metal. The fluxes have different characteristics, varying in their effect on weld metal composition, metal fluidity, bead contour, deposit soundness and ease of slag removal. Consumption can vary considerably, depending on arc length and current, but fusion of 1 to 1½ pounds of flux per pound of wire used is a reasonable estimate. The unmelted flux, if clean, can be collected for further use. Also, the portion that was fused can be salvaged, pulverized and reused. A portion of this can be mixed with new flux, the ratio being limited by the effect on weld quality.

Special fluxes may contain ferroalloys and other metal ingredients, thus contributing alloy additions to the deposit as well as protection to the weld pool. They are intended for use with carbon or low-alloy steel electrodes, and must be precisely proportioned to the wire if the desired composition is to be achieved. Such fluxes cannot satisfactorily be reclaimed and reused.

For manual arc welding flux protection is provided by a dipped or extruded covering. This covering sometimes is a composite of flux ingredients and alloying elements, in which case the core wire may be a simple steel or have a composition quite different from that of the intended filler metal. It is for this reason that surfacing filler metal compositions refer to the undiluted deposit rather than to the metal core of a covered electrode. This circumstance also makes inadvisable the use of electrodes from which part of the covering has been removed or broken off.

MANUAL OXYACETYLENE SURFACING WITH WELDING RODS

This method, described in Chapter 41, has great usefulness for smooth, precise and extremely high quality surfacing deposits. The freedom from base metal dilution can be very important where filler and base metals differ considerably, as with cobalt-base filler metals applied to steels. Here the addition of iron is known to be detrimental to the overlay properties.

The oxyacetylene welding operation lends itself to very close scrutiny and control by the welder. Tiny areas can be surfaced. Grooves and other recesses may be accurately filled, and very thin layers may be smoothly applied. Rods containing tungsten carbide may be used with minimum solution of the wear resistant particles and with controlled particle distribution. The preheating and slow cooling tend to minimize cracking, even with extremely wear resistant but brittle overlays.

The base metal should be clean, as dirt or oxide may interfere with the uniform wetting action desired. A flux is seldom necessary with most alloys. The flame adjustment should be as recommended by the manufacturer for the specific filler metal, to ensure proper melt behavior and intended deposit properties. Most surfacing filler metals are applied by a reducing flame (Figure 44.2) that prevents loss of carbon. This may actually add some carbon to the deposit. The effect of the flame on the composition of the deposit is anticipated in the formulation of the welding rod during manufacture. A degree of welding skill is needed for high quality oxyacetylene deposits as improper flame adjustment or manipulation and the production of excessive oxide can cause defects. The welding rod used, which is often a casting, must be of good quality.

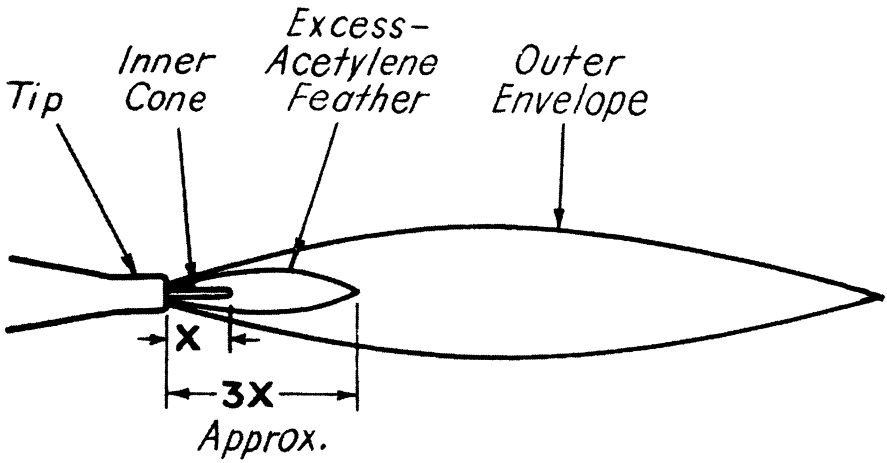


Fig. 44.2.—Approximate dimensions for carburizing flame used for surfacing by oxyacetylene welding.

In a typical application a low melting point high-carbon filler metal, such as a high chromium iron or a Cr-Co-W alloy is deposited on a low or medium carbon steel that has a high melting point. Using a 3X feather to cone ratio (Fig. 44.2), the base metal is preheated uniformly over a small area. The reducing flame carburizes the surface, and lowers its melting point, and finally melts a film on the surface. This is signalled by a "sweat" or glistening appearance. The tip of the surfacing rod, which should have been preheating on the fringe of the flame, is now moved into the hot center of the flame and melted. It should wet the surface as it melts, and spread smoothly over the heated area. As the flame is moved to the edge of the surfaced area, the welding rod tip is moved before it, progressively melting the rod as needed. This method of application is known as the forehand method. It minimizes the dilution of the base metal that occurs when the backhand method is used. Many welders use a weaving motion of the flame and the rod to maintain the balance between surface heating and rod melting.

Special preparation of the base metal may be helpful. Grooves or pockets can be ground or machined where surfacing is needed (Fig. 44.3), and filled with the molten deposit. This not only aids in precise positioning, but also tends to protect the edge of the deposit from chipping under impact.

Surfacing deposits that have a considerable plastic range, such as the austenitic high chromium irons, can be wiped or "struck off" to shape with a steel straight edge while the weld is still only partially solidified.

Because of preheating requirements, and because of the nature of the flame and of the process, oxyacetylene surfacing does not have the capability for high deposition rates offered by most of the arc welding processes. However, for many applications it is clearly the most satisfactory process. Well established uses include the surfacing of steam valves, automotive diesel engine valves, chain saw bars, plowshares and other agricultural implements.

Although ductility may be decreased, the pick-up of carbon from a reducing flame is generally beneficial for those alloys that rely on carbides for abrasion resistance. Oxyhydrogen welding, which is now seldom used, has features much like those of the oxyacetylene technique, but it cannot carburize the metal.

MANUAL OXYACETYLENE SURFACING WITH POWDERED FILLER METAL

This variation of the gas welding process utilizes an oxyacetylene torch fitted with a powder hopper and a powder feed control device. (See also Section 2, Chapter 29). The surfacing powder is aspirated into the gas stream and exits with the gas from the burner tip. This can result in a sprayed deposit that is only mechanically bonded to the surface. However, by the proper technique, a fusion bond may be obtained by "sweating" the base metal and applying the surfacing alloy. The fusion of the surfacing alloy with the base metal occurs in one operation.

The equipment is inexpensive and excellent results can be obtained by even the inexperienced operator. One advantage of this method is that many alloys not readily obtainable in rod or wire form are available as suitable powders. Smooth, thin, porosity free deposits can be made, with thicknesses from a few thousandths of an inch up to about one eighth inch, in one pass. Deposition rates will vary with torch size. Large torches with tips producing bulbous flames are able to deposit up to 10 pounds of metal per hour. The thickness is controlled by the rate of powder flow and movement of the torch.

When deposits are intended to be mechanically bonded, grit blasting to roughen the surface is generally used to aid the bonding. The deposit is characteristically porous. Where lubricated wear is intended, the pores may serve as oil reservoirs in case of boundary lubrication. Also, where the deposit is a sacrificial metal, as for example in the case of protecting steel from corrosion by an overlay of sprayed zinc, the pores may not be objectionable. However, for resistance to abrasion the mechanically bonded overlay is quite inferior. If the composition of the deposit is otherwise suitable, its performance against abrasion can be enhanced by fusing it in place by a separate operation.

SEMIAUTOMATIC OXYACETYLENE SURFACING

Where the number and symmetry of parts are such that an orderly sequence of preheating, deposition and postheating can be arranged, it may be economical and efficient to set up a semiautomatic installation. For this, specially designed burners and mechanized part handling are utilized. The operator using a welding rod six or more feet long, intermittently feeds the hard facing filler metal as it is required. Good judgment is needed as to deposition control, but manual skill is less important, productivity is higher and a more uniform product results than with manual gas welding. This method has been well developed in some plants where repetitive production of many small parts is involved. The facing of truck and engine valves is an example. The burner arrangement assures directional solidification. Deposit quality is held at a high level. Cast welding rods, made by butt welding of shorter pieces together, are

commercially available for the important alloys used for valve facing. A somewhat different application utilizes long tungsten carbide filled welding rods for the hard facing of feed mill hammers; the narrow hammers are fixtured in series to provide a large flat surface for welding.

The process that feeds the filler metal through the flame and sprays it onto a cylindrical surface being treated lends itself well to automation. Thermal Spraying is described in some detail by Chapter 29 in Section 2. The bond may be mechanical, based on roughening the surface before spraying, or metallurgical in the case of self-fluxing alloys that are fused to the base metal.

Since specialized burners and fixtures are needed for mechanized hard facing by gas welding, it is advisable to consult equipment manufacturers when planning in this field.

SURFACING BY ARC WELDING

A number of arc welding processes are used for surfacing. While some are suitable for small, precise overlays, as in oxyacetylene welding, many offer high deposition rates which make very extensive surfacing practical. Large parts can be surfaced economically with relatively low heat buildup and minimum distortion. Arc welding is the only process recommended for applications on manganese steel, and is the preferred process for other work where excessive heat buildup must be avoided.

Manual, semiautomatic and automatic arc welding methods are all used extensively for surfacing. Several of the arc welding processes are adaptable to more than one mode of application; the variety of useful methods and process combinations available is shown in Table 44.1.

For many applications the appropriate welding method will be obvious. For others, two or more options may be reasonable; for these careful weighing of the cost factors involved can lead to maximum economy.

The high temperature of the arc makes melting of a base metal layer likely. Admixture with the molten filler metal may produce an undesirable composition at the base metal-weld metal interface.

MANUAL ARC SURFACING WITH COVERED ELECTRODES

Low equipment cost, great versatility and general convenience make manual arc welding very popular. The welding machine, which is essentially a power conversion device, is usually the main item of equipment needed. It may be a motor-generator, a transformer, a transformer-rectifier combination, or a fuel operated engine combined with a generator. The arc power may be from either direct or alternating current. The filler metal is in the form of covered electrodes. (Bare electrode arc welding is a rarity today, though it is feasible with austenitic manganese steel electrodes). Welding can be done in almost any position or location and is practicable for a variety of work ranging from very small to quite large. For some applications it is the only feasible method and for many others (especially where continuous methods do not offer significant benefits) it is the economical choice, (see also Section 2, Chapter 22).

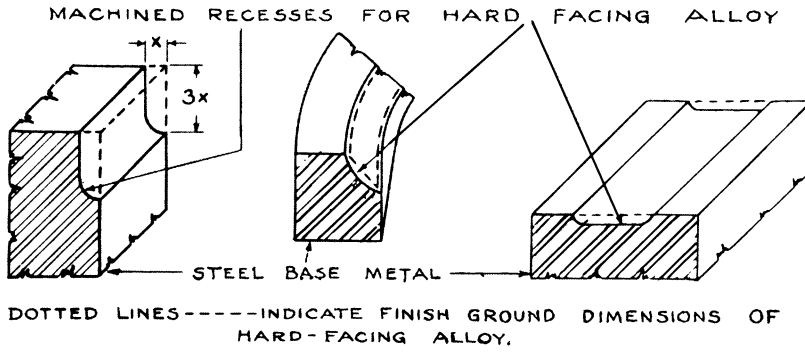


Fig. 44.3.—Typical recesses for localizing surfacing deposits.

The operation is under observation and control of the welder, who can easily cover irregular areas and often correct for adverse conditions. It is also helpful if the welder exercises judgment in other matters, such as holding arc power down to minimize cracking, keeping a short arc to minimize loss of expensive alloying elements in the filler metal, avoiding excessive puddling for the same reason and to minimize dilution with base metal and restricting moisture pick-up especially with low-hydrogen electrodes. Process variables involved with this welding method are discussed in Section 2, Chapter 22, of this Handbook.

SURFACING BY SEMIAUTOMATIC ARC WELDING

Semiautomatic welding often has an economic advantage over other manual methods because it can continue for a considerable time without interruption so the percentage of arc time and deposition rates can be high. It is particularly advantageous for extensive overlays, or when large numbers of parts are involved. The equipment outlay is lower than for other automatic methods because only an electrically controlled wire feed device is needed besides the power source.

A bare electrode is used. Therefore, the arc and the weld pool are in contact with air unless a shielding gas is supplied. To prevent the problems associated with oxidation, some electrodes contain components that provide deoxidation. Much surfacing is done with tubular "open-arc" electrodes, thereby gaining the advantages of good visibility of the weld pool, lower heat input to the base, less penetration and dilution, and less distortion than with submerged arc methods. However, while the open-arc is an aid to deposit control, it is very intense and protection for the welder's skin and eyes is important.

Some alloys require that the melt be protected by a flux cover, or by a gaseous shield to prevent adverse effects (porosity, embrittlement, etc.) from oxygen, nitrogen or hydrogen (from moisture) pickup. These can be combined with the semiautomatic process but auxiliary equipment for handling gas or flux, or sometimes water cooling of the nozzle, are then needed.

While the welder controls the arc travel and metal placement, the wire feed motor is controlled by electrical feedback from the arc voltage drop. The arc voltage can be set and has some effect on welding behavior.

With most tubular electrodes reverse polarity, direct current is recommended or preferred. Current ranges usually overlap but do not extend so high as those for submerged arc welding with its larger wire sizes. Most surfacing is done downhand (Fig. 44.4).

The deposition rates for a given electrode size are greatly affected by welding current, voltage and electrode extension. Increased current, other factors being equal, increases penetration and dilution as well as deposition rate. As a practical matter, because of the useful current ranges and effect of current density, the smaller diameter welding electrodes deposit metal faster than larger diameters. Voltage, or wire speed, should be adjusted to obtain a stable arc with minimum spatter; excessive voltages increase loss of carbon and other elements by vaporization. Travel should be such as to provide the deposit thickness desired, but avoiding excessive molten pool time.

A great advantage of the semiautomatic arc-welding processes is that the equipment may be transported to the work, rather than having to carry the work to a shop, as is usually the case with fully automatic equipment. Because of this feature, semiautomatic arc welding is greatly favored for maintenance, rebuilding and surfacing.

SURFACING BY AUTOMATIC ARC WELDING

This process uses machine control of the arc position and motor feed of the filler metal (usually wire drawn continuously from coils or drums) with electrical feedback to control arc length. The demands on the operator are only for set-up and correct operation of the controls. The method lends itself best to flat or symmetrical curved surfaces and large scale or repetitive work. Compared to the simple semiautomatic wire feed device, the equipment is heavy, not usually portable, and considerably more expensive. The significant savings are in manpower. Specialized units are available (e.g. machines for crusher roll rebuilding, track link surfacing, and tractor roller reclamation). Sometimes a special work positioner is needed in addition to the automatic machine.

Automation is possible with both types of gas shielded-arc welding—the gas tungsten-arc and the gas metal-arc processes—as well as the submerged arc process. The last is the most popular of these for surfacing. The power sources, process variables and techniques for submerged arc welding. are described in Chapter 24, Section 2 of this Handbook. Surfacing differs from other applications of this process chiefly in its focus on relatively thin, broad area deposits. For this reason the multiple arc variations of the process, (see Section 2, Chapter 24) and the other special adaptations to surfacing should receive consideration in planning for large scale overlays. With these variations it is possible to attain deposition rates up to 100 pounds of filler metal per hour of arc time.

Except for some use of coiled strip and solid electrodes for corrosion resistant alloy surfacing, (Fig. 44.5) and the feeding of granular alloy mixtures ahead of the arc ("bulk welding"), most submerged arc surfacing employs tubular electrodes.

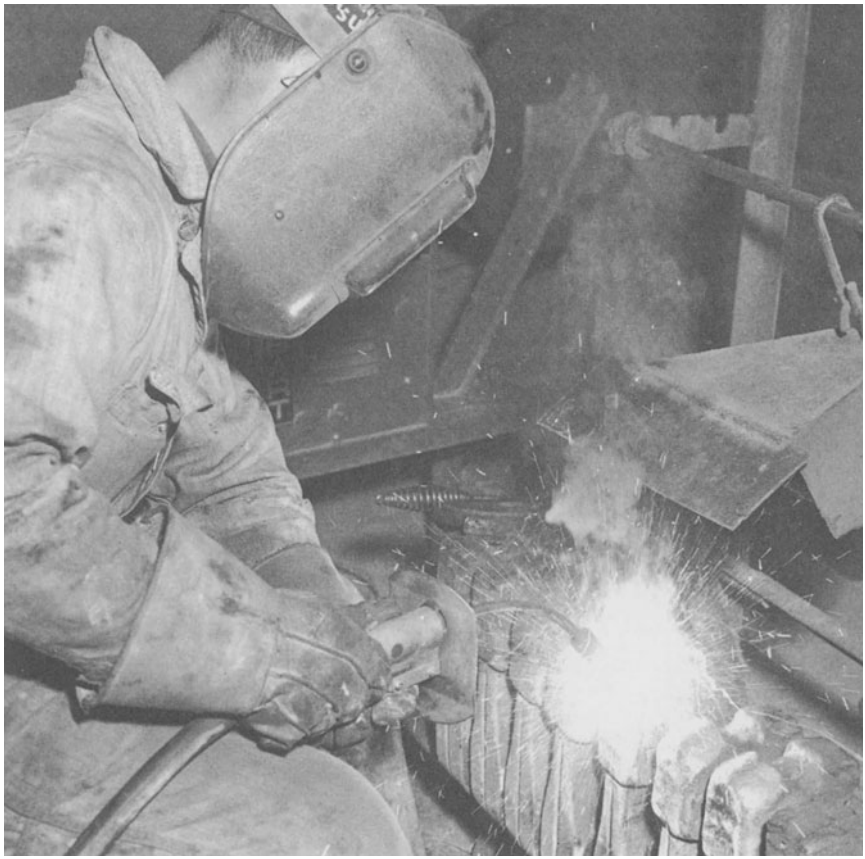


Fig. 44.4.—Semiautomatic surfacing of a row of pulverizing hammers, using a high-chromium iron overlay supplied as a composite tube electrode in coils.

SUBMERGED ARC SURFACING

For this method the electrode is a continuous wire, either solid or tubular, and the arc zone is protected by a blanket of granular flux. The electrode compositions are usually formulated to work with a specific flux grade. Because of its many advantages the submerged arc, single-electrode process is today the most widely used automated technique for hard facing. It utilizes high welding currents and has the advantage of very high deposition rates. A wide range of electrodes give good results, and they can usually be used with either direct or alternating current. Deposits characteristically are of high quality and with many filler metals are practically flawless. There is no spatter that might require cleaning, and the absence of the ultraviolet radiation of an exposed arc is advantageous in a shop. The process may be readily adapted to many applications that can utilize larger electrodes than used in the semiautomatic method. (See also Section 2, Chapter 24).

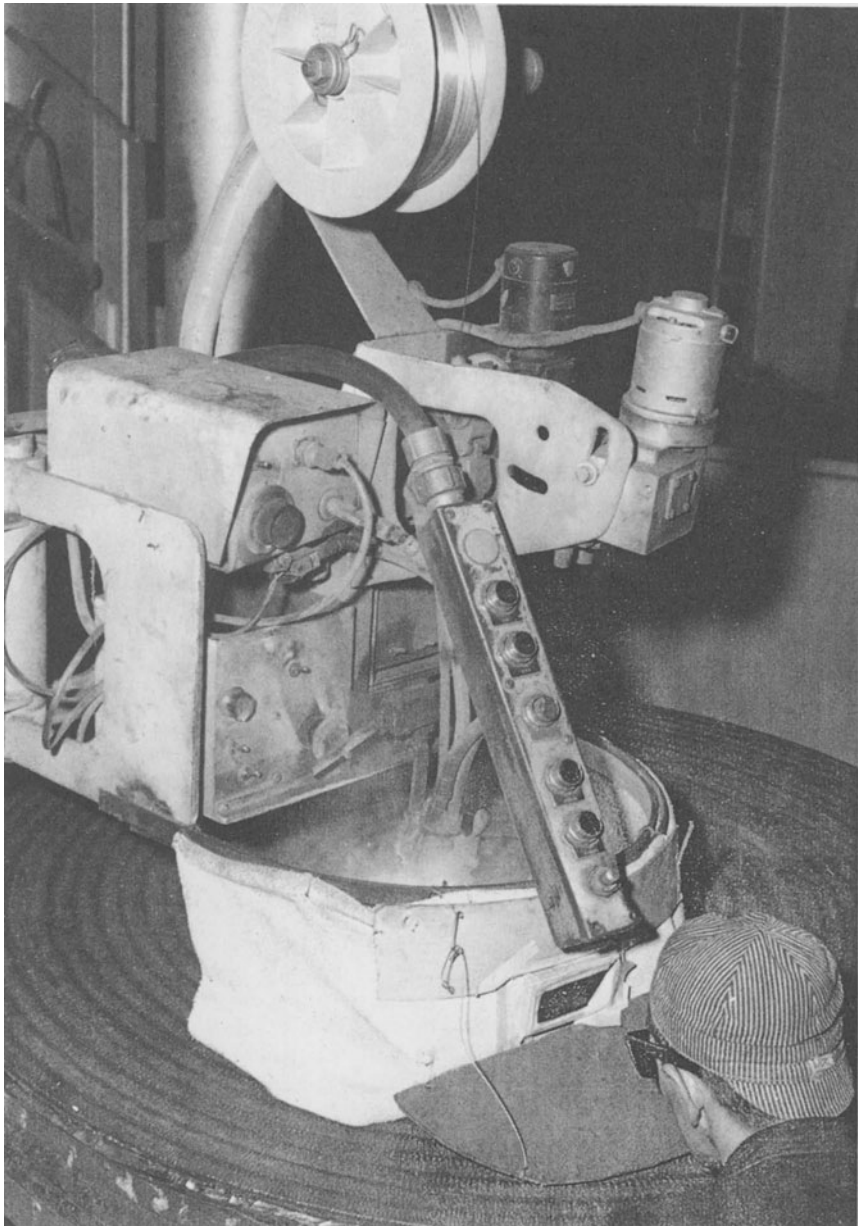


Fig. 44.5.—Heat exchanger tube sheet, a composite weldment made by overlaying mild steel with aluminum bronze (CuAl A-1) by means of automatic gas metal-arc welding.

The high quality of the deposit is advantageous for overlays requiring strength, toughness, or abrasion resistance. However, it should be realized that this method, with its relatively deep penetration and protective flux cover, puts more heat into the work piece than other arc welding processes. With the dilution that takes place and the gain or loss of different elements from the molten flux, full properties of the surfacing filler metal are ordinarily not attained until two or more layers are deposited.

Though quality in the sense of freedom from porosity and slag pockets is assured, the high thermal gradients may cause cracking. Crack avoidance may require preheating and postheating, usually with special equipment. With some surfacing deposits, such as the high carbon chromium irons, a fine pattern of surface cracking is normal on large parts and those subjected to high restraint. This behavior is characteristic of the brittle hard facing alloys, and is not always undesirable.

Those methods that feed extra filler metal to the arc zone make more efficient use of the heat of the arc, while increasing deposition rates and decreasing dilution from the base metal. The extra filler metal may be one or more wires or strips, the latter being used primarily for stainless steels and nickel-base alloys.

The "bulk process" is a variation that feeds powder onto the surface of the work ahead of the arc, after which the blanketing flux is added. The arc heat melts the granular filler metal mix as well as the electrode and the base metal all three of which combine to make the deposited metal. The powder filler metal is formulated for this admixture, based on a fixed set of welding conditions. Arc power, bead size, travel speed, electrode feed speed, and alloy powder metering must all be correct and carefully controlled if the intended composition is to be obtained. Weaving of the electrode during deposition may be used to reduce dilution by melting of the base metal. Expected advantages of the process are less expensive filler metal, high deposition rates, low penetration and little dilution from the base metal.

GAS TUNGSTEN-ARC SURFACING

This process employs a nonconsumable tungsten electrode shielded by argon or helium. A wrought, tubular or cast welding rod is fed into the arc area where heat for melting the filler metal is supplied by an arc between the tungsten electrode and the work. Fluxes are not used with this process. Though slower than other arc welding methods it provides overlays of excellent quality (see also Section 2, Chapter 23).

A common use is the semiautomatic application of cobalt-base alloys, which are available only in welding rod form and not as continuous wire. Weld quality is comparable to that obtained from oxyacetylene welding, but the carbon content of the deposit will tend to be lower, since no carburizing flame is involved. Dilution is somewhat greater, but much less than is ordinarily obtained with gas metal-arc welding. This method requires very little preheating and is faster than oxyacetylene surfacing. It results in less heat buildup, minimizes distortion, affects the base metal less and avoids the adverse effect of the oxyacetylene flame on some base metals.

In one variation of surfacing with gas tungsten-arc welding, hard facing filler metal in the form of granules rather than wire is fed into the arc area. As the base metal is melted by the tungsten arc, the granules (usually tungsten carbide) are embedded in the fused metal matrix. This method is frequently used for surfacing drill pipe joints. The carbide particles are essentially undissolved and well placed at the pipe surface.

GAS METAL-ARC SURFACING

This process as a type of automatic surfacing is basically like that described in Section 2, Chapter 23 of this handbook. The arc and the weld pool are shielded by a flow of inert gas from an external source. Alloying elements to produce the desired deposit analysis are contained in the electrode, which may be either solid or tubular. Shielding gases include helium, argon, and carbon dioxide, which may be used singly, in various mixtures, or with small amounts of oxygen. The type of shielding has some effect on deposit composition and other characteristics. (See also Section 2, Chapter 23).

The cost of gases and equipment for gas shielding add to the expense of surfacing. Open arc welding is entirely satisfactory for many hard facing overlays, largely because fluxing and deoxidizing materials are contained in the core of the tubular electrode. Where gas shielding is added, its effects should be clearly warranted.

The shielding gases used in this process prevent oxidation and alloy loss. Their use contributes to superior weld quality and makes feasible the deposition of some metals, such as the aluminum bronzes that cannot be applied by other semiautomatic or automatic methods. Some of the lower carbon and low alloys steels, particularly if available only as solid electrodes, without the benefit of internal fluxing ingredients, require gas shielding for good quality overlays. In some applications, shielding with carbon dioxide has been found to modify the arc and deposit characteristics in such a way as to make its use desirable even though not required for weld perfection. Variations of this process that have distinct characteristics include gas metal-arc auxiliary-wire and gas metal interrupted-arc methods.

The auxiliary wire modification feeds extra filler metal to workpiece potential into the weld puddle; the arc energy absorbed by melting it reduces penetration and dilution while the deposition rate is increased about 1½ times. By choosing an auxiliary filler metal differing in composition from that of the electrode, deposit modifications can be made. This method is likely to be favored over the high deposition submerged arc processes when suitable granular fluxes are not available for the alloy being deposited. A notable application of the gas metal-arc auxiliary wire process is artillery shell banding with gilding metal where dilution by base metal must be held to less than 3%.

Another modification features short circuiting metal transfer. Using quite small solid electrode, (steels being available in 0.030, 0.035 and 0.045 inch diameters) metal transfer occurs only while the arc is extinguished, which is at a steady rate of 20 to over 200 times per second. Deposition rates are slightly higher than with covered electrodes, while dilution and workpiece distortion are minimized. This modification is usually employed with semiautomatic equipment.

ATOMIC HYDROGEN SURFACING

This method uses the large amount of heat (about 200 btu per gram of hydrogen besides that of combustion) released at the work by the recombination of arc dissociated hydrogen. It is best used for surfacing where a heavy workpiece requires a small overlay without undercut and where very rapid localized heating is acceptable. A typical application is the surfacing, with composite tungsten carbide welding rods, of the teeth of rotary rock drill bit cutters used for oil wells. The teeth are so small that it is not practical to use shielded metal-arc welding.

As an alternate to welding with composite welding rods the tungsten carbide granules are sometimes applied directly. The base metal is painted with an adhesive, such as sodium silicate solution, and the granules are sprinkled onto this layer. After drying, the granules are fused in place.

The atomic-hydrogen welding process provides a low-velocity, soft arc which transfers the heat to the work with high efficiency. The welders may start applying the tungsten carbide after preheating for only two or three seconds. Preheating and surfacing are performed practically simultaneously because of the rapid transfer of heat. A considerably longer time is required when an oxyacetylene torch is used with a low-velocity tip of the proper size. Since the areas to be surfaced are small, the preheating is an important cost factor.

Although the danger of melting the tungsten carbide particles is greater with the atomic-hydrogen process than with oxyacetylene welding, the former process will provide equivalent wear resistance if reasonable care is taken. During the surfacing operation the welder can vary the distance between the tungsten electrodes, thus changing the size and character of the arc. The atomic-hydrogen deposit will often have superior appearance because of its surface smoothness. Other comparisons appear in Table 44.2.

THERMAL SPRAYING

This group of techniques, which includes metallizing, fused metallizing with self-fluxing alloys, manual oxyacetylene surfacing with powdered filler metal and plasma-arc spraying is mentioned with related subjects in this chapter and is extensively treated in Chapter 29 "Thermal Spraying" in Section 2 of the Welding Handbook. When the deposit is fused in place, it is one of the best methods of applying a thin, smooth, abrasion and corrosion resistant layer that accurately follows surface contours.

PLASMA-ARC POWDER SURFACING

Plasma-arc powder surfacing is a relatively new process adapted to the application of hard surfacing alloys. The ultra high temperature of the plasma flame, which may be in the 10,000 to 40,000°F range (5,555 to 22,222°C), and the use of various nonreactive combustion gases greatly extend the capabilities of deposition. Both transferred arcs, struck between the electrode and work piece, or non-transferred arcs are used for surfacing. While filler metal is supplied in powder form, the process differs from metallizing in that deposits are homogeneous and fused to the base metal.

Table 44.2—Comparison of surfacing methods for tungsten carbide composites

	Oxyacetylene	Atomic-Hydrogen	Shielded Metal-Arc	Open Arc	Submerged Arc
Cost of equipment	Low	High	Medium	Medium	High
Cost of operation (gas, electricity)*	High	Medium	Low	Very low	Low
Speed of application of composite carbide	Medium	Medium	High	Very high	High
Time required to start application (preheat time)	Long	Short	Very short	Very short	Very short
Surface of deposit	Smooth	Very smooth	Irregular	Irregular	Smooth
Percent particles dissolved	Low	Low	Medium to high**	Medium to high	Medium to high

*Depends upon local costs of electricity, acetylene, oxygen and hydrogen.
**An experienced operator can deposit tungsten carbide and obtain good particle distribution with minimum of particles lost by solution.

Properly fused plasma deposited layers are similar in metallurgical structure to gas tungsten-arc welded overlays. A number of cobalt, nickel, and iron-base alloys are available as homogeneous powders. Tungsten carbide particles may be added, under different conditions, to the alloy powders being applied or directly to the weld pool.

Plasma-arc powder surfacing is performed downhand when surfacing round or curved items. The arc is offset slightly ahead of the vertical centerline, as with other processes. Layers can be applied in a considerable range of thicknesses, with deposit thickness, dilution and deposition rate being interelated. These variables are to a considerable extent dependent upon the characteristics of the alloy being applied. While heat input into the base metal is low, compared to other welding processes, some distortion can be expected and must be considered. As with other surfacing methods, procedures to prevent cracking are generally determined by the properties of the alloy and the size of the part. Particular advantages of plasma-arc powder surfacing include: the ability to deposit a wide range of engineering materials, including refractories, suitability for surfacing lower melting point base materials, controlled application of very thin (as well as relatively thick) layers and close control over surface finish that helps to minimize grinding and machining. Normal deposition rates of 12 lbs. per hour are reported.

Equipment costs for the plasma process are relatively high and considerable exacting technology is involved.

The process is fully mechanized and particularly suited to high production hard facing of new parts. Applications include hard facing of flow control valve parts, tool joints, extruder screws and lawn mower components.

PLASMA-ARC HOT-WIRE SURFACING

This new fully mechanized process was designed for overlaying at high metal deposition rates and low dilution levels with filler metals available as continuous solid or tubular wire. Basically, it consists of two separate systems operating together in a single weld puddle. Two electrodes are heated to their melting point by resistance heating and continuously deposited beneath a plasma arc. Deposition rates are high and because of independent control

between the plasma arc and hot wires, control of penetration and dilution (generally less than 10%) is claimed to be exceptional. The process is finding application for overlaying pressure vessels and related components with stainless steel, nickel-base alloys and various bronzes. Equipment cost is high but for many applications considerably lower surfacing costs can result.

DETONATION SURFACING

This is a proprietary process which operates by controlled detonation of acetylene and oxygen in a special gun that shoots out a surfacing powder (usually tungsten carbide) at high velocity. Upon impingement on the work, fusion, volatilization, decomposition, flattening and splashing can occur simultaneously with alloying and phase changes. Useful applications have been surfacing of plug gages, chain saw guides, bearing seals, core rods for the powdered metals industry, tools, machine parts and precision aircraft parts subject to fretting corrosion. A salient advantage is lack of tempering or distortion of the base metal, which can be anything from soft aluminum to hardened tool steel. Coatings 5 to 10 mils thick are usual, and they generally wear better than chromium plate.

MAGNETIC FLUX WELDING

This process, which feeds flux and other ingredients as a jacket around a solid electrode, where it clings because of the magnetic field around the electrode, is largely obsolete except as an adjunct to gas metal-arc welding that is shielded with carbon dioxide gas. Semiautomatic welding with flux-cored tubular electrodes has displaced it.

THERMAL STRESSES

The success of an overlay application sometimes depends upon the magnitude of the internal stress pattern and whether the external stresses are shearing, tensile or compressive. Residual stresses from the welding operation may add to or oppose those of service, and thus accentuate or oppose the tendency to crack in use. Since overlays are not often stress-relieved, the residual thermal stresses, which result from hindered thermal expansion and contraction, may be formidable. Whether these stresses cause warping, cracking or other troubles depends largely on the strength and ductility of the overlay and the base.

Among the surfacing alloys, the austenitic steels are the toughest, with both high ductility and moderate strength in both tension and compression. The martensitic steels, though low in ductility, are high in both tensile and compressive strength. As weld deposits of these steels cool, they are likely to bend the softer and weaker base metals upon which they are deposited. The high carbon irons are strong in compression but apparently weak and brittle in tension. On a soft base metal, unless it is thin and yields readily, tensile strength is likely to be exceeded during cooling, with resultant cracks.

Blast furnace bell surfacing has emphasized the importance of thermal stresses and their effects. Both large and small bells are subjected to erosion or low stress sliding and scratching abrasion on the burden area. Recent changes in furnace practice have made better abrasion resistance imperative, which has led to hard facing. Among the best alloys for such wear resistance are the martensitic and high chromium irons. They are applied by continuous automatic arc welding over many square feet in the case of bells (Fig. 44.6). The base is thick and heavy and upon cooling the overlay is subjected to great restraint. The extensive network of cracks that follows is considered unacceptable by those who would not risk the possibility that the surface cracks might propagate through the tougher base. By sacrificing abrasion resistance for toughness and freedom from cracking, some overlays have been used that give no better wear resistance than the carbon steel upon which they are deposited. Though the problem can be defined and the several properties involved evaluated independently, the practical choice depends on certain opinions and judgement, and as a result the optimum compromise between wear resistance and toughness has not been clarified. The use of intermediate alloys is common, but their selection is still largely empirical and experimental. Were it not for thermal stresses the choice would be easy.

DILUTION AND CONTAMINATION

Welding with dissimilar alloys that mix in the weld pool involves a series of metallurgical problems that stem from changed compositions and possibly metallurgical structures. The hybrid composition in a given weld bead can be calculated from the ratio of the base metal melted to the entire weld bead volume. This ratio can be based on area measurements of an etched cross section. Sometimes estimates based on the expected behavior of the process are satisfactory, but critical applications, especially involving corrosion resistance, demand more exact knowledge and control of the deposit composition at the surface. Nonferrous filler metals with restricted iron content, for example, may be seriously contaminated if they are deposited on a steel base. Sometimes a buffer layer of a different alloy is needed between them to minimize contamination. Good engineering practice requires a knowledge of the effect of composition on corrosion resistance or other critical property, quantitative evaluation of the dilution or mixing pattern, and perhaps allowance for the cooling rate after welding and its effect on metallurgical changes.

As an approximation, the first layer of a manual arc weld will probably contain about 50% base and 50% filler metal. With care this might be restricted to 30% base and 70% filler. The second layer would then contain 25% to 10% of the base metal composition and the third layer 12% to 3%. Routine submerged arc welding and gas metal-arc welding can give similar dilution values. A series arc between two electrodes, or the feeding of additional cold filler metal to the weld pool, results in less heating of the base metal and a reduction of dilution to as low as 10%. With a short arc, gas metal-arc welding (dcsp) can limit dilution to as low as 5%. With all methods, weaving or oscillation of the electrode tends to reduce dilution. The shape of the weld bead and its location in successive layers can also influence dilution. Broad thick beads are preferable.

Gas tungsten-arc, modified gas metal-arc, and oxyacetylene welding are generally selected when minimum dilution rates are needed, as in some nonferrous surfacing on steel. The latter process can provide a good metallurgical bond with almost no metal dilution, if the overlay has the lower melting point, but carburization or decarburization may occur at this junction.

The user of corrosion resistant surfacing filler metals probably will need to make his own calculations and control of mixture compositions and dilution, but these factors are frequently compensated for in the design of hard surfacing electrodes for specific applications. Even so, the process and techniques (arc voltage, current, number of layers and bead contour) should conform as closely as possible to the design conditions and the recommendations of the electrode manufacturer.

A common error is to evaluate a hard surfacing filler metal as deposited on carbon steel, and then use it on a 13% manganese steel base metal without due consideration. If it is an air-hardening type that depends on transformation to martensite upon cooling, the pick-up of manganese from the base metal may so stabilize the austenite of the deposited weld metal that it does not harden normally. Instead, the use of multiple layers (not desirable with high carbon overlays) to minimize the manganese content at the surface, or electrodes formulated to allow for manganese pickup are advisable.

With stainless steel, dilution can sometimes be compensated for by selection of a more highly alloyed filler metal. Thus, if 18Cr-8Ni properties are needed on the surface, instead of E308 electrode the E309 (24Cr-12Ni) or E310 (26Cr-20Ni) electrodes may be employed.

SURFACING FOR CORROSION RESISTANCE

While both applications abound with technical considerations, there is a greater amount of accessible literature on corrosion resistance than there is for abrasion. There is also a larger number of obvious variables. Not only can a small difference in composition of an alloy or a corrosive environment be important, but also changes in the internal structure of an alloy can have a profound effect on corrosion behavior. "Weld decay" from the intergranular corrosion of stainless steels is an example. Environment may further complicate performance with mechanical factors as in stress corrosion. Therefore, the prospective user or designer of welded overlays for corrosion resistance should study the literature, and should review carefully the appropriate chapters in Section 4 of the Welding Handbook.

The factors of corrosion resistance, the effect of dilution, and the speed and cost of weld deposition should dominate the selection and application of surfacing against corrosion. Large areas are usually involved (as in lining big tanks), which demand the speed and economy of automatic welding. Manual welding is usually confined to localized repair of the surface or the joining of clad plates. Since multiple layers are more costly than one, a single layer de-

posit is desirable if dilution can be properly compensated by selection of a more highly alloyed electrode. However, composition control or avoidance of contamination may dictate multiple layers and perhaps a barrier layer next to the base metal. Most surfacing against corrosion employs stainless steel, nickel-base alloys, or copper-base alloys. There is some surfacing done with silver by gas tungsten-arc welding and with lead by atomic-hydrogen, oxy-hydrogen or oxyacetylene torches. With lead, special techniques are employed and potential toxicity should be considered.

Control of dilution is effected by the apparatus selected and by welding technique. Equipment designed for series-arc welding (with the arc between two electrodes rather than to the base metal), perhaps supplemented by a third "cold" filler metal wire, concentrates arc energy on melting the filler metal rather than the base metal. As low as 10% dilution is attainable, whereas 30-50% may be expected from single-electrode submerged arc welding, and deposition rates are higher. Similar dilution is also likely with gas metal-arc welding, but it can be reduced to 10% by an additional "cold" filler metal wire and by directing the arc at a portion of the preceding weld bead. Dilution is also curtailed by using the (dcrp) short arc technique. The gas tungsten-arc method is penalized by a low deposition rate, but dilution is well limited and there is the advantage that strips cut from wrought sheets can be used as filler metal. Sometimes this permits overlays that are not available in wire form. Another process exploits stainless steel strip as the filler metal for submerged arc welding, facilitating wide beads and high deposition rates. A modification using dual strips has been developed in the U.S.A., as shown in Figs. 44.7 and 44.8.

Technique should aim at wide flat weld beads as thick as are feasible, avoiding both feather edges (because of dilution and cracking tendency) and square edges that can trap slag. The beads should overlap to avoid gaps and areas of low alloy content. An oscillating welding head aids in making wide beads. Where dilution exceeds the tolerable level even with all precautions, or where contamination from the base impairs overlay properties, a barrier layer may be required. Highly alloyed filler metals are favored for these. For copper overlays a barrier of nickel, Inconel, or aluminum bronze can be suitable.

Corrosion can selectively attack small defects. Thus surface perfection is imperative. Avoidance of cracks, pinholes, and slag inclusions is much more important than in most abrasive service. Final inspection of the surface should not be neglected. This is usually done with a liquid penetrant method, since magnetic powder methods are not suited to the nonmagnetic austenitic alloys.

The austenitic stainless steels are frequently solution heat-treated and rapidly cooled to enhance their corrosion resistance. A heat treatment is more likely to be imposed for deposited overlays because of requirements such as those of the ASME Boiler and Pressure Vessel Code for the steel base metal. Stress-relief may also be a motivation for heat treatment. Temperatures appropriate for carbon and low alloy steels are not likely to affect the overlay adversely, but if the high alloy surface is to be stress-relieved there is need for caution. The required temperatures are higher, because of the greater hot strength of stainless steels and nickel base alloys. Heating in the range of 900 to 1600°F (482 to 871°C) may cause embrittlement by precipitation of either carbides or the sigma phase, and these are usually unfavorable for corrosion resistance.

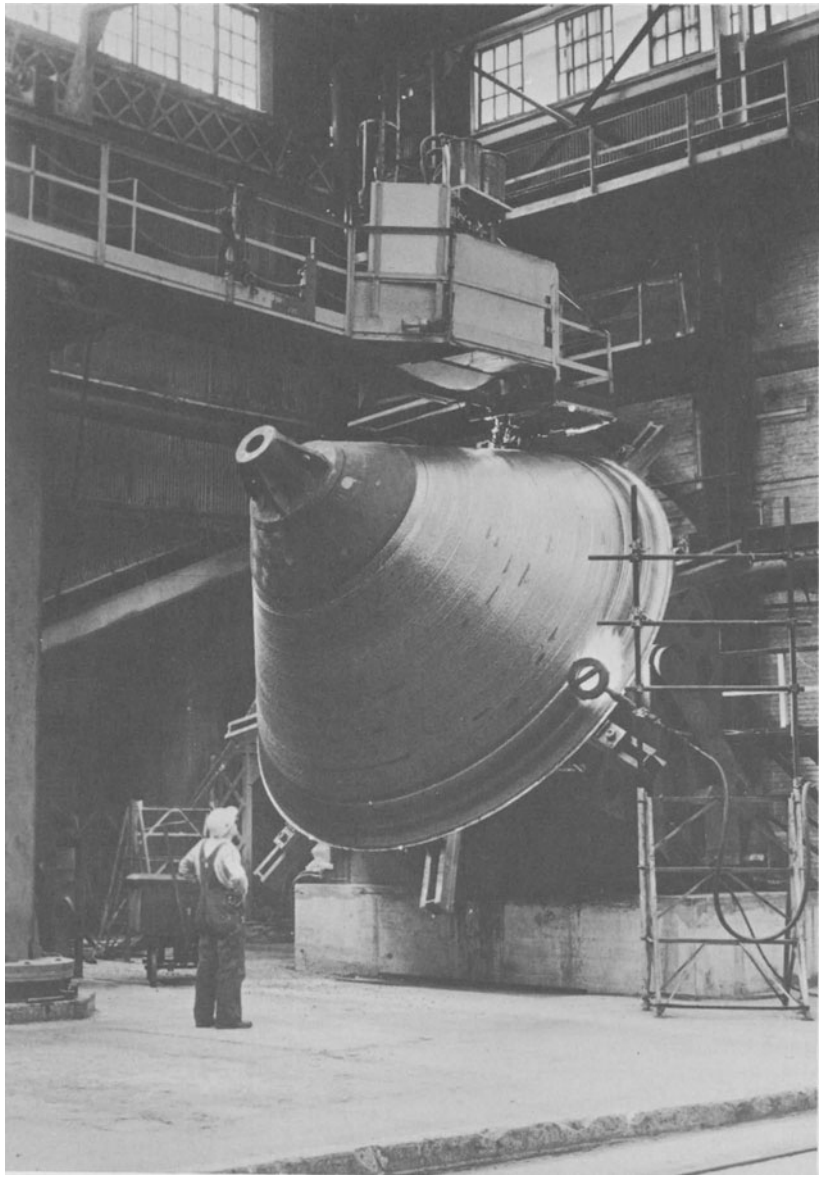


Fig. 44.6.—Automatic hardsurfacing of a large blast furnace bell. This was continuously preheated during welding and was stress-relieved after welding. The bell itself is a weldment consisting of a casting for the upper third and three formed pieces of 2¼ inch thick steel plate for the lower cone. The worn bell can also be returned to service after hardsurfacing again.

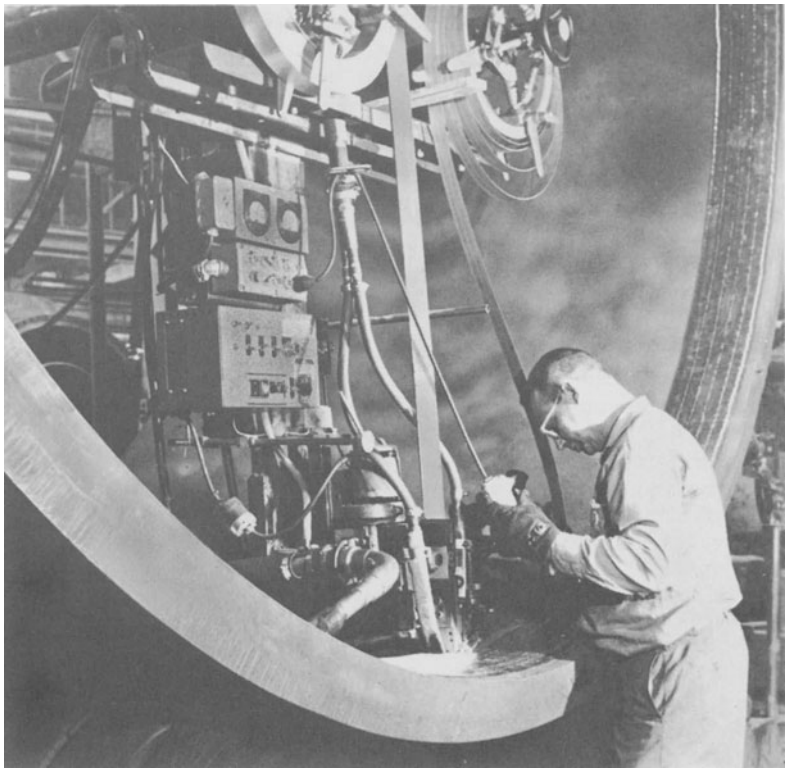


Fig. 44.7.—Surfacing of a low-alloy steel with a corrosion-resistant alloy by means of automatic welding. This modification of the process employs two auxiliary filler metal strips to increase deposition rates, make more efficient use of arc power and minimize dilution of the deposit by molten base metal.



Fig. 44.8.—The interior of this 5 inch thick Hydrocracking Pressure Vessel has been given corrosion resistance by means of an overlay of 18% Cr—8% Ni stainless steel applied by the dual strip automatic arc welding process.

The thermal history of weldments is likely to be more complex than that of a simple corrosion resistant part. Thus each aspect, from the reheating of successive weld beads to the influence of service temperatures, should be considered carefully. Conditions that lead to "weld decay" (See Chapters 65 and 66 in Section 4 of the Welding Handbook) are especially bad. Space permits only this warning note rather than specific instructions.

SURFACING FOR ABRASION RESISTANCE

Abrasion resistance is the original and the most important application of surfacing. Filler metals should be selected on the basis of a careful analysis of the conditions causing wear and their availability for the most economical welding method. The analysis is dominated by the factors of abrasion and impact, but heat and sometimes corrosion may also be present. Even fatigue may be involved. While there is usually a rough correlation between hardness and abrasion resistance, hardness is not a dependable index of merit. Neither is alloy content, which is sometimes used as a criterion. The best approach is to identify various factors, such as identity, character, hardness, sharpness and toughness of the abrasive, the levels of stress involved, the amount of associated impact, the kind of support provided to the overlay, the nature of the imposed stress (tensile, compressive or shear), the operating temperature, and any other apparently significant environmental conditions; and then compare surfacing alloys on the basis of their response to these factors under carefully controlled conditions.

The test data used for evaluation, whether from service or a laboratory, should be examined critically. The tests should have demonstrated reliability (or reproducibility), ranking ability, and a valid relation to service performance. The latter requires service tests that will meet the first two conditions, but unfortunately field tests that will do so are quite rare.

It is helpful to classify abrasion into three types that are recognizably different. Designated as (1) low stress scratching abrasion or erosion, (2) high stress grinding abrasion and (3) gouging abrasion, they may be exemplified by (1) sand sliding down a chute or a plowshare working in sandy soil, (2) action in a ball mill where abrasive ore fragments are crushed between metal faces, and (3) the gouging, grooving action on dipper teeth and gyratory crusher faces from sharp rocks. The corresponding machine shop operations are (1) polishing with loose abrasive on a soft cloth, (2) lapping and (3) metal removal by a cutting tool or a grinding wheel. These three conditions frequently rank abrasion resistant materials in the same order, but there are important exceptions and reversals of ranking.

Hardness is usually an asset under erosive conditions, especially when the microhardness of individual constituents of an alloy is evaluated. Tungsten carbide, the hard high-chromium irons, and the martensitic irons are excellent for resisting this kind of wear.

There are examples of grinding abrasion where relatively soft, but tough, alloys will outwear harder materials. Impact may also be present and to cope with the various combinations of wear and impact a group of alloys, ranging from tough austenitic manganese steel (including air hardening steels) to the martensitic irons, are currently used according to the application.

Gouging abrasion also may place a premium on toughness rather than hardness. Very high stresses and impact are likely to be involved and toughness to resist heavy impact may dominate the choice. Massive parts must be tough enough to resist fracture, and when their surfaces are protected with more abrasion resistant but brittle alloys, the design should be such that the overlay is adequately supported and stressed in compression rather than tension or shear. Under these conditions hard facing can provide impressive economies. Sometimes conditions are so severe that great toughness is imperative. In these cases austenitic manganese steel (see appropriate chapter in Section 4 of the Welding Handbook) is the preferred material and surfacing is a matter of replacing worn steel with suitable manganese steel filler metal sometimes supplemented with bars, plates, and special shapes of the same alloy.

SURFACING FOR IMPACT

Impact may be classified as light (where kinetic energy is absorbed and returned by elastic action), medium (where elastic action is largely operative but some plastic deformation is unavoidable), and heavy (where the strongest materials must either fracture or deform). This classification permits a logical selection of surfacing alloys: martensitic irons, martensitic steels, and austenitic manganese steel in the same order as the impact classification.

Certain austenitic irons are intermediate between martensitic irons and steels in toughness. Typical compositions contain about 15% chromium. They lack the high compressive yield strength of the martensitic irons, and thus are less suitable for light impact, but they are more resistant to thermal stress cracking and to moderate impact.

Some applications involve metal-to-metal wear with heavy impact as in steel mill machinery and railway trackwork. The base is often 13% manganese steel and surfacing is done to rebuild battered and depressed areas. For these applications a manganese steel filler metal with a relatively high yield strength is desirable.

Sometimes an overlay of manganese steel is deposited on a carbon steel base metal. This should be done cautiously as the fusion zone of mixed metals may become a hard, relatively brittle martensitic steel. However, some of these applications are quite successful.

BASE METALS FOR HARD FACING OVERLAYS

Frequently the base metals for hard surfaced parts are dictated by structural design or forming considerations. The weldability and suitability of such materials must be considered on an individual basis. However, there are many cases where the overlay properties are of chief concern and there is considerable latitude in base metal selection.

For a simple operation the best base metal selection is usually unalloyed carbon steel. The practical range extends from AISI — SAE 1020 up to 1095 (0.20% to 0.95% carbon), though welding difficulties increase with carbon content. A favorable base metal combining good weldability and strength after welding is 1045 steel, (Table 44.3). If the steel is clean and well killed, welding difficulties are minimized. The microstructure of 1045 steel usually consists of ferrite and pearlite.

The amount of pearlite can be increased by raising carbon content, and the pearlite itself made somewhat harder by a modest addition of alloys. The weldability of the base metal tends to suffer from these modifications. They should not be imposed unless their strengthening is needed.

If a very tough base is needed, austenitic manganese steel is probably the toughest available; it is surprisingly economical in the form of castings. Its nature should be understood by the welder, since embrittlement from careless procedure is possible, but it is weldable and provides a yield strength of about 55,000 psi. (Refer to Section 4, Chapter 66 for detailed information). Higher yield strength grades are also available. The contribution of manganese to the fusion zone must be considered because beads of filler metal next to the base metal may be rendered austenitic by manganese pick-up.

CLASSIFICATION OF SURFACING ALLOYS

The primary purpose of a classification system is to provide logical designations and a rational basis for selection of hard facing alloys. Well-defined types of alloys are desirable, and the engineering data associated with these types are important. Available hard facing information only partially meets this need. Composition and microscopic structure both have an important influence on the performance of the hard facing alloys. Neither, when used alone, provides a satisfactory basis for classification. Together they can provide a useful framework for the selection of wear-resistant alloys.

Nearly all of the generally available surfacing alloys have a base of iron, nickel, cobalt or copper. Compositions are detailed in various tables presented hereafter, and represent either the solid bare welding rod or an undiluted weld deposit.

Carbon is the most important auxiliary element, and further alloying with chromium, molybdenum, tungsten, manganese and silicon is common. Vanadium, nitrogen, titanium and other elements may be included.

Carbon in low percentages influences matrix hardness. Above 1% it forms hard carbides that increase brittleness and resistance to low-stress abrasion. Above 1.7% to 2.0% carbon the iron-base-alloys are cast irons. Many of the very abrasion-resistant alloys are in this group.

Alloying elements form hard carbides. In order of decreasing hardness they are: (1) titanium, (2) tungsten, (3) chromium, (4) molybdenum and (5) iron. High percentages of tungsten or chromium with 2 to 4% carbon form distinctive carbide crystals that are harder than quartz. Tungsten carbide for hard facing consists of a fused mixture of W_2C and WC, ranging from 3.0 to 4.0% carbon. It is the most abrasion-resistant constituent commonly employed for surfacing. Chromium carbide is usually the Cr_7C_3 compound found in high-chromium (20 to 30%) irons. It is softer and more brittle than tungsten carbide but less expensive and better adapted to fine dispersion. Iron carbide (Fe_3C), or cementite, is present in many hard facing alloys. It is usually modified by the presence, in moderate percentages, of Cr, Mo or W as alloying elements. At higher levels these elements produce double carbides, such as $(Fe,W)_6C$, $(Fe,Mo)_6C$, and related complex compounds containing chromium such as those that may be found in high speed steel.

Carbide-forming elements also contribute to matrix properties. Tungsten, molybdenum, vanadium and chromium confer high-temperature strength and secondary hardening in the 900 to 1200°F (480 to 650°C) range. Chromium makes a unique contribution to oxidation and scaling resistance. A 25% chromium content provides effective protection up to 2000°F (1090°C). The presence of vanadium is undesirable at high temperatures, since its low-melting oxide acts as a flux by removing protective scales.

Desired hot strength may be obtained by the selection of iron, nickel or cobalt as the alloy base. The cobalt-base alloys protected with 25-30% chromium and strengthened with 5-15% tungsten are highest in hot-hardness and creep resistance above 1200°F (650°C). The abrasion resistance of this group depends on carbon content. Nickel, cobalt and chromium confer corrosion resistance and also promote oxidation resistance. Nickel is approximately one-third as effective as chromium. The nickel-chromium alloys containing boron also have high hot hardness.

The matrix of iron-base alloys can exhibit a wide range in properties. Low-carbon steels with a ferrite matrix are of little use in surfacing. As the carbon increases towards 0.8%, the weld deposit becomes more pearlitic and harder (up to approximately 400BHN). Pearlite forms near 900 to 1200°F (480 to 650°C) as the weld deposit cools from the higher temperatures where the matrix is austenitic. Alloy additions in small quantities make pearlite finer, harder and slower to form. Larger alloy additions prevent pearlite formation entirely, whereupon transformation may occur below 900°F (480°C), forming the harder structures of bainite or martensite. Even larger alloy percentages (12% manganese or 18% Cr + 8% No for example) will prevent transformation entirely and confer an austenitic matrix at ordinary temperatures.

Table 44.3—Properties of AISI-SAE 1045 steel*

	Yield Strength, Psi	Ultimate Strength, Psi	Elong. in 2 In., %	Red. Area, %	Hardness		Heat Treatment, ° F, Quench
					RC	BHN	
Natural hot rolled	48,500	90,000	19	42	9	180	...
Cold drawn	87,000	105,000	14	40	14	207	...
Quenched and drawn at 1000° F	71,000	106,000	22	52	18	220	1500 (820°C) —water
As-rolled, at 0.4% C	56,000	95,000	25	51	..	...	...
As-rolled, at 0.5% C	60,000	101.000	22	43	..	...	...
Normalized, at 0.4% C	58,000	94,000	27	53	..	...	...
Normalized, at 0.5% C	62,000	100,000	23	46	..	...	...
Annealed, at 0.4% C	52,000	86,000	28	55	..	...	...
Annealed, at 0.5% C	54,000	92,000	26	54	..	...	...

* 1½ in. dia round stock, water quenched from 1500° F.(820°C).

The matrix of the nickel or cobalt base alloys is generally of the austenitic type. The hardness of these alloys depends largely on the amount and size of the carbides or other compounds that are dispersed in the matrix.

The properties and the rational selection of surfacing alloys thus depend on a knowledge of both composition and microstructure.

Martensite is the hardest and strongest matrix constituent. It is characteristic of tool steel that has been quenched from red heat. In weld deposits it occurs upon normal cooling if the alloy content is properly balanced. Martensitic steels for surfacing applications depend on such a balance and on a carbon content from 0.25-1.5 percent. The lower carbon martensites are tougher while the higher carbon grades are more abrasion resistant. Martensite has a high yield strength, making it desirable for resisting light and medium impact.

The properties of bainite fall between those of martensite and pearlite. It is less likely to occur in surfacing deposits, and thus is not included in the classification.

Pearlite is moderately hard and tough. Low alloy steels with from 0.4-0.9% carbon are pearlitic steels when air cooled from welding heat, whereas they may form martensite if quenched. They are the least expensive of the hard surfacing alloys.

Whether a weld deposit of alloy steel is martensitic, austenitic or a mixture of these structures depends on alloy content, carbon level and weld cooling rates. Precise compositions associated with sharply defined properties and well-described cooling rates are rare in hard facing unless the alloy grade has seen considerable development as a tool steel or a structural type. The more vague descriptions of "air hardening", "semiaustenitic" and "work hardening" are common for surfacing steels. This entire group is popular because it includes good combinations of toughness and abrasion resistance at relatively low cost. These alloys serve a large percentage of the hard surfacing market.

Austenite is soft, strong and tough. It has a remarkable capacity to work harden as it is deformed. The air hardening steels usually contain at least a small percentage of austenite, and as alloy content rises the austenitic proportion also increases, until at high alloy levels the steel may become entirely austenitic.

Wholly austenitic steels usually depend on high manganese or chromium and nickel content. They have low or moderate yield strengths, and thus may deform under medium impact, but their great toughness makes them excellent for heavy impact applications. Because of their stability above 1400°F (760°C), the Cr-Ni grades are preferred for elevated temperature service.

Ferrite is soft and weak (e.g., soft, pure iron) and is avoided in hard surfacing by using sufficient carbon to produce the harder structures previously listed. Ferritic steels are used as a base for hard surfacing rather than as overlays.

Carbide as a matrix is possible in the cast iron range. Some martensitic irons (e.g., 3.0C, 4.5 Ni, 1.5Cr) have a matrix of cementite containing islands of martensite. Such alloys have high compressive strength, good resistance to light impact and good abrasion resistance.

The high chromium irons may be martensitic, or reverse the pattern and exhibit spine-like crystals of Cr_7C_3 in a matrix of either martensite or austenite, depending on alloy content and cooling rate. The high carbon (e.g., 2.5%) Cr-Co-W alloys have structures similar to the austenitic high chromium irons, but are complicated with additional hard compounds. Except for the high chromium alloys the austenitic irons are usually of the carbide matrix type. The carbide matrix may be prominent and extensive, or it may diminish to a network, depending on carbon content. It confers resistance to low stress abrasion, but not to high stress crushing or grinding conditions. Weld deposits of the austenitic irons are brittle because of the carbide network, but are less prone to cracking from weld cooling conditions than the martensitic irons.

Most hard facing is intended to improve wear resistance that usually involves both abrasion and impact. Table 44.4 may be used as a guide with regard to these factors. The general trend from maximum abrasion resistance for tungsten carbide at one extreme to maximum impact resistance for manganese steel at the other is approximately valid for the iron base alloys. The nonferrous alloys have important exceptions.

Definite chemical compositions are needed to supplement the general data in Table 44.4. There are six broad types currently covered by AWS Specification A 5.13 — *Surfacing Welding Rods and Electrodes* that can be described as follows:

(1) high-speed steels (Fe5)
(2) austenitic manganese steels (FeMn)
(3) chromium-cobalt-tungsten or cobalt-base alloys (CoCr)
(4) copper-base alloys (CuZn, CuSi, and CuAl)
(5) austenitic high-chromium irons (FeCr)
(6) nickel-chromium-boron alloys (NiCr)

Table 44.4—Classification of surfacing alloys

Classification by Basic Types	Important Features	Successful Applications
Tungsten carbide deposits	Maximum abrasion resistance	Oil well rock drill bits and tool joints
Granules or inserts		A wide range of severely abrasive conditions
Coarse granule tube rods	Worn surfaces become rough	
Fine granule tube rods	Best performance when gas welded	
High chromium irons	Excellent erosion resistance	
Multiple alloy type	Hot hardness from 800-1200°F (410-650°C) with W & Mo	Abrasion by hot coke
Martensitic type	Can be annealed and rehardened	Erosion by (1000°F) (510°C) catalysts in refineries
Austenitic type	Oxidation resistant	Agricultural equipment in sandy soil
Martensitic alloy irons	Excellent abrasion resistance	General abrasive conditions with light impact
Chromium-tungsten type	High compressive strength	Machine parts subject to repetitive metal-to-metal wear and impact
Chromium-molybdenum type	Good for light impact	
Nickel-chromium type		
Austenitic alloy irons	More crack-resistant than martensitic irons	General erosion conditions with light impact
Chromium-molybdenum type		
Nickel-chromium types		
Chromium-cobalt-tungsten alloys	Hot strength and creep resistance	
High carbon (2.5%) type	Brittle and abrasion-resistant	Hot wear and abrasions above 1200°F (650°C)
Medium carbon (1.4%) type		
Low carbon (1.0%) type	Tough and oxidation-resistant	Exhaust valves of gasoline engines. Valve trim of steam turbines
Nickel base alloys	Good hot hardness and erosion resistance	
Nickel-chromium-boron type		Oil well slush pumps
Nickel-chromium-molybdenum-tungsten type	Corrosion resistance	
Nickel-chromium-molybdenum type	Resistant to exhaust gas erosion	Exhaust valves of trucks, buses and aircraft
Nickel-chromium type	Oxidation resistant	
Copper base alloys	Anti-seizing; resistant to frictional wear	Bearing surfaces
Martensitic steels		General abrasive conditions with medium impact
High carbon (0.65–1.7%) type	Fair abrasion resistance	
Medium carbon (0.30–0.65%) type	Good resistance to medium impact	Hot working dies
Low carbon (below 0.30%) type	Tough, economical	
Semi-austenitic steels	Tough, crack resistant	General low-cost hard facing
Pearlitic steels	Crack resistant and low in cost	Base for surfacing or a build-up to restore dimensions
Low alloy steel	Suitable for build-up of worn areas	
Simple carbon steel	A good base for hard facing	
Austenitic steels	Tough; excellent for heavy impact	General metal-to-metal wear under heavy impact
13% manganese—1% molybdenum type	Fair abrasion and erosion resistance	Railway trackwork
13% manganese—3% nickel type	Lower yield strength	
13% manganese-nickel-chromium type	High yield strength for austenitic types	
High carbon nickel-chromium stainless type	Oxidation and hot wear resistant	Frictional wear at red heat; furnace parts
Low carbon nickel-chromium stainless type	Oxidation and corrosion resistance	Corrosion resistant surfacing of large tanks

Subdivisions within the specification define some 45 grades of surfacing welding rods and electrodes. In the tables of this specification they are listed with their AWS designations, together with composition ranges. The nominal compositions of other grades not yet covered by specifications are also listed. No attempt has been made to include all known surfacing alloys as many are not standardized and engineering data are scarce.

The AWS classification system attempts to feature the important elements and thus facilitate quick identification. Designations such as RCoCr-A and EcoCr-C symbolize high-chromium cobalt-base alloys. The prefixes "R" and "E" denote welding rods and welding electrodes, respectively. The suffixes serve to identify classifications within a basic group. Further subdivision is possible by adding the number 1, 2, etc. after the suffix, such as ECuA1-A2.

In the following sections the important types outlined in Table 44.4 will be characterized in more detail.

Table 44.5—Comparison of sintered and cast tungsten carbides

	Cast Types		Sintered Carbides
	Straight Carbide	Alloy Type	
Composition	W + 4% C	W + 4% C + 5 to 15% cobalt	Powdered WC bonded with cobalt
Toughness	Brittle	Not as brittle as straight carbide	Low cobalt—brittle High cobalt—tougher than cast types
Scratch hardness	High	Medium	High
Resistance to oxidation at 1000° F	Poor	Good	Good
Resistance to solution in molten iron	Very Good	Good	Poor

COMPOSITE TUNGSTEN CARBIDE

Sintered carbide-tipped metal cutting tools illustrate one method of hard facing. The hard tip is a product of powder metallurgy that is brazed in place on a steel tool. While cast inserts or sintered shapes and blanks (like tool tips) are frequently brazed or welded in place, the usual hard facing consists of a composite deposit of sized WC-W_2C granules submerged and anchored in an iron-base alloy. (See Table 44.5). It is achieved by melting a steel tube containing the granules. The resulting matrix is a tungsten iron or steel. Occasionally a Cr-Co-W alloy is used as the matrix.

Tungsten carbide composites, in tube form, generally contain 60% tungsten carbide and 40% steel tube, by weight. The tungsten carbide contains 3.5 to 4.0% carbon, and is sized from about 8-10 mesh down to −100 mesh (per inch). It is usually a cast and crushed product consisting of a mixture of WC

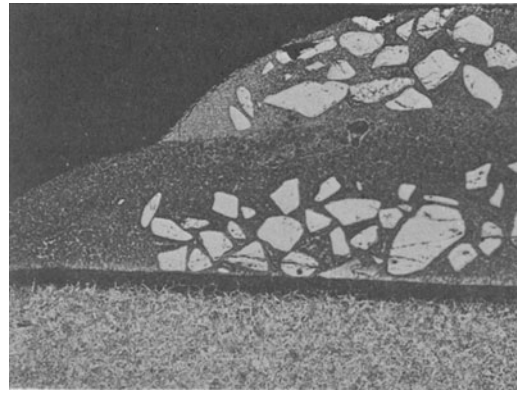
and W_2C, as contrasted with the metal bonded WC that is made by powder metallurgy methods for cutting-tool tips. The cast WC-W_2C alloy has better abrasion resistance than the sintered cobalt bonded WC product unless the cobalt content of the latter is quite low. Table 44.5 contains a comparison of sintered and cast tungsten carbide. Tubular products are available with several different sizes of granules, described in terms of standardized sieves. Sizes range from about 8-10 mesh down to below 100 mesh.

The melting point of the WC-W_2C alloy, containing about 3.8% carbon, is near 4700°F (2610°C). As a result this alloy can go unchanged through some welding operations. It is the toughest of the straight carbides. The melting point is lowered and toughness may be increased by including cobalt in the melt. The hardness of the 3.8% C granules is near 2500 VPN, while the matrix is like hardened tool steel. Its hardness usually ranges upward to Rockwell C-65, depending on application method and technique. The hardness of quartz and the hard silicates, which account for most abrasion, is between these. Thus abrasive wear tends to selectively cut the matrix and permit the granules to stand in relief. This is a disadvantage if a smooth wearing surface is required, or an advantage if cutting action is needed.

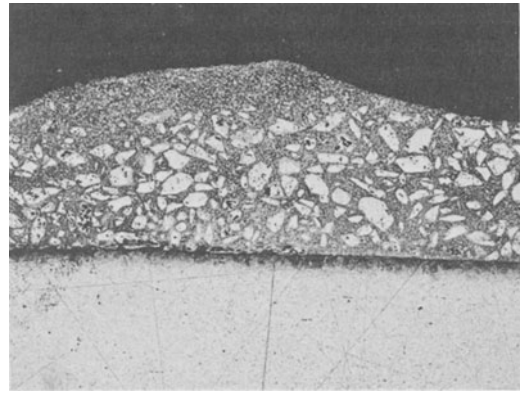
Oxyacetylene and atomic-hydrogen welding are preferred for such critical applications as oil well drilling bits. The former process can add carbon to the matrix, supplementing the tungsten and carbon contributed by moderate solution of the granules. Such weld deposits have higher abrasion resistance than any other type of hard facing.

Welding operations can have a pronounced effect on weld deposit properties, since the matrix composition depends on the amount of carbide granules dissolved during welding. Arc welding tends to dissolve the tungsten carbide more readily and in an extreme case, with very fine granules, may dissolve them all (Fig. 44.9C). Such a matrix, though hard, is inferior to the composite that contains a good volume of granules anchored in a hard, strong matrix (Fig. 44.9 A & B). Fusion with the base metal and consequent weld dilution is also associated with arc welding. Satisfactory arc welds can be made, but it is desirable that the welder understand what occurs during fusion and minimize puddling time if optimum results are to be obtained. Because of its lower cost, arc welding is generally used for the hard facing of earth handling and digging equipment.

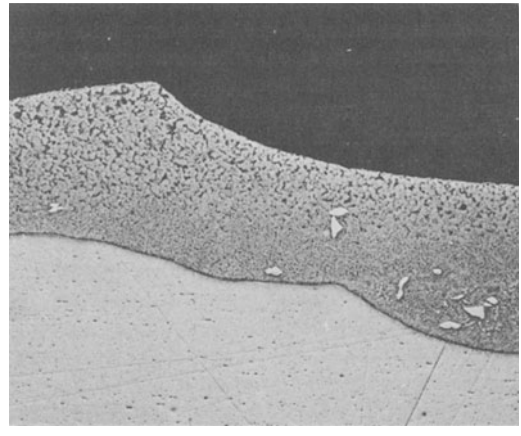
The hot hardness of deposits depends chiefly on matrix composition. As arc welding dissolves more tungsten in the matrix, higher hot hardness results. However, temperatures above 1200°F (650°C) are not advisable since the granules oxidize readily. The iron base matrix is neither oxidation nor corrosion resistant. It is brittle, but can withstand light and sometimes medium impact if the base metal is sufficiently strong. Heavy impact should be avoided. The tungsten carbide granules render deposits unmachinable and difficult to grind.



(A) Gas weld from a welding rod containing 100% of the granules sized 30/40 mesh. The heavy carbide granules sink to the bottom of the molten pool, dissolving only enough to provide a hard supporting matrix (10X)



(B) Gas weld from a welding rod containing 100% of the granules sized 40/120 mesh. Here also the solution of the carbide by molten steel has been moderate and beneficial (10X)



C) Arc weld from an electrode containing 100% of the granules sized 0/120 mesh. The high arc temperatures have caused most of the carbide granules to dissolve and abrasion resistance is thereby reduced (10X)

Fig. 44.9.—Variation in distribution and abundance of tungsten carbide granules in composite hard surfacing overlays.

HIGH CHROMIUM IRONS

The common feature of these alloys is the presence of spine-like crystals of Cr_7C_3. (Fig. 44.10). This carbide has a hardness of approximately 1700 VPN and confers excellent resistance to erosion by quartz and hard silicates. It is brittle and must receive matrix support. Soft austenite is not strong enough to provide adequate support if the stress applied through the abrasive is high. However, these carbides contribute outstanding resistance to low-stress erosion or scratching abrasion even with an austenitic matrix. If the matrix is hardened, the range of abrasive conditions for which these irons are good is broadened.

Table 44.6 lists compositions of some high chromium-iron filler metals. There are a number of high-carbon iron base alloys containing from 18 to 30% chromium. The most common alloys fall in three groups: (1) the austenitic types, such as the EFeCr and RFeCr grades; (2) the heat-treatable (martensitic) grades; and (3) the molybdenum and tungsten alloyed modifications. These are listed in order of increasing resistance to high stress abrasion. The 2.5C-26Cr grade requires a simple heat treatment to develop its best properties. When air cooled from 2000°F (1090°C) this alloy develops a martensitic matrix and combines the virtues of the high-chromium and martensitic irons. It is an important alloy for casting as well as for hard facing.

The austenitic high-chromium irons (see AWS Specification A5.13 — Appendix, A1.4) are usually high in carbon, which confers a wide plastic range during solidification. This aids in shaping the deposit by hot "wiping" or "striking." These alloys serve best and are economical for applications involving low stress abrasion and low stress metal-to-metal wear. They are brittle and crack readily from thermal stresses either from weld contraction or cyclic temperature service. An important use is to protect agricultural equipment working in sandy soil. Heat treatment of weld deposits is not appropriate; the austenite is too well stabilized to permit hardening transformations.

The hardenable 26% Cr type is lower in carbon (2.5-3.0%), and when deposited is tougher than the austenitic high-chromium irons. The usual deposit is austenitic, excellent against low stress abrasion and oxidation, but mediocre against high stress abrasion. It has a sharper melting point and is more fluid in gas welding than the RFeCr types, and has the added virtue that it may be softened by annealing (12 to 24 hr at 14-1450°F, 760-790°C). Some simple machining operations are possible after annealing and it can subsequently be rehardened.

Additions of tungsten, molybdenum or vanadium increase the hot hardness of these alloys and may add to abrasion resistance. Alloy balance and carbon content are critical.

Hot hardness holds up well below 800°F (430°C). Above this temperature it falls rapidly unless aided through the secondary hardening conferred by molybdenum or tungsten, which is most effective between 800 and 1200°F (430-650°C). (See Table 44.7). Oxidation resistance is good as a result of the chromium content.

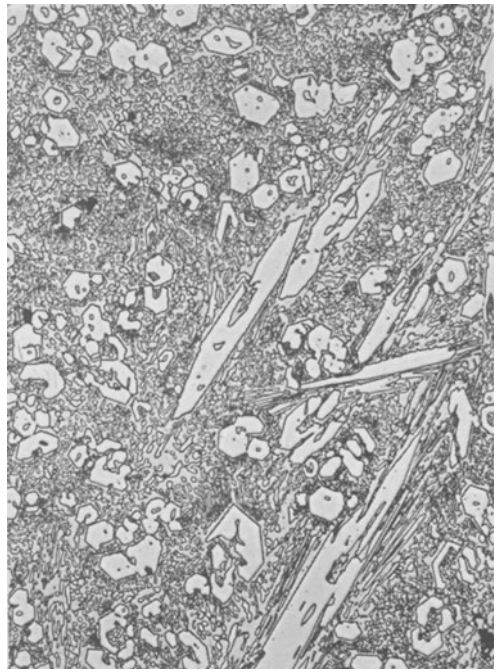


Fig. 44.10.—Gas weld deposit from RFeCr-A1 austenitic high chromium iron welding rod. The overall hardness is about 530 BHN but the crystals of chromium carbide, Cr_7C_3, have a hardness of about 1750 VPN and are very resistant to erosion (100X).

MARTENSITIC IRONS

The alloys of this group are composed basically of iron and carbon. Incidental elements such as manganese, silicon and minor tramp elements, as well as alloying elements, are present. Alloying elements, such as chromium, nickel and tungsten, control the structural constituents (chiefly martensite and carbides) which form during cooling after weld deposition. They must be carefully balanced to produce the desired structures.

Ordinary cast iron is a mixture of steel (which usually is ferritic or pearlitic) and iron carbide, or steel and graphite. The former (white cast iron) is brittle, hard (about 450 BHN) and has good resistance to some types of abrasion, though high stress abrasion wears it rapidly. The latter (gray cast iron) is soft, machinable, and while it does well in metal-to-metal friction, it has low resistance to severe abrasion.

Martensitic irons are characterized by the steel portion of the structure in the form of martensite, or martensite associated with untransformed austenite. The matrix of the structure is carbide. This carbide, which contains a portion

Table 44.6—Compositions of high chromium iron-base surfacing filler metals

Grade	C.%	Mn.%	Si.%	Cr.%	Mo.%	Ni.%	W%	V%	Co%
Austenitic Types									
R FeCr A1*	3.7-5.0	4.0-8.0	1.0-2.5	27-32	...	...	...	...	...
R FeCr A2*	3.7-5.0	1.0 max	0.5-2.0	27-32	...	2.5-4.5	...	...	...
E FeCr A1*	3.0-5.0	4.0-8.0	1.0-2.5	26-32	...	...	...	...	...
E FeCr A2*	3.0-5.0 4.5	1.0 max 6.0	0.5-2.0 1.5	26-32 30	...	2.5-4.5	...	...	...
Martensitic Types									
Annealable grade	2.5	1.0	0.7	26	...	...	...	...	...
Rods	4.0	1.5	2.0	30	...	...	...	...	...
Electrodes	4.5	1.0	2.0	30	...	...	...	...	...
Multiple Alloy Types									
Cr-Ni-Mo	1.8	1.0	1.5	30	1.5	3.0	...	...	...
Cr-Mo-Co-V	3.0	...	...	17	16	...	...	1.9	6.3
Cr-Mo	3.1	1.0	1.0	28	3.5	...	...	...	...
Cr-Mo	3.5	1.2	0.8	31	1.0	...	...	...	...
Cr-Mo	4.5	1.0	1.0	27	3.5	...	...	...	...
Cr-Mo	4.5	2.0	3.0	26	1.0	...	...	...	...
Cr-Mo-W-V	4.5	0.3	0.9	21	6	...	2	0.7	...
Cr-Mo-W	6.0	0.5	1.5	22	7	...	5	...	...

*All other elements except iron limited to a maximum total of 1.0% included in AWS Specification A5.13. The other 13 grades have not been standardized by AWS.

of the alloying elements, it about 1200-1400 VPN. The martensitic areas may be 400-700 VPN. The average hardness of the composite structure, as determined by conventional hardness tests, may range from 500 to 750 BHN or RC-50 to 66.

The high chromium irons that have a martensitic matrix might be included here, but are grouped separately because the Cr_7C_3 crystals formed are distinctive, rather than a carbide matrix.

Table 44.8 lists the compositions of typical martensitic iron filler metals.

The structure and properties of the hard facing deposit can be modified by welding methods and cooling rates. Gas welding with the recommended reducing flame, which has a feather 2 to 3 times as long as the inner cone, tends to add carbon to the deposit, increasing brittleness and hardness. Arc welding, however, tends to burn out carbon, increases dilution with the base metal, and may produce tougher but less wear-resistant deposits unless the electrode composition is formulated to compensate for this.

A cross section through a chromium-molybdenum martensitic iron gas weld deposit shows that advantage is taken of carbon diffusion in surfacing by carburizing the steel surface with the torch until a thin layer of iron reaches the eutectic composition and melts at 2000-2100°F (1090-1150°C). The appearance of this layer, which glistens when it melts, is termed "sweating" and signals to the welder that the overlay can be readily flowed and bonded onto the heated surface.

Table 44.7—Properties of high-chromium hard facing alloys

	Nominal Chemical Composition							
	Austenitic Type				Hardenable Type			
	C, %	Mn, %	Si, %	Cr, %	C, %	Mn, %	Si, %	Cr, %
	4.5	6	2	30	2.5	1	1	28
	Oxy-Acet. Gas Welds	Small Castings	Electric Arc Welds		Oxy-Acet. Gas Welds	Small Castings	Electric Arc Welds	
Hardness-Rockwell: as-welded or as cast at:								
70°F (20°C)	C56	C56	...		C55	C56	...	
600°F (320°C)	C55	C50	...		...	...	...	
800°F (430°C)	C48	C47	...		...	...	...	
1000°F (540°C)	C40	C36	C37		...	...	...	
1200°F (650°C)	C25	...	C 6		...	...	...	
Annealed at 1400°F (760°C), 70°F (20°C)	...	...	...		C42	...	...	
Hardened from 1950°F (1070°C) at:								
70°F (20°C)	...	...	...		C59	C65	C60	
800°F (430°C)	...	...	...		...	C54	...	
1000°F (540°C)	...	...	...		...	C48	...	
1200°F (650°C)	...	...	...		...	C 5	...	
Resistance to flow under repeated impact	(Good)				(Excellent)		(Good)	
Resistance to cracking under repeated impact	(Low)				(Fair)			
Tensile toughness	(Low)				(Low)			
Average compression properties								
Yield strength, psi	(72,500)				(145,000*)			
Ultimate strength, psi	(260,000)				(404,000*)			
Elastic deformation, %	(0.9)				(1.2*)			
Plastic deformation, %	(2.2)				(2.5*)			
Resistance to wet quartz sand grinding abrasion (high stress)	Fair				Excellent*		Good*	
Resistance to dry quartz sand scratching abrasion (low stress)	Outstanding		Good		Outstanding		Good	
Oxidation resistance Useful up to:	1800-2000°F (980-1090°C) Excellent				1800-2000°F (980-1090°C) Excellent			
Thermal expansion coefficient								
70°F to 1500°F (20°C to 820°C)	0.0000103 in./in./°F				0.0000081 in./in./°F			
1700°F to 2000°F (930°C to 1090°C)	0.0000138 in./in./°F				0.0000143 in./in./°F			

* Hardened by air cooling from 2 hr at 2000°F (1090°C).

Table 44.8—Composition of Martensitic Iron Surfacing Filler Metals*

Grade	0%	Mn%	Si%	Ni%	Cr%	Mo%	W%	Fe%
CrMoW	3.0	1.0 max	1.0	—	8	2	15	Bal.
CrMo	3.5	1.0 max	1.0	2.0 max	4	4	—	Bal.
CrMo	4.0	1.0 max	1.0	—	8	2	—	Bal.
CrMo "15-3"	3.5	0.7	1.0 max	—	15	3	—	Bal.**
NiCr	3.5	1.0 max	1.0	4.5	1.5	—	—	Bal.

* These have not been standardized by AWS action.
** Martensitic structure developed by air cooling from 1750°F (950°C). Stress relief at 400-500°F (200-260°C) after hardening is advisable to increase toughness.

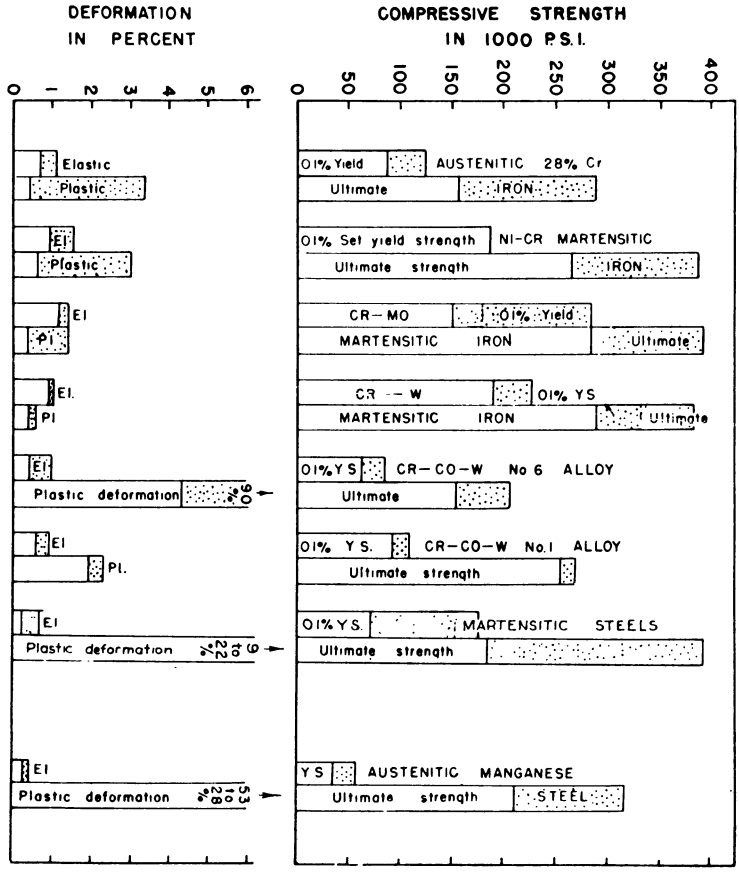


Fig. 44.11.—Comparative compression and deformation properties of various hard surfacing alloys.

The hard composite structure of the martensitic irons confers good resistance to abrasions of all kinds, which is primarily the reason for their selection (Table 44.9). Moreover, of all the common hard facing alloys, this group appears to have the highest compressive strength and thus provides the elasticity to resist light, direct, compressive impact blows (Fig. 44.11). Resistance to erosion or scratching abrasion depends largely on the volume and hardness of the carbide constituent.

High chromium irons, because their carbides are harder, usually show better erosion resistance than the martensitic irons, but as stress on the abrasive rises, this pattern reverses. This has led to wide use of martenitic irons for general abrasion resistance. Their selection for light impact is much less common but it should be realized that both properties can be had in one alloy.

The elastic compression strength, and consequently resistance to light impact

deformation, is very high for the martensitic irons. Ultimate compression strength up to 400,000 psi can be obtained by heat treating both irons and steels. In weld deposits, where the desired structural development depends on transformation during air cooling, the irons seem superior. This is shown by the scatter bands of Fig. 44.11. The yield strengths of the irons are generally at a higher level.

The influence of design, where these irons are subjected to impact, deserves great emphasis. Their strength in compression is much greater than in tension. Shear and tensile stresses should be avoided. They should receive support with sufficient thickness in the deposit to spread the stress over an adequate area of the supporting material.

AUSTENITIC IRONS

The austenitic iron compositions used for surfacing lend themselves to production as composite electrodes for manual welding and as filled tubular wires for semiautomatic and automatic open arc welding. They are relatively inexpensive and find use in applications where more brittle iron deposits might spall under impact, and where more erosion resistance is needed than martensitic steels will provide.

The popularity of the austenitic irons rests upon their suitability for a wide range of medium-impact, medium-abrasion service. They are less susceptible to cracking and spalling than the martensitic irons and the FeCr-A1 and A2 high-chromium irons; this is paramount in many applications where resistance to moderate impact as well as abrasion and erosion is required.

Structurally, if chromium is relatively low, as in the Ni-Hard materials, the addition of more austenite stabilization (e.g. more manganese or nickel) will produce islands of austenite in a matrix of carbide. This pattern is likely to degrade abrasion resistance without a compensating increase in toughness, as the carbide matrix still permits a continuous brittle path through the alloy. However, if the austenite stabilization is produced in association with chromium high enough to reverse the structural pattern and provide island chromium carbides in a matrix of austenite, a significant increase in toughness is possible.

The most popular austenitic irons are of the moderately high chromium type, some of which are detailed in Table 44.10. If their deposits do not have excessive amounts of the large hypereutectic carbide crystals and have no continuity of brittle carbide, they will have some plasticity under impact deformation and are moderately resistant to cracking. They also have operator appeal because as-welded deposits of moderate area can be crack free. The martensitic irons must contend with both thermal stresses and the stresses from martensitic reactions at temperatures too low to permit effective stress relief. Thus, the martensitic alloys, while inherently high in abrasion resistance, frequently develop stress-relief cracking to an extent that worries some users.

Chromium carbides of the Cr_7C_3 type are harder than iron carbide, Fe_3C, thus contributing to erosion resistance. There is a hint that they are toughened by molybdenum, but good evidence in this area is scant. Three percent molybdenum will produce a martensitic 15% chromium iron, which in light sections (as castings) provides good all-around abrasion resistance. A cutback to around 1% Mo is needed to keep air-cooled weld deposits austenitic, unless the austenite is stabilized with nickel or manganese.

Table 44.9—Properties of martensitic irons

	Chrome-Nickel Type			Chrome-Molybdenum Type			Chrome-Tungsten Type		
	Gas Welded	Small Castings*	Arc Welded	Gas Welded	Small Castings*	Arc Welded	Gas Welded	Small Castings*	Arc Welded
Type Composition	4.5% Ni——1.5% Cr			4% Cr——4% Mo			8% Cr——15% W		
Resistance to flow under repeated impact	Good			Good			Excellent		
Tensile toughness	Low			Low			Low		
Resistance to cracking under repeated impact	Low			Fair			Fair		
Oxidation resistance	Low			Low			Medium		
Maximum temperature considered advisable	1000°F (540°C)			1100°F (590°C)			1200F° (650°C)		
Creep resistance	Low			Fair			Fair		
Rockwell hardness† at:									
70° F (20°C)	C60	...	C64	C63	...	C57	C62	...	C65
600° F (320°C)	C51	C48	...	C51-54	...	...	...	...	...
800° F (430°C)	C51	C42	...	C52	...	...	...	...	...
1000° F (540°C)	C27	C17	C42	C43-46	...	C43	C50	...	C51
1200° F (650°C)	C13	...	C8	C7-19	...	C4	C32	...	C27
Compression strength:									
Yield, psi	180,000			172–185,000			184–226,000		
Ultimate, psi	260–380,000			310–386,000			292–334,000		
Elastic deformation, %	0.9–1.6			1.2–1.4			0.9–1.0		
Plastic deformation, %	0.6–3.0			0.3–1.4			0.3–0.5		
Abrasion resistance	Good	Good	Fair	Excellent	Excellent	Good	Excellent	...	Good
Wet sand abrasion factor	0.37–0.57	0.30–0.65	0.60–0.74	0.30–0.46	0.34–0.47	0.38–0.54	0.28–0.50	...	0.40–0.60
Erosion resistance	Good	...	Fair	Excellent	...	Good	Excellent	...	Good
Tensile strength, psi	22,000–43,000								
Brinell hardness	500–650								

* Properties considered between those of gas and electric weld deposits. Used for some test specimens to eliminate welding variables and defects.
† Instantaneous values.

Table 44.10—Composition of austenitic iron surfacing filler metals

Grade*	C, %	Mn, %	Si, %	Ni, %	Cr, %	Mo, %	W, %	Fe, %	Others, %
	2.0	2.6	0.7	...	28	3	...	bal.	...
	2.3	2.0	1.5	...	15	...	...	bal.	...
	3.0	2.5	1.5	...	12	1.5	...	bal.	...
	3.2	...	...	6	16	8	...	bal.	...
	3.5	2.0	2.5	...	14	1	...	bal.	low
	4.0	...	...	2	16	8	...	bal.	...

* Filler metals of these compositions have not been standardized.

Table 44.11—Composition of cobalt-chromium surfacing filler metals*

Grade	C, %	Mn, %	Si, %	Cr, %	W, %	Fe, %
R CoCr-A	0.9–1.4	1.00 max.	0.4–2.0	26.0–32.0	3.0–6.0	3.0 max.
R CoCr-B	1.2–1.7	1.00 max.	0.4–2.0	26.0–32.0	7.0–9.5	3.0 max.
R CoCr-C	2.0–3.0	1.00 max.	0.4–2.0	26.0–33.0	11.0–14.0	3.0 max.
E CoCr-A	0.7–1.4	2.00 max.	0.4–2.0	25.0–32.0	3.0–6.0	5.0 max.
E CoCr-B	1.0–1.7	2.00 max.	0.4–2.0	25.0–32.0	7.0–9.5	5.0 max.
E CoCr-C	1.75–3.00	2.00 max.	0.4–2.0	25.0–33.0	11.0–14.0	5.0 max.

* All grades are 1.00% maximum Mo, 3.0% maximum Ni, 0.5% maximum total others with the exception that the balance is cobalt. These are included in AWS A5.13.

Compared to the martensitic irons, the austenitic irons are lower in resistance to high-stress abrasion and in compressive strength. There are transition types in which the matrix may consist of some martensite included with austenite. This austenite will work-harden readily, but there is little evidence that work-hardening contributes much to abrasion resistance.

COBALT-BASE SURFACING FILLER METALS

Table 44.11 indicates the compositions of the CoCr-A, CoCr-B and CoCr-C cobalt-base surfacing filler metals most commonly used for hard surfacing applications. The contact surfaces of exhaust valves in internal combustion engines are frequently surfaced with the softer or CoCr-A alloy. This alloy has high oxidation, corrosion and heat resistance. Higher carbon filler metals such as CoCr-B and CoCr-C are used in applications where greater hardness and abrasion resistance are needed.

Table 44.12 indicates the hardness of the CoCr-A and C alloys when applied by either gas welding or arc welding. The CoCr-A filler metal is usually employed as a high quality oxyacetylene welded overlay. Little or no base metal dilution takes place. CoCr-C filler metal may be used for applications requiring high wear resistance under rough service conditions where arc welded quality is adequate. CoCr filler metals are not subject to tempering, although they do have reduced hardness at elevated temperatures. When the weld deposit is cooled, the original hardness returns. Elevated temperature strength and hardness are outstanding properties of this group. They are generally considered superior to other surfacing alloys where these properties are required above 1200°F (650°C).

At temperatures above 1000 to 1200°F (540-650°C), weld deposits of these CoCr filler metals have greater resistance to creep than any other commercially available surfacing alloys for which data are available. This distinction and their hardness at 1200°F (650°C) and above, are the primary reasons leading to their selection for many applications.

Carbon content has much to do with the response to abrasion. At 1.0% carbon (CoCr-A), the performance may be inferior to that of mild steel; at 2.5% carbon (CoCr-C) the resistance to high stress grinding abrasion is good. Under the low stress conditions of scratching abrasion, laboratory tests indicate that CoCr-C gas welds may wear at one-twentieth the rate of mild steel, while for CoCr-A deposits the rate is nearly one-fifth.

There has been considerable field use of CoCr-C filler metal to withstand abrasion. Some of this experience dates back to the time when the cobalt-base metals were practically the only surfacing materials available. It should be noted that equivalent performance can currently be obtained with less expensive iron-base filler metals if heat and corrosion are unimportant service factors.

The CoCr filler metals are well suited for metal-to-metal wear because of their ability to take a high polish, their high resistance to galling, and their low coefficient of friction.

None of the deposits from these filler metals are easily machined. Difficulties increase with increased carbon content. However, CoCr-A deposits are regularly machined, preferably with sintered carbide tools. With deposits of the CoCr-C classification, grinding is the accepted method of finishing.

These filler metals contain 25 to 33% chromium, which confers oxidation resistance, and 3.0 to 14% tungsten, which promotes elevated temperature strength. The cobalt base gives corrosion resistance and provides a solid-solution matrix. Carbon is an important element that contributes strength and in combination with chromium provides abrasion resistance. Different levels of carbon and tungsten are responsible for the distinctive properties of the three classifications.

Oxyacetylene welding may increase the carbon content of the deposit, while arc welding tends to reduce carbon and at the same time dilute the CoCr deposit with elements from the base metal. These changes will be reflected in the structures.

The CoCr alloys are not subject to hardening transformations like steel and have negligible response to heat treatment. Occasionally a stress relief treatment may appear advisable to minimize cracking, but usually they go into service in the as-welded condition.

Table 44.12—Properties of cobalt base surfacing filler metals

Type Composition	AWS Class CoCr-A			AWS Class CoCr-C		
	Gas Welded	Small Castings*	Arc Welded	Gas Welded	Small Castings*	Arc Welded
	1% C—28% Cr—5% W 55% Co			2.5% C—31% Cr—13% W 43% Co		
Resistance to flow under repeated impact	Fair			Good		
Tensile toughness	Moderate			Low		
Oxidation resistance	Excellent			Excellent		
Maximum temperature considered advisable	2100° F (1150°C)			2100° F (1150°C)		
Creep resistance	Outstanding			Excellent		
Rockwell Hardness† at:						
70° F (20°C)	C37–47	C40–45	C35–45	C45–60	C53–55	C45–60
600° F (320°C)	C37	C41	C37	C50	C51	C53
800° F (430°C)	C31–36	C40	C35	C47–48	C50	C50
1000° F (540°C)	C27–35	C28–39	C31	C44–46	C45–47	C35–47
1200° F (650°C)	C21–31	C22–35	C27	C40–44	C41–45	C35–36
Compression strength:						
Yield, psi	64,000–120,000			90,000–145,000		
Ultimate, psi	155,000–230,000			255,000–268,000		
Elastic deformation, %	0.4–1.0			0.6–0.9		
Plastic deformation, %	4.3–9.0			1.9–2.2		
Abrasion resistance	Poor	Poor	Poor	Fair	Good	Poor
Wet sand abrasion factor	1.05–1.30	...	1.15–1.35	0.63–0.85	...	0.85–1.20
Erosion resistance	Fair	...	...	Excellent	...	...
Dry sand erosion factor	0.17	...	...	0.15	...	...
Tensile strength, psi	105,000			95,000		
Elongation, %	1.0			0–1%		
Brinell hardness	340					

* Properties considered between those of gas and electric weld deposits. Used for some test specimens to eliminate welding variables and defects; and available as small centrifugal castings for use where a composite weldment is less appropriate.
† Instantaneous values.

For oxyacetylene welding a 3X feather-to-cone reducing flame is recommended. Preheating the cleaned surface with a neutral flame up to at least 800°F (430°C) is advisable for heavy sections. For shielded metal-arc welding, dc reverse polarity is used, with a short arc. For a ¼ in. dia electrode, a current of approximately 190 to 200 amp is recommended. All deposits should be cooled slowly to prevent cracking.

CoCr-C weld deposits are quite brittle and crack readily when impact flow occurs. CoCr-A deposits, while they deform more easily, can withstand some plastic flow under compression before cracking. A tough martensitic steel is considered superior in both flow resistance and toughness.

The presence of over 25% chromium promotes the formation of a thin, tightly-adherent protective scale under oxidizing conditions. For deposits of these filler metals at temperatures up to 1800°F (980°C), this means a scaling rate below 0.10 in. per year in common oxidizing atmospheres. Scaling resistance to combustion products of internal combustion engines is also generally adequate, even in the presence of lead compounds from "doped" fuels.

Cobalt base filler metals, as deposited, are frequently used where both abrasion and corrosion are involved. They can be considered corrosion resistant in the less severe media. If an application involving corrosion is under consideration, general statements should be confirmed by a field test, if possible.

NICKEL-BASE ALLOYS

The compositions of some of the nickel-base alloy surfacing filler metals are shown in Table 44.13. The nickel-base alloys are particularly valuable for their heat and corrosion resistance. High nickel alloys are very susceptible to attack by sulfur and hydrogen sulfide. As a result they are generally unsuitable for use in reducing atmospheres containing sulfur above about 100 grains per cubic foot.

As protective overlays these nickel-base alloys, when available as continuous electrodes, are best applied by gas shielded arc welding. In this way carbon pickup is avoided as well as complications resulting from the use of flux. The automatic deposition lends itself to coating cylindrical vessels that must be protected from corrosion.

At least five types of nickel-base alloys have important applications as overlays. Frequently one of them is selected because it provides better hot strength, toughness, or surface protection than the more economical iron-base alloys.

The important nickel-base alloys are:

1. Nickel-chromium alloys, chiefly of the 80% nickel-20% chromium grade
2. Nickel-chromium-iron compositions corresponding to well-known heat-resistant alloys
3. Nickel-chromium-iron-silicon-boron alloys
4. Nickel-chromium-molybdenum-tungsten alloys
5. Nickel-iron-molybdenum alloys
6. Nickel-copper (Monel) alloys

The nickel-silicon alloy that is related to high silicon cast iron is not commonly used as an overlay.

The 80% Ni-20% Cr grade is a relatively soft and ductile alloy selected for hot gas corrosion resistance. It is used for facing the crown (or top) of internally cooled aircraft exhaust valves and sometimes for the seat of the valve.

Table 44.13—Compositions of nickel-base surfacing filler metals

Grade	C	Si	Ni	Cr	B	Co	Fe
Nickel—Chromium—Boron Types							
E/R NiCr-A	0.30–0.60	1.25–3.25	75–85	8–14	2.0–3.0	1.50 mx	1.25–3.25
E/R NiCr-B	0.40–0.80	3.00–5.00	71–81	10–16	2.0–4.0	1.25 mx	3.00–5.00
E/R NiCr-C	0.50–1.00	3.50–5.50	65–75	12–18	2.5–4.5	1.00 mx	3.50–5.50

	C	Si	Ni	Cr	Mo	W	Fe
Nickel—Molybdenum Types							
	0.5 2.0	0.5 ...	Balance Balance	16 26	16 8	4 ..	5 —

	C	Si	Ni	Cu	Ti	Fe	Al	Mn
Nickel—Copper Types								
ERNiCu7	0.15 max.	1.25 max.	62.0- 69.0	Bal.	1.5- 3.0	2.5 max.	1.25 max.	4.0 max.
ERCuNi	0.04 max.	0.15 max.	29.0- 32.0	Bal.	0.2- 0.5	0.4- 0.7	...	1.0 max.

	C	Si	Ni	Cr	Cb	Fe	Ti	Mn
Nickel—Chromium Types								
80-20	0.2	0.3	Bal.	21.0	...	...	...	...
ERNiCr3	0.10 max.	0.50 max.	67.0 min.	18.0- 22.0	2.0- 3.0	3.0 max.	0.75 max.	2.5- 3.5
ERNiCrFe5	0.08 max.	0.35 max.	70.0 min.	14.0- 17.0	1.5- 3.0	6.0- 10.0	...	1.0 max.
ERNiCrFe6	0.08 max.	0.35 max.	67.0 min.	14.0- 17.0	...	10.0 max.	2.5- 3.5	2.0- 2.7

	C	Si	Ni	Fe	Al	Ti
High Nickel Types						
ERNi3	0.15 max.	0.75 max.	93.0 min.	1.0 max.	1.5 max.	2.0- 3.5

The relatively low hot strength of the 80% Ni-20% Cr type can be improved by the addition of carbon and molybdenum or tungsten. An alloy with 2% C, 26% Cr and about 8% Mo has proved excellent for facing aircraft valves, where it sometimes exhibits resistance to engine combustion products superior to that of the 1% C CoCr-A type.

The nickel-chromium-iron heat resistant alloys can be considered to represent a continuous series from the 80% Ni-20% Cr type to the iron-base stainless steels. Experience has tended to standardize certain grades within this range for castings and wrought products. These can be drawn as wire for welding electrodes. However, the properties that justify special grades as castings are not prominent in weld deposits. Since they all are likely to have adequate oxidation resistance in the absence of sulfur, expansion coefficients provide the most logical reason for selection of the higher nickel alloys. Fig. 44.12 indicates the relationship existing between nickel content and percentage of expansion for various temperatures. The difference between grades is not large.

Hot ductility tends to increase with nickel. The alloys are quite soft, though they are creep resistant. Even the inclusion of considerable carbon does not harden them markedly.

Nickel-base alloys containing chromium and boron are the most common nickel-base hard facing materials. They are also adapted to spray gun application. When sprayed they are subsequently fused by close application of a hot gas flame to produce a thin hard overlay. The spray technique permits covering irregular contours more uniformly than is possible with conventional welding (for details of this process see Section 2 Chapter 29). The alloy for this use is available as loose powder and as a plastic bonded powder in "wire" form. It is also commonly used as a cast rod (nominally 70% Ni, 17% Cr and 3.75% B) for oxyacetylene welding. Its wetting and flowing qualities are very good. It has a melting point below 1900°F (1040°C). Gas weld deposits from such alloys may exceed Rockwell C-62 and may retain hardness as high as Rockwell C-48 at 1000°F (540°C). They also have excellent resistance to low stress scratching abrasion, but poor resistance to high stress abrasion. (The latter is a case where hardness is not a good indication of wear resistance.) (See Table 44.14.) Their virtues indicate that they should be selected primarily for applications combining low stress abrasion with corrosion or heat. The 2.5% C-Cr-Co-W alloy is superior in hot strength and oxidation resistance above 1500°F (820°C) (Fig. 44.13). The presence of boron may lead to loss of heat resistance at higher temperatures because of the formation of low melting constituents.

Where erosion resistance is the primary requirement the high chromium irons should receive first consideration because of their lower cost. The microstructure of gas welds from both these types exhibits carbide spines of the Cr_7C_3 type. The very hard chromium borides that occur in the nickel-base alloy do not clearly confer superiority in abrasion resistance.

Table 44.14 contains data from the hardest of these alloys. Modifications are available that feature reduced chromium and boron, thereby improving machinability at the expense of both hardness and abrasion resistance.

Table 44.14—Properties of nickel-base alloy surfacing filler metals*

	Ni-Cr-B Type (AWS Class BNiCr-C)		Ni-Cr-Mo-W Type	
	Gas Welded	Arc Welded	Gas Welded	Arc Welded
Type composition weight per cent	70 Ni—17 Cr—3.75 B—4.5 Si		50–60 Ni—13 Cr—0.10 C—18 Mo—5 W	
Tensile toughness	Low		High†	
Resistance to cracking under repeated impact	Low		High	
Oxidation resistance	Good		Good	
Creep resistance	Good		Good	
Rockwell hardness at:				
70° F	C56–62	C42–50	C24–32‡	C10
600° F	C55	C49	...	...
800° F	C52	C46	...	...
1000° F	C48	C39	C16	...
1200° F	...	...	C7	...
Resistance to high stress abrasion	Poor	Poor	Poor	Poor
Wet sand abrasion factor	0.90	1.06	0.97	...
Resistance to low stress abrasion	Good	...	Poor	...
Dry sand erosion factor	0.08	...	0.73	...
Machinability	By grinding only		Can be lathe cut with carbide tools	

* See also Section 4 of the Welding Handbook for additional information on nickel alloys.
† Specimen properties on small castings are 71,500 psi ultimate strength, and 15% elongation, 190 Brinell hardness.
‡ Welded with carburizing flame.

Another group of nickel-chromium alloys features molybdenum and sometimes tungsten and iron. They were developed primarily for corrosion resistance and provide outstanding stability in some severly corrosive media. The most popular grade, for which data appear in Table 44.14, is also used in hot wear applications. Its properties depend partially on intermetallic compounds that play the same role as carbides in the cobalt-base alloys. When gas welded the properties may be modified somewhat by carbon pickup from the flame. The abrasion resistance of gas welds is relatively poor.

A 60Ni-20Mo-20Fe alloy is employed primarily for resistance to hydrochloric acid which rapidly attacks practically all of the stainless steels. Even weaker acid concentrations may be destructive if they are at elevated temperatures. The molybdenum content confers marked resistance to such corrosion. The alloy also performs well in sulfuric, formic and acetic acids, salt spray environments, and in alkalies. It is vulnerable to nitric acid and to free chlorine. A modification with 65% nickel, 30% molybdenum and 5% iron is appropriate for handling boiling hydrochloric acid and wet HCl gas.

For some purposes the nickel-base alloys provide the best performance obtainable. For some applications requiring corrosion resistance the stainless steels are frequently as satisfactory and less expensive.

COPPER-BASE ALLOYS

The copper-base alloys are employed as overlay surfaces chiefly to resist corrosion, cavitation erosion, and metal-to-metal wear. They are nonmagnetic and practically nonsparking. Where copper alloy bearing metals are normally employed as homogeneous parts, it is sometimes more economical to apply them as overlays on a less expensive base metal, usually iron.

Table 44.15 summarizes the commonly available copper-base alloys used for surfacing. Most of them are resistant to atmospheric attack, salt and fresh water corrosion, alkaline solutions (except those that are ammoniacal), and many acids (especially those of the reducing type). They have poor resistance to sulfur compounds that can produce a corrosive copper sulfide, but are generally good with other saline solutions. They have poor abrasion resistance under high-stress grinding conditions and they should not be subjected to other than mild abrasion. They are unsuitable at elevated temperatures above 400-500°F (200-260°C).

For "soft" bearing surfaces, where the bearing is expected to wear in preference to the mating face, the phosphor bronzes (CuSn-A, CuSn-C), the softer aluminum bronzes (CuAl-Al, CuAl-A2, and CuAl-B), and the brasses (CuZn-B, -C, and -D) may be appropriate. They are usually selected so as to be 50 to 75 Brinell hardness numbers softer than the other face. For the reverse, where the bearing surface is to be the harder of the two, the hard aluminum bronzes (CuA1-C, CuA1-D, and CuA1-E) are used. Refer to Table 44.15 for welding methods. Silicon bronze is not intended for bearing use.

Though all these alloys are machinable, machinability tends to decrease as alloy content increases. Most difficult are the CuSn-A and CuSn-C alloys, whereas the CuSn-E alloy is the easiest to machine.

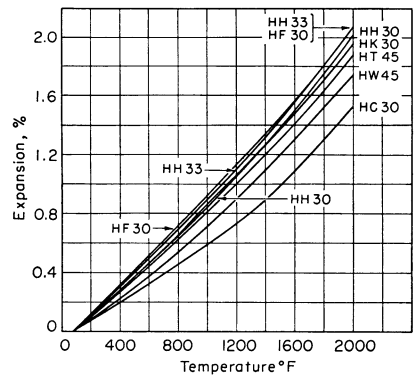


Fig. 44.12.—Thermal expansion characteristics of the common nickel-chrominum-iron-heat-resistant alloys. (HC30, 27Cr; HH30, 26Cr-12Ni; HH33, 26Cr-12 Ni; HK30, 26Cr-20Ni; HF30, 21Cr-9Ni; HT45, 16Cr-35Ni; HW45, 12Cr-60Ni).

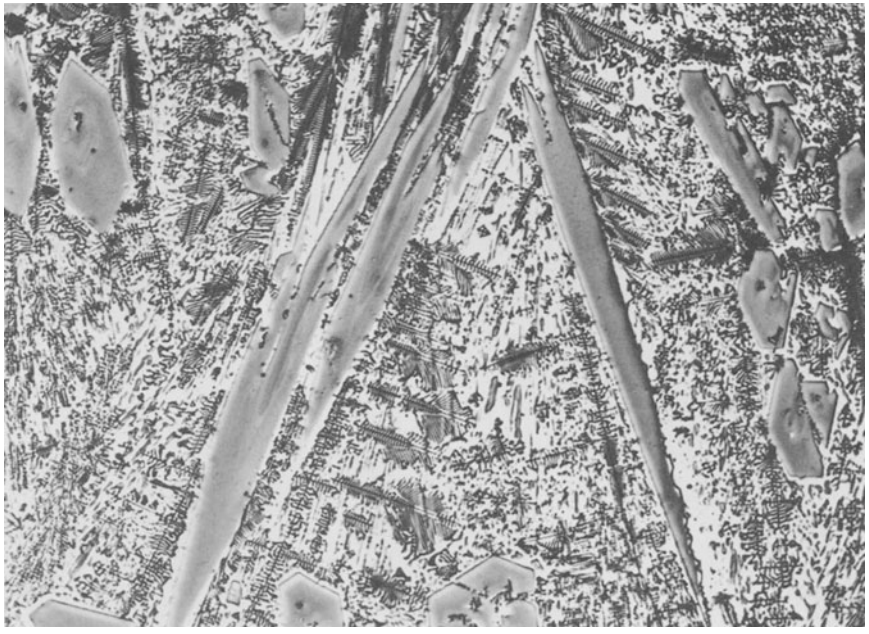


Fig. 44.13.—Arc weld deposit of ECoCr-C (2.5C, 31Cr, 43Co, 14W) electrode that is characterized by high hot hardness. The complex matrix is very creep resistant, oxidation resistant and stainless, while the Cr_7C_3 type carbides confer good abrasion resistance.

A salienta characteristic of the aluminum bronzes is their good resistance to metal-to-metal wear under "adhesive" or "welding wear" conditions. When clean surfaces of metals come into intimate contact, they tend to weld together at the contact points. These welds may break in normal service, but the occurrence gives rise to seizing, scuffing, galling and related troubles. Thin films separating such surfaces prevent the welding. Aluminum bronzes tend to develop films of aluminum oxide that are tightly adherent, very hard, and quite effective in preventing adhesive wear. Many of their successful applications (such as for: dies for drawing and forming aluminum, titanium and stainless steels; gears; cams; sheaves and wear plates) probably depend on such films. The films also effectively make oxyacetylene welding impractical.

Welding techniques will affect properties. Iron pickup from a steel base metal is a hardener. To limit this effect at the surface, an overlay should be about ¼ inch thick (preferably in a recess with fillets greater than a ¼ inch radius) and consist of three or more layers. Gas and gas tungsten-arc methods are preferred. Manual shielded metal-arc and gas metal-arc processes require minimum amperage (to limit pickup), and they also allow a fast, wide push-weaving technique for the initial layer. The opposite effect (softening from loss of alloys during deposition) is minimized by inert gas shielding. Temperature control of the base can be important (Table 44.16), and should not be neglected.

Table 44.15—Copper-base surfacing filler metals and their properties

AWS-designation(a)	Composition range of filler metal, %	Nominal mechanical properties: Ultimate strength in compression, ksi	Nominal mechanical properties: Elastic limit in compression, ksi	Deposit hardness, Brinell (Avg.)	Processes Applicable(g)	Applications
Cu Zn B	Cu 56-60, Sn 0.75-1.10, Fe 0.25-1.25, Si 0.04-0.15, Ni 0.2-0.8, Zn rem.	80.0	21.0	95(b), (f)		Bearing and corrosion-resistant surfaces
Cu Zn C	Cu 56-60, Sn 0.75-1.10, Fe 0.25-1.25, Si 0.04-0.15, Zn rem.	75.0	19.0	90(b), (f)		Bearing and corrosion-resistant surfaces
Cu Zn D	Cu 46-50, Si 0.04-0.15, Ni 9-11, Zn rem.	85.0	22.0	100(b), (f)		Bearing and corrosion-resistant surfaces
Cu Si A	Cu 91 min., Si 2.8-4, Zn 1.5 max., Sn 1.5 max., Mn 1.5 max., others 0.5	58.0	20.0	80(b), (f), 100(b), (e)		Corrosion-resistant surfaces
Cu Si	Si 2.8-4, Sn 1.5 max., Mn 1.5 max., Fe 0.5., others 0.5, Cu rem.	60.0	22.0	95(b), (e)		Corrosion-resistant surfaces Not for bearings
Cu Sn A	Sn 4-6, P 0.10-0.35, Cu rem.	40.0	9.0	70(b), (f), 85(b), (e)	SMAW GMAW	Bearing and corrosion-resistant surfaces
Cu Sn C	Sn 7-9, P 0.05-0.35, Cu rem.	50.0	10.0	90(b), (d), 95(b), (e)	SMAW GMAW	Bearing and corrosion-resistant surfaces
Cu Sn D	Sn 9-11, P 0.10-0.30, Cu rem.	65.0	12.0	90(b), (f), 110(b), (e)	CAW GTAW AHW	Bearing surfaces
Cu Sn E	Pb 14-18, Sn 5-7, P 0.3-0.5, Cu rem.	20.0	5.0	50(b), (f)	OAW	For locomotive journal boxes only providing a porous deposit to retain oil
Cu Al A-1	Al 6-9, Cu rem.	105.0	16.0	125(c), (e)	CAW GTAW AHW	Corrosion-resistant surfaces
Cu Al A-2	Al 9-11, Fe 1.5 max., Cu rem.	120.0	25.0	150(c), (d), 160(c), (e)	SMAW GMAW	Bearing and corrosion-resistant surfaces
Cu Al B	Al 10.25-11.75, Fe 3-4.25, Cu rem.	130.5	26.0	160(c), (d), 207(c), (e)	CAW GTAW AHW	Bearing and resist cavitation
Cu Al C	Al 12-13, Fe 3-5, Cu rem.	146.0	45.0	200(c), (d), 269(c), (e)	SMAW GMAW	Bearing and resist cavitation
Cu Al D	Al 13-14, Fe 3-5, Cu rem.	160.0	50.0	250(c), (d), 340(c), (e)	CAW GTAW	Bearing surfaces
Cu Al E	Al 14-15, Fe 3-5, Cu rem.	171.0	65.0	300(c), (d), 390(c), (e)	AHW SMAW	Bearing surfaces
Ni Al Bronze	Al 8.5-9.5, Ni 4-5.5, Fe 3-5, Mn 0.6-3.5, Cu rem.	130.0	45.0	187(c), (d), 196(c), (e)		Surfaces to resist corrosion and erosion
Mn Ni Al Bronze	Al 7-8, Fe 2-4, Ni 1.5-3, Mn 11-14, Cu rem.	135.0	30.0	185(c), (d), 217 (c), (e)		Surfaces to resist corrosion and erosion

(a) Where applicable. Refer to AWS Specification A5.6-69 and A5.7-69. (b) 500 kg load. (c) 3000 kg load. (d) Manual metal-arc. (e) Inert-gas. (f) Oxyacetylene.

(g) Process applicability Code: ca = carbon arc, with covered welding rods.
gw = fuel gas welding. tig = gas tungsten-arc welding.
ah = atomic hydrogen welding. sma = shielded metal-arc welding.
mig = gas metal-arc welding.

44.54 / Surfacing

Table 44.16—Preheat, interpass and postheat temperatures for copper-base alloy surfacing*

Base metal	Filler metal	Preheat temperature, °F			Interpass temperature, °F			Post treatment
		Manual metal-arc	Gas tungsten-arc; oxy-acetylene	Gas metal-arc	Manual metal-arc	Gas tungsten-arc; oxy-acetylene	Gas metal-arc	
Aluminum bronze under 9% Al(a)	Cu Al A-1	Process not used	None(b)	None	Process not used	150 max.(b)	150 max.	Air cool
9-13% Al(a)	Cu Al A-2, B, C Ni-Al bronze Mn-Ni-Al bronze	300	None(b)	None	400 max.	400 max.(b)	400 max.	Air cool
Over 13% Al(a)	Cu Al D, E	1100 min.	1100 min.(b)	Process not used	1100 min.	1100 min.(b)	Process not used	Cool rapidly from 1100° F with fan or air blast
Silicon bronze	Cu Si, A Cu Al A-2	None	None	None	150 max.	150 max.	150 max.	Air cool
Tin bronze	Cu Sn A, C, D	400	None	None	400	400	400	Cool rapidly from 400°F with fan or air blast
Manganese bronze	Cu Zn B, C	Process not used	None	Process not used	Process not used	500	Process not used	Air cool
	Cu Al A-2	500	None(b)	None	500	500	500	
Carbon steels to 0.40% C	Cu Al A-1	Process not used	None	None	Process not used	150 max.(b)	150 max.	Air cool
	Cu Al A-2, B, C	None	None(b)	None	None	600 max.(b)	600 max.	Air cool
	Cu Al D, E	None	None(b)	Process not used	None	600 max.(b)	600 max.	Air cool
	Cu Sn A, C, D, E	None	None	None	None	600 max.	600 max.	Air cool
	Cu Zn B, C, D, E	Process not used	None(c)	Process not used	Process not used	600 max.	Process not used	
Carbon steels	Cu Al A-2, B, C	400 min.	400 min.(b)	400 min.	400-600	400-600(b)	400-600	Cool slowly from interpass temperature preferably in lime or asbestos
Over 0.40% C Alloy steels and cast iron	Cu Al D, E(d)	400 min.	400 min.(b)	Process not used	400-600	400-600(b)	Process not used	

(a) Aluminum equivalence. (b) Gas tungsten-arc only. (c) Oxyacetylene only. (d) Buffer layer Cu Al A-2.
*From "Surfacing with Bronze," *Welding Journal*, April 1967.

The gas metal-arc process is recommended for large area repair of copper-base alloys; for minor repairs the gas tungsten-arc method used with thoriated electrodes is favored. The copper-zinc alloys can be deposited only by gas welding, but gas metal-arc overlays of phosphor bronze (CuSn-C) on low (red) brass, and aluminum bronze (CuAl-A2) on high (yellow) brasses, are feasible.

Common applications include brass (CuZn-B, -C and -D) overlays for bearings and corrosion-resistant uses. For example, RCuZn-C is used for rebuilding manganese bronze ship and boat propellers. Silicon bronzes are used for rebuilding eroded and corroded surfaces, such as silicon bronze impellers (Fig. 44.14). The copper-tin alloys are used for bearing surfaces (the CuSn-E alloy is used for rebuilding locomotive journal boxes; the iron-free CuAl-A1 is employed for rebuilding pistons where a hardness of BHN 125 is required, or wherever a minimum of iron is tolerable; the CuAl-B alloy is used for bearing surfaces subject to shock loading or for cavitation resistance when deposited with a process using inert gas shielding). The CuAl-A2 grade is quite versatile, and is used for pickling hooks, ship propellers, turbine runners, tube sheets (Fig. 44.5), and piston surfaces requiring a hardness of 140-160 Brinell (Fig. 44.15).

MARTENSITIC STEELS

The martensitic air-hardenable iron-base alloy filler metals are used to deposit overlays with moderate resistance to both low and high stress abrasion. Table 44.17 lists a variety of martensitic alloy steels with their nominal compositions.

Assuming that the composition is balanced to form martensite upon air-cooling, the deposited hardness will depend largely on carbon and chromium content. Up to about 0.20% carbon will provide a maximum hardness near Rockwell C-45, and the deposits will be machinable although tungsten carbide tools may be needed in the upper hardness range. They are most often used to resurface worn areas of machinery parts as they exhibit the strength and toughness characteristics of heat treated steels without the necessity of quenching and tempering. Steels with carbon between 0.7 and 1.5% are used for overlays where moderate abrasion and impact are expected. If carbon and chromium are both high, they may gain some toughness from retained austenite. This austenite is metastable and work hardenable.

The low-carbon low-alloy types are appropriate for steel mill wobblers, tractor sprockets, tractor rollers, tamping tools, and steel pulverizer hammers. The medium carbon steels may be used for die surfacing, rail ends, steel shafts, gears, cams, pins, steel rolls and parts that can be finished by grinding. Typical high-carbon applications are crusher rolls, hammers, die rings, and muller tires.

In Table 44.17 only the Fe5 types have been standardized by the current AWS specifications. Considerable variation can be expected within the other grades as shown in the tables, and the relationship between composition, properties and appropriate applications is not close. Though the types are not standardized, unless they correspond to accepted tool steels, the designation and classification system is outlined in the Appendix to AWS A5.13.

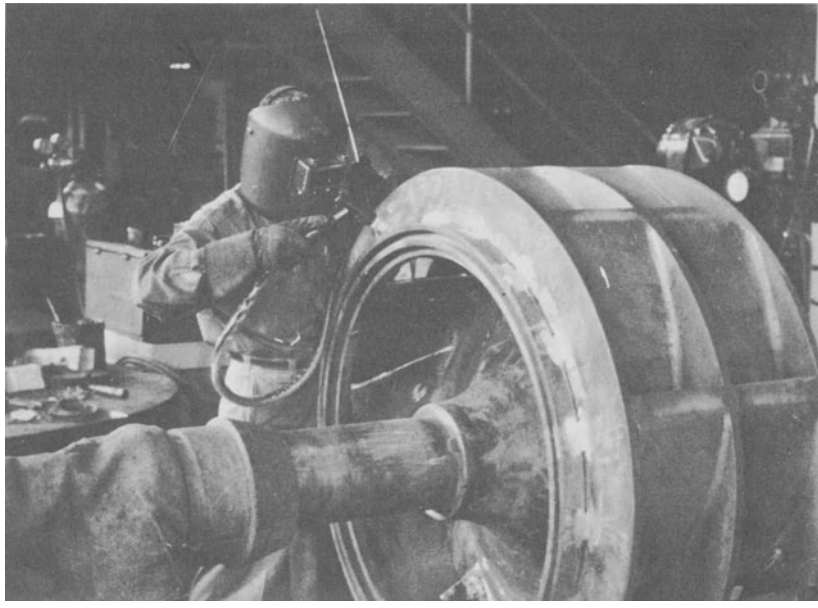


Fig. 44.14.—Pump impeller weighing 20,000 pounds being rebuilt with silicon bronze to resist corrosion and erosion.

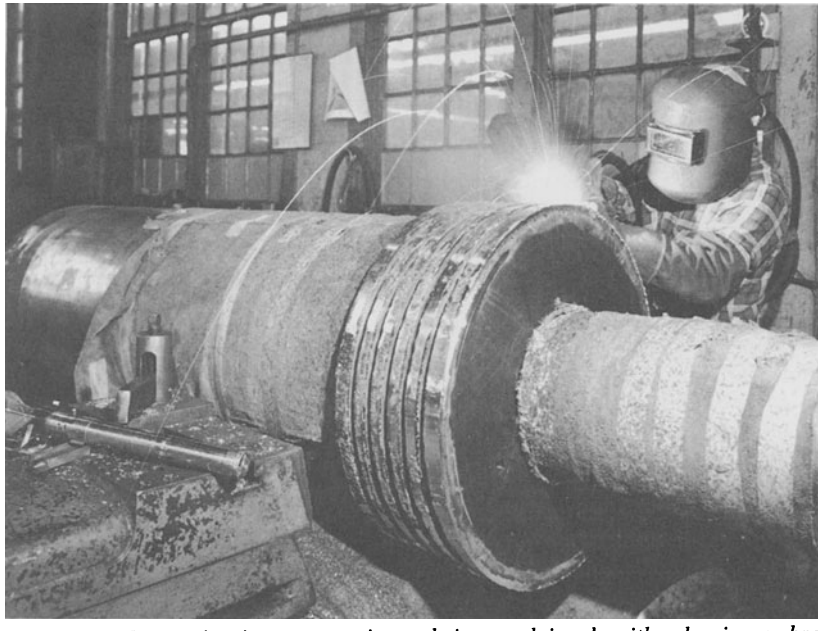


Fig. 44.15.—Large forging press piston being reclaimed with aluminum bronze overlay (CuAl A-2) to resist metal-to-metal adhesive wear.

Table 44.17—Compositions of martensitic steel surfacing filler metals*

Grade†	C, %	Mn, %	Si, %	Cr, %	Ni, %	Mo, %	W, %	V, %
E502	0.10	1.00	0.90	4.0–6.0	0.40	0.45–0.65	...	...
E430	0.10	1.00	0.90	15.0–18.0	0.60	...	...	...
E410	0.12	1.00	0.90	11.0–13.5	0.60	...	...	...
	0.20	2.7	0.80	3.5	...	1.0	...	0.4
	0.25	1.8	0.7	2.8	1.3	0.5	...	...
	0.25	2.0	0.7	4.3	...	0.8	...	...
	0.30	1.75	0.75	4.0	...	0.5	...	0.3
	0.30	0.75	0.75	4.5	...	1.5	1.5	...
	0.30	2.0 max	1.0 max	0.3–2.5	2.0 max	2.0 max	...	...
	0.35	0.45	0.5	13.0	0.2	...	...	...
	0.3–0.7	2.0 max	1.0 max	1.5–3.5	2.0 max	2.0 max	...	...
	0.3–0.7	2.0 max	1.0 max	4.5–8.5	2.0 max	2.0 max	...	...
	0.3–0.7	2.0 max	1.0 max	11–15	2.0 max	2.0 max	...	...
	0.6	1.5	0.8	5.0	...	0.5	...	...
	0.6	1.1	...	2.5	...	0.4	...	...
	1.0	...	...	5.0	...	1.5	...	...
	1.0	1.0	0.8	5.3	...	0.5	...	...
	0.7–1.5	2.0 max	1.0 max	5.5–9.5	2.0 max	2.0 max	...	...
	0.7–1.5	4.5 max	1.0 max	11–15	2.0 max	2.0 max	...	...
High-speed steel types								
E Fe5-A	0.7–1.0	0.5 max	0.7 max	3.0–5.0	...	4.0–6.0	5.0–7.0	1.0–2.5
E Fe5-B	0.5–0.9	0.5 max	0.7 max	3.0–5.0	...	5.0–9.0	1.0–2.5	0.8–1.3
E Fe5-C	0.3–0.5	0.5 max	0.7 max	3.0–5.0	...	5.0–9.5	1.0–2.5	0.8–1.2
R Fe5-A	0.7–1.0	0.5 max	0.5 max	3.0–5.0	...	4.0–6.0	5.0–7.0	1.0–2.5
R Fe5-B	0.5–0.9	0.5 max	0.5 max	3.0–5.0	...	5.0–9.5	1.0–2.5	0.8–1.3

* The balance of these compositions is iron, with a maximum total of all elements not listed of 1.0% for the Fe-5 grades and of 2.0% for all others.

† Types not designated in this column have not been standardized by AWS action.

The Fe5 group are high speed steels and are almost interchangeable, except that the high-carbon EFe5-A and EFe5-C grades are more suitable for cutting and machining applications, and the lower-carbon EFe5-B grade is better for hot working and service requiring toughness. The Fe5 types, in general, are used as electrodes, and have proven popular for applications where hardness, wear resistance and toughness are required at temperatures up to 1100°F (590°C). Some typical surfacing applications are cutting tools, shear blades, reamers, forming dies, guides, ingot tongs, broaches and similar tools.

The air-hardening steels will range from Rockwell C-25 to C-65 in hardness, depending primarily on the carbon content and the amount of transformation to martensite. Cooling rate and the content of alloying elements play an important part. Even though heat treatment (other than ordinary weld cooling) may not be used, the tempering effect of successive weld beads may also be influential. Faster cooling tends to make underalloyed compositions harder and overalloyed deposits softer. The EFe4-C types, as usually formulated, are intentionally overalloyed with C, Cr and Mn to produce considerable unstable austenite.

Dilution, or mixing with the base metal in the weld pool, can have an important effect on hardness. A decrease in hardness is expected after welding on manganese steel, in comparison with welds on carbon steel. However, the low-alloy grades are not recommended for build-up on austenitic manganese steel, because of the hard brittle zone that may develop at the interface.

Secondary hardening can occur with the high-speed steels and this contributes to their usefulness in the 800-1100°F (430-590°C) range.

The air-hardening martensitic steels are preferred for medium impact service, because they may combine toughness with high compressive strength. They are often used as a high-strength build-up prior to surfacing with a more brittle and more abrasion resistant overlay.

Those alloys that contain 11 to 15% chromium (EFe4-B and EFe4-C) have oxidation and corrosion resistance similar to that of Type 420 stainless steel. The other types have relatively poor corrosion resistance though with several percent of chromium they tend to rust less rapidly than carbon steel.

These alloys resist metal-to-metal wear and low stress abrasion (erosion) much better than low-carbon steel, but they are not considered highly resistant to high-stress abrasion. Abrasion resistance tends to increase with carbon and chromium content, but the high speed types are the best of the group at both ambient and elevated temperatures up to 1100°F (590°C). Hardness is not a reliable index of abrasion resistance but there is some correlation under low stress erosion conditions. The martensitic steels generally are the best and most economical overlays to resist abrasion when their ranges of toughness and strength are also needed.

The low-carbon low-alloy steels may be machined with sintered carbide tools, but as carbon and alloy content rise grinding becomes the preferred method. The high carbon grades are considered unmachinable in the as-deposited condition, but most of them up to 1.7% carbon can be annealed (1600°F/870°C — hold one hour per inch of thickness — furnace cool) and then machined (EFe4-C is an exception).

A thermal history other than weld deposition is not usual for steel overlays, but for dies and other special parts that are repaired and rebuilt with matching alloys, it may be desirable to give the base metal a standard heat treatment. As this is a specialized field, the recommendation of the filler metal manufacturer should be followed. An example of a heat treating sequence for high-speed steel types is:

1. Anneal at 1550-1650°F (840-900°C) (as above) if necessary.
2. Harden by air or oil quenching from 2200-2250°F (1200-1230°C)
3. Temper at 1025°F (550°C) for two hours and air cool to room temperature
4. For maximum toughness repeat (3) again

Preheating and postheating are sometimes used to minimize cracking, but are ordinarily not considered necessary. Softening anneals can be used as previously described. Oil quenched hardening is usually feasible, unless the steels are over-alloyed. The higher alloy grades should air harden satisfactorily with less tendency to crack than when liquid quenches are employed. If suitable detailed instructions do not accompany the filler metal package, handbook information for a similar tool steel can be adapated. Of course hardening is seldom necessary as a separate operation, unless the weld deposit has been softened for machining.

Flame hardening is applicable to the low alloy steels with a minimum tendency to cause hardening cracks.

PEARLITIC AND BUILD-UP STEELS

While pearlitic steels are sometimes used for surfacing, a more appropriate and important use is for the "buildup" of carbon steels, prior to surfacing with more wear resistant materials. There are often both economic and performance reasons for using buildup welds when more than two or three layers are needed to bring a part to size. Many of the more wear resistant alloys are both relatively expensive and unsuited for thick multiple layer deposits.

Buildup alloys designed for the purpose should be used, as steels too low in strength are likely to flow in service, causing tensile failure of the overlay above. Thus, a buildup material should have sufficient yield strength to provide proper support for surfacing. It should also have adequate ductility to protect against sudden fracture and to contribute to toughness. From the welding standpoint, it should readily provide multiple layer deposits of good quality. (The low carbon martensitic steels, as well as pearlitic steels, are used for buildup. On austenitic base metal, similar austenitic buildup filler metal is used.)

A few of the many pearlitic steel surfacing filler metals are shown in Table 44.18. The simple steels that contain from 0.4-1.0% carbon will consist largely of pearlite upon normal cooling from the welding temperature. They are inexpensive and are readily deposited by welding. However, it should be noted that these and similar low alloy steels are sensitive to dilution and cooling rate, and that hardness and other properties can vary widely. Procedures and conditions must be such that the desired results are attained with the particular product used.

When pearlitic steels are used for final overlays, resistance to frictional wear is most often the proprety sought. Such attributes as machinability and forgeability are sometimes factors in selection. However, unless the alloy content is high enough to cause some martensite to form upon air cooling, the deposits are likely to be uneconomical for surfacing applications. The cost of applying the deposit is so high, in comparison with the cost of the alloy in the form of welding rods or electrodes, that it is difficult to justify alloys with mediocre wear resistance.

SEMIAUSTENITIC STEELS

Table 44.19 indicates the compositions of semiaustenitic steel surfacing filler metals. The semiaustenitic steels are transition grades whose structures usually contain austenite, some martensite, and occasionally bainite or pearlite.

The semiaustenitic alloys are air-hardenable. This indicates that at least a partial transformation of the austenite occurs when the weld deposit cools.

Weld deposits that are largely austenitic are popular, as the softer austenite has less tendency to crack. Although the austenite is work hardenable, this change in hardness adds little resistance to high stress abrasion by quartz and hard silicates. This characteristic, however is a definite advantage in applications involving soft abrasives such as dolomite and limestone.

Table 44.18—Compositions of pearlitic steel surfacing filler metals, build-up and hard-facing base types

Grade	C, %	Mn, %	Si, %	Cr, %	Mo, %
AISI 1045	0.5	...	...	1.5	0.2
	0.5	0.8	0.3	1.0	...
	0.45	0.7	0.2	...	...
	0.4	1.5	0.6	4.0	...
	0.3	1.0	0.7	2.5	...
	0.2	1.0	0.5	1.5	...

Table 44.19—Compositions of semiaustenitic steel surfacing filler metals

Grade	C, %	Mn, %	Cr, %	Mo, %
	0.4	1.5	4.0	...
	1.0	4.0	12.0	...
	1.2	1.5	8.0	0.5
	1.7	1.0	3.5	...

AUSTENITIC STEELS

The austenitic work-hardenable steels, due to their inherent toughness, make the best build-up materials on austenitic manganese steel parts. Higher build-ups can be obtained with less chance of cracking or pulling loose from the base metal than can be obtained with the air-hardenable alloys. Where abrasion is accompanied by severe impact they are often used as the final overlay.

Table 44.20 lists a number of grades of austenitic work-hardenable alloys classified on the basis of their chemical composition.

The Cr-Mn and Cr-Ni-Mn electrodes are used to build up either carbon steel or work-hardening austenitic manganese-base metals prior to a more abrasion-resistant overlay. These electrodes may also be used when depositing the final overlay where moderate abrasion and severe impact resistance are required. Some major applications include railroad frogs, crossovers, rail ends and tampers.

The high manganese alloys in Table 44.20 are listed in order of increasing yield strength, which may be important in certain applications. Those with low phosphorus content and high alloy levels with an excess of austenite stabilizing elements are frequently used for joining 13% manganese and carbon steels. Metallurgically, this is undesirable because the fusion zone next to carbon steel can be characteristically hard and brittle. Practically, such weldments are frequently satisfactory because the hard zone is quite strong. Tensile failure of such joints may occur in the weaker carbon steel base metal.

The 0.07% maximum phosphorus content shown in Table 44.20 is not a desirable limit. It was imposed because electrodes in these grades could not be obtained with a lower phosphorus limit. Such filler metal usually carries from 0.04 to 0.06% phosphorus. Weld bead cracking is closely related to phosphorus content which should not exceed 0.035% in the weld deposit. Premium grades that do not depend on solid manganese steel core wire are available as composite electrodes. They permit a desirable freedom from weld bead cracking.

Table 44.20—Compositions of austenitic steel surfacing filler metals(a)(b)

AWS Classification	C, %	Mn, %	Si, %	Ni, %	Cr, %	Mo, %	Fe, %	V, %	P, %	Total Others, %
EFeMn-A bare	0.55–0.90	12.5–16.0	0.4–1.3	2.75–5.0	0.50	...	bal.	...	0.07	1.0
EFeMn-A covered	0.5–0.9	11.0–16.0	0.3–1.3	2.75 min	0.50	...	bal.	...	0.07	1.0
EFeMn-B bare	0.65–0.90	12.5–16.0	0.4–1.3	...	0.50	0.6–1.4	bal.	...	0.07	1.0
EFeMn-B covered	0.5–0.9	11.0–16.0	0.3–1.3	...	0.50	0.6–1.4	bal.	...	0.07	1.0
EFeMn-C bare	0.55–0.90	12.0–16.0	0.2–0.8	1.00 min	2.5–5.0	...	bal.	...	0.035 max	1.0
EFeMn-C covered	0.55–0.90	12.0–16.0	0.2–0.8	1.00 min	2.5–5.0	...	bal.	...	0.035 max	1.0
Nominal Compositions not covered by specifications (h)										
	0.6	14.5	...	3.5	4.0	...	bal.	...	...	...
	0.8	16.0	...	...	...	1.0	bal.	...	...	...
	0.75	16.5	0.35	1.1	4.0	...	bal.	...	...	...
	1.2	14	0.8	1.0	15	...	bal.	...	...	...
	0.6	4	0.6	9.5	20	...	bal.	...	...	...
	0.4	4	0.6	9.5	20	...	bal.	...	...	...
	0.4	4	0.6	9.5	20	1.4	bal.	0.6	...	...
	0.4	14	0.5	1.0	14	1.6	bal.	...	...	...
	0.4	15	...	1.0	15	...	bal.	...	...	...
	0.9	16	...	2.0 max	16	2.0 max				

Austenitic stainless steels (c)

AWS Classification	C, (d) %	Mn, %	Si, %	Ni, %	Cr, %	Mo, %	Cb plus Ta, %	S, %	P, %
E308	0.08	2.5	0.90	9.0–11.0	18.0–21.0	...	...	0.03	0.04
E308L	0.04	2.5	0.90	9.0–11.0	18.0–21.0	...	...	0.03	0.04
E309	0.15	2.5	0.90	12.0–14.0	22.0–25.0	...	...	0.03	0.04
E309Cb	0.12	2.5	0.90	12.0–14.0	22.0–25.0	...	0.70–1.00	0.03	0.04
E309Mo	0.12	2.5	0.90	12.0–14.0	22.0–25.0	2.00–3.00	...	0.03	0.04
E310	0.20	2.5	0.75	20.0–22.0	25.0–28.0	...	...	0.03	0.03
E301Cb	0.12	2.5	0.75	20.0–22.0	25.0–28.0	...	0.70–1.00	0.03	0.03
E310Mo	0.12	2.5	0.75	20.0–22.0	25.0–28.0	2.00–3.00	...	0.03	0.03
E312	0.15	2.5	0.90	8.0–10.5	28.0–32.0	...	...	0.03	0.04
E16–8–2	0.10	2.5	0.50	7.5– 9.5	14.5–16.5	1.0 –2.0	...	0.03	0.03
E316	0.08	2.5	0.90	11.0–14.0	17.0–20.0	2.00–2.50	...	0.03	0.04
E316	0.04	2.5	0.90	11.0–14.0	17.0–20.0	2.00–2.50	...	0.03	0.04
E317	0.08	2.5	0.90	12.0–14.0	18.0–21.0	3.00–4.00	...	0.03	0.04
E318	0.08	2.5	0.90	11.0–14.0	17.0–20.0	2.00–2.50	6 × C min. to 1.00 max.	0.03	0.04
E330	0.25	2.5	0.90	33.0–37.0	14.0–17.0	...	...	0.03	0.04
E347	0.08	2.5	0.90	9.0–11.0	18.0–21.0(e)	...	8 × C min.(f) to 1.00 max.	0.03	0.04
E349(g)	0.13	2.5	0.90	8.0–11.0	18.0–21.0	0.35–0.65	0.75–1.2	0.03	0.04

(a) Single values shown are maximum percentages except where otherwise specified.
(b) AWS Specification A5.13.
(c) AWS Specification A5.4.
(d) Carbon shall be analyzed to the nearest 0.01%.
(e) Chromium shall be 1.9 × Ni, min., when so specified.
(f) Tantalum shall be 0.10 max, when so specified.
(g) Titanium shall be 0.15 max.
(h) Single values represent nominal compositions

EFeMn-A and EFeMn-B electrodes are substantially equivalent, except that the yield strength of EFeMn-B weld deposits is higher. The applications where EFeMn electrodes are most useful are those dealing with metal-to-metal wear and impact, where the work-hardening quality of the deposit becomes a major asset. Soft rock crushing operations, involving limestone or dolomite, for example, can also benefit from such protection. Abrasion by angular quartz particles does not seem to be altered in laboratory tests by work-hardening manganese steel. Severe service with quartz abrasion is best dealt with by using manganese steel as a tough base metal and overlaying with a martensitic iron.

Certain standardized stainless steels, such as Types 308, 309, 310, etc., are included among the work-hardenable austenitic types (Table 44.20). These grades are described in AWS Specification A5.4. They are generally used for surfacing because of their corrosion resistance.

The Cr-Ni and Cr-Mn grades of the work-hardenable alloys have oxidation and corrosion resistance similar to Type 308 stainless steel. Because of their higher carbon content, they are less resistant to intergranular corrosion than type 308.

Columbium in stainless steels, employed to confer hot strength or to minimize intergranular attack, frequently accentuates the tendency to crack. Some ferrite in the austenitic matrix has been recognized as an aid to crack prevention and from 4% to 8% may be desirable. The amount of ferrite in a weld deposit can be estimated by plotting its composition on a stainless steel constitution diagram as developed by Schaeffler. Recent investigations indicate that a manganese modified Type 310 (25Cr-20Ni) filler metal wire is useful for producing sound, crack-free, fully austenitic weld overlays. About 9% manganese is considered necessary.

The as-deposited hardness of the austenitic work-hardenable alloys will range from 170 BHN (austenitic manganese electrodes) to 285 BHN (austenitic chrome-nickel electrodes). With deformation they can work-harden rapidly to 450-550 BHN.

Hot hardness of high manganese work-hardenable alloys is not a property that can be exploited because reheating of the EFeMn deposits above 500 to 600°F (260 to 320°C) will cause serious embrittlement.

The austenitic work-hardenable alloys are considered the outstanding engineering materials for heavy impact service. For this purpose, where heavy buildups are required, the work-hardening alloys are superior to air-hardening types.

The resistance of the austenitic work-hardenable alloys to high stress abrasion from hard sharp angular particles like quartz is only moderate. Resistance to metal-to-metal wear or low stress abrasion is frequently good. The chromium-bearing grades are often favored over the EFeMn alloys because of their higher compressive yield strengths.

In the group of work-hardenable alloys, the chief constituent of the weld deposit is austenite, the nonmagnetic form of iron that can hold considerable carbon in solid solution. Austenite that is nearly saturated with carbon is responsible for the properties of these filler metals.

In the EFeMn weld deposits, austenite is not entirely stable and will reject some carbon at intermediate temperatures or during deformation. This precipitated carbon takes the form of fine manganese-iron carbide particles, films at grain boundaries, flat brittle plates or pearlite. Carbide precipitation in any of these forms leads to increased hardness and brittleness. Deformation (work-hardening from impact) raises hardness most effectively with the least loss in toughness. Carbide precipitation, caused by slow cooling from the completely austenitic range, or by reheating the tough structure, is undesirable.

Carbide precipitation in manganese steel base metal, which is usually higher in carbon than these filler metals, is the major form of weld damage in the heat-affected zone. Manganese steel should be welded with rapid heating and cooling, low current and time control such that overheating is avoided. For the same reason, gas welding is almost never used.

Weld deposits of the work-hardenable alloys are not usually heat treated. It may sometimes be advisable to heat treat the FeMn classification to restore toughness after embrittlement by too much reheating. Water quenching after two hours at 1850°F (1010°C) is usually sufficient for this purpose. The weld deposit should be free of cracks if this is done; otherwise, oxidation of the cracks may cause considerable structural damage and cancel the benefits of the toughening heat treatment.

All grades of the austenitic high manganese alloys are very difficult to machine with ordinary tools and equipment. Finished surfaces are usually ground.

APPLICATIONS

This section provides examples of successful surfacing experience with comments on the wear analysis and material selection aspects.

ROCK DRILL BITS FOR OIL WELL DRILLING

Cone type rotary drill bits are held with great weight against the rock face while they are turned, the cutting action being largely a failure of the rock (chipping and cracking) under the very high compressive and shear stresses. Some erosion from rock chips and drilling mud occur, but the high stress abrasion is paramount. Tungsten carbide is the peerless protective agent, applied by oxyacetylene or atomic-hydrogen welding. Finer granule deposits (e.g., 10-30 mesh) are also used to protect the joints of the long string of drill pipe. Better protected parts of the drill (bearing surfaces) may employ high chromium iron or AWS Class CoCr-C surfacing filler metal.

SCREW CONVEYORS AND CLASSIFIERS

Such service is usually typical of low stress scratching abrasion and high-chromium iron surfacing is a logical choice. However, in some cases the more expensive but more abrasion resistant tungsten carbide (used as a fine granule deposit) may prove more economical. Martensitic iron and HC250 castings may be used; surfacing these worn parts is seldom feasible as they tend to crack from the heat of welding.

AGRICULTURAL EQUIPMENT PARTS

These usually operate under conditions of low stress erosion by sand (even in clay soils the chief abrasive is quartz in finely divided particles) and austenitic high-chromium iron is a popular overlay. It wears to a high polish, reducing drag. However, if the soil is rocky, impact may be present to ruin the overlay by chipping. The matrix of a fine granule tungsten carbide overlay may provide the extra toughness needed, or it may be necessary to use lower carbon and tougher alloys. Gas welds are usually used for agricultural hard-facing.

TRACTOR PARTS

Tractor rollers and idlers involve serious wear problems. The most abrasion resistant alloys cannot be used because they lack sufficient toughness. The compromise evolved by experience is low carbon air-hardening martensitic steels, applied by automatic arc welding. Special equipment has been designed for this purpose. The deposits are of high quality and because of the low carbon content (usually below 0.25%) are relatively free from thermal stress cracks that would plague the more abrasion resistant alloys.

JET PIERCER DRILL STEMS

This service involves a combination of high and low stress abrasion and high-chromium or martensite irons would be logical alloys. However, the most economical surfacing method has modified the choice. The automatic submerged arc process has been adapted, using a continuous, spiral, slightly overlapping bead on the cylindrical surface. Fluted areas of the stem are filled before surfacing with carbon steel inserts that are later removed. The best wear life is obtained with the EFeCr high-chromium irons, but the crack prone deposit may lead to eventual failure of the base AISI 1040 steel tubing. Base tube life is extended considerably by use of a modified Type 420 stainless steel deposit, free from cracking, though the wear life was only 75% of that of EFeCr deposits.

HOT EROSION BY GAS BORNE ABRASIVES

Fan blades blowing hot sinter, powdered coke, etc., and the ducts of catalytic petroleum cracking plants, typify this area. For the latter, operating near 1000-1100°F (540-590°C), high-chromium irons have done well and techniques for surfacing large areas of pipe have been developed. Economy may dictate a single layer deposit, in which case the formulation of the electrode to compensate for dilution by the base metal (with due regard for the welding method) is an important technical consideration. Iron ore pelletizing operations require protection of fan impellers from hot wear. Repeated hard facing led to base metal failure, with the result that the design was changed to include replaceable wear plates. These are now surfaced with EFe5-B (high speed steel) for 800-900° (430-480°C) service. Tungsten or molybdenum alloyed high-chromium iron has given excellent service in some

hot coke and ash handling systems. The field of hot erosion has many variables, and it may be difficult to transfer experience effectively from one installation to another. In general, the severity of wear will increase with the temperature and the velocity of the abrasive. An arbitrary upper limit is 1200°F (650°C) for the iron base alloys. Above this temperature, the 2.5% carbon Cr-Co-W or Ni-Cr-B alloys probably would be better.

STEEL MILLS EQUIPMENT

Almost the entire gamut of surfacing applications can be found in the steel industry. Ingot tong bits may be protected with a chromium-tungsten cobalt-base alloy; bar mill guides, with an austenitic high-chromium iron; pickling tank parts, with corrosion-resistant copper-base alloys; and parts subject to frictional wear, with some lubrication, with aluminum bronze (Fig. 44.15). Martensitic and high-chromium irons applied by gas welding have been used successfully for mill buttons, guides, rollers, etc., where light impact and some abrasive wear are involved and where the overlay must be free from defects to avoid marring the surface finish of the hot-rolled product. Shear blades have been made of 1045, 1060 or 1090 steel with the cutting edges manually arc welded on as a martensitic steel overlay. Excellent life in both hot and cold shearing operations has been obtained. The welds were not always crack free, but the cracks did not prevent good performance. Austenitic manganese steel has been widely used for metal-to-metal wear with heavy impact in such items as large mill coupling boxes, pinions, spindles and the like. Although it is recommended that the base metal in such cases also be austenitic manganese steel, it is common to find that the application of the austenitic steel as an overlay on carbon steel is successful.

One of the more dramatic applications of surfacing is on blast furnace bells (Fig. 44.6). Several thousand pounds of overlay are required for protection. For the burden area, where some thermal cracking is acceptable, (refer to section on Thermal Stress) erosion resistant irons may be used, but the seat area must be machinable and crack free, requiring a softer and tougher filler metal. The soft nickel-base alloys have proved to be poor in erosion resistance. American practice includes use of a low-carbon martensitic steel for the seat and a higher-carbon chromium steel or iron for the burden surface. A Ni-Cr austenitic manganese steel has been successfully used at an Indian steel plant for both surfaces.

Hot wear applications are numerous, many of them being served by the cobalt-base alloys. In some cases small castings of hard facing alloys compete with weldments. For larger parts, especially if automatic welding can be employed, surfacing is clearly superior (Fig. 44.16). It is worthwhile for someone in a steel mill to become a well informed hard facing specialist, as space does not permit discussion here of all the alloys that are currently being used.

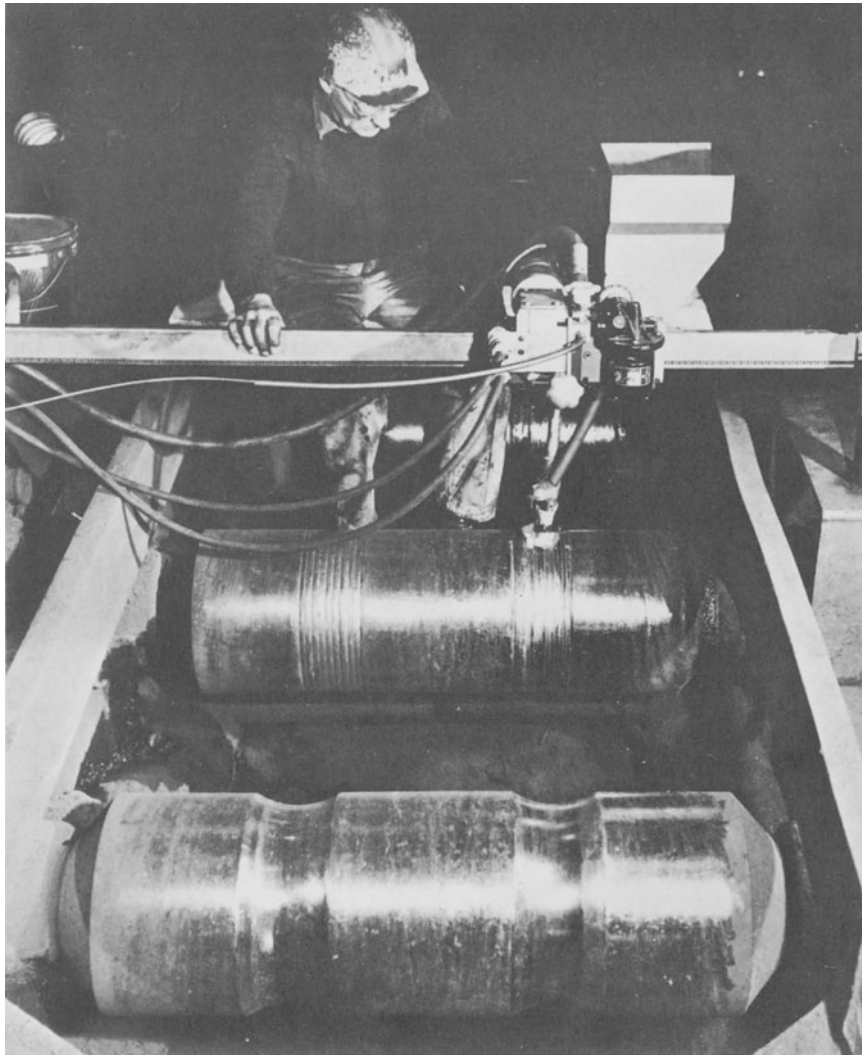


Fig. 44.16.—Automatic submerged arc resurfacing of worn steel mill table rollers with a low carbon Ni-Mo-Mn martensitic steel under a neutral flux. Rebuilding in place is faster and more economical than changing the worn rollers.

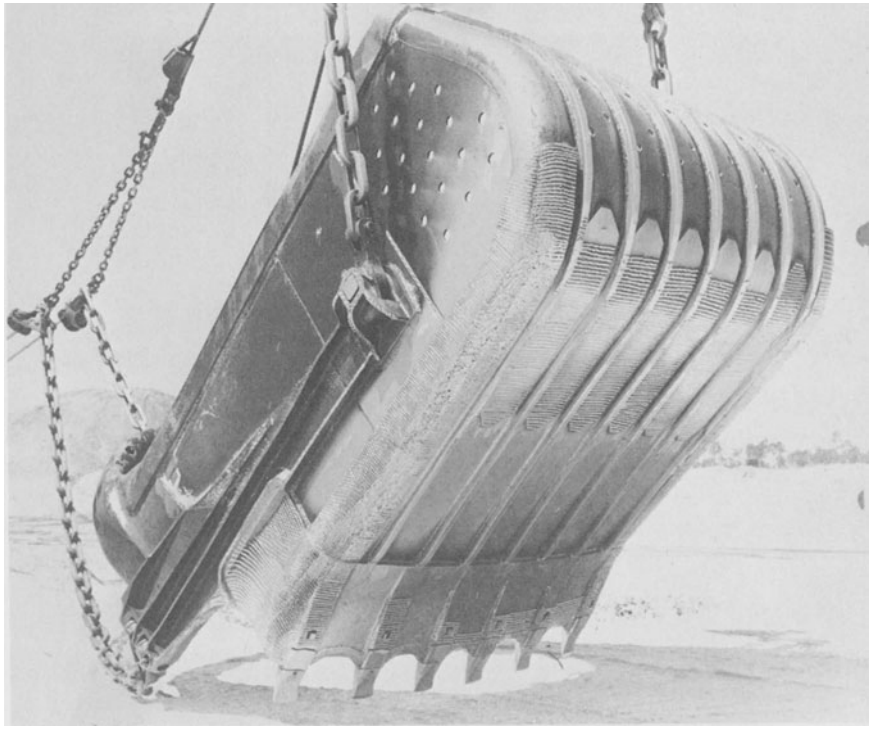


Fig. 44.17.—Dragline bucket with bottom protected by beads of abrasion resistant iron surfacing alloy. The pattern of the beads is based on performance in service against loose sand abrasion.

MINING AND CONSTRUCTION EQUIPMENT

Many kinds of wear are involved with power shovels, dredges, scrapers, and the like (Fig. 44.17). Toughness is vital to many of the parts, leading to use of austenitic manganese steel or high strength construction steels. Manganese steel surfacing is common, especially where wear is obviously gouging abrasion from sharp rocks. If martensitic or austenitic iron weld beads can be protected from the effects of impact, as by placing them in grooves in the base metal, they can increase the life of the manganese steel base. Dipper teeth are frequently surfaced, both on the replaceable tips and the massive bases or adapters. Shovel lips and sides are protected with hard-facing beads in many patterns. Material selection should be in the order of (1) austenitic manganese steel, (2) low-carbon (about 0.30-0.60% C) martensitic steel, (3) high-carbon (about 1.0% C) martensitic steel, (4) austenitic irons, (5) high-chromium or martensitic irons, and (6) composite tungsten carbide. These are in order of decreasing toughness and increasing abrasion resistance. Unless experience from a very similar installation is available, experimentation is necessary to determine how far up the list toward maximum abrasion resistance selection can go before impact failures become a problem.

For the many partially protected surfaces, where wear is frictional but is accentuated by dirt and grit contamination as in bearings, surfacing with low or medium carbon air-hardening steels (with hardness restricted to a level that permits machining) by automatic arc welding is common.

ROCK AND ORE CRUSHERS

Roll crusher shells are frequently resurfaced by arc welding, sometimes on a regular maintenance schedule. Martensitic steel and high-chromium iron overlays are common. Both high stress abrasion and medium impact are usual. Less often gyratory crusher parts of manganese steel are rebuilt by automatic arc welding, which involves the possibility that the continuous heat input will overheat the austenitic base and cause carbide precipitation embrittlement. Very high compressive stresses characterize gyratory crusher liners and toughness is needed.

Practice in this area is still evolving. One mine rebuilds deeply worn grooves with austenitic manganese steel, topping off with a Cr-Mo martensitic iron. Another may alternate beads of manganese steel and a hard iron side by side. Overlays of Cr-Mo martensitic iron have been used experimentally on new austenitic manganese steel mantle and bowl liner castings; in one crusher this had been advantageous while in another the added life did not justify the expense of surfacing. Apparently the cost and performance factors must be worked out at each installation.

RAILWAY TRACKWORK

Because of the safety conferred by its toughness and slow crack propagation austenitic manganese steel is the standard material for frogs, crossings and other special trackwork parts that receive severe service. It batters down eventually under repeated impact of wheel loads. Repair involves removing the work-hardened material by grinding and replacing it with lower carbon alloyed manganese steel. High yield strength is an asset to this surfacing, enabling it to better resist deformation from impact (See Chapter 66 on Austenitic Manganese Steel in Section 4).

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CHAPTER 45

HIGH FREQUENCY WELDING

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CHAPTER 45

HIGH FREQUENCY WELDING

FUNDAMENTALS OF PROCESS

DEFINITION AND GENERAL DESCRIPTION

High frequency welding is a welding process in which coalescence is produced by the heat obtained from the electrical resistance of the work to the flow of high-frequency electric current with or without the application of pressure. High frequency welding may be divided into two categories: (1) high frequency resistance welding, in which the high frequency current is introduced into the work by direct electrical contact; and (2) high frequency induction welding, in which the high frequency current is induced in the work by the use of an inductor coil, without electrical contact. (High Frequency induction welding is sometimes called induction resistance welding).

High frequency resistance welding, in which the current is introduced by means of direct contact, may be utilized for a large number of configurations and types of welding. In turn, it may be divided into continuous high frequency resistance welding, in which two or more pieces of metal are continuously welded together at a high rate; and into finite-length or individual-piece high frequency resistance welding, in which the whole area to be welded is heated at once and a weld produced. Induction welding of any kind can be used only in cases where there is a closed-loop path, or a complete circuit for the flow of current wholly in the work; this may, in turn, be divided into fixed position static butt and lip-type welding, generally of a circular nature (such as for pipe ends); and continuous high-speed welding (such as for side seams of tubing).

The current for high frequency welding of either type may be produced by: high frequency motor generators; solid-state inverters; or for higher frequencies, by vacuum-tube oscillators. Frequencies used are in two ranges: the lower is from 3,000 to 10,000 Hertz; and the upper is from 300,000 to 500,000 Hertz.

High frequency current flowing in metallic conductors tends to flow on the surface of the material at relatively shallow depths. For example, at 450,000 Hertz the depth of penetration of the current in steel at a temperature of 2,000°F (1,093°C) is about 0.030-in; at 10,000 Hertz the depth in steel at a temperature of 2,000°F (1,093°C) is about 0.2-in. High frequency current introduced into the work by means of contacts or by induction, may have its path in the work controlled by variations in the inductance of the circuit and the nearness of its own return circuit. The latter is called the proximity effect.

Because high frequency current tends to travel on the surface of the material in a restricted path area, the effective resistance of the current path in the work increases with the frequency. This means that high surface heating rates can be achieved with relatively low currents and higher voltages, as compared to 60 Hertz deep heating.

High frequency current may be introduced in the work by means of fixed or sliding contacts with very little area and pressure, as compared to that required for low frequency currents. High frequency current introduced either by induction or direct contact methods, travels on the surface; its path may be controlled; less current is required for high rates of heating, and the current may be introduced to the work by very simple contacts, or by a simple noncontacting induction coil. These factors make the process suitable for efficient, very high-speed welding, as compared to other processes.

Both magnetic and nonmagnetic material may be heated by high frequency currents. In nonmagnetic materials all of the heating is from resistance; in magnetic materials there is some slight additional heating from hysteresis. This is usually negligible.

Electrical resistance heating has been employed for many years using frequencies as low as 25 Hertz for purposes such as: (1) melting; (2) heating heavy masses of metal for annealing; (3) pre- and postheating; and (4) forging. Subsequently, with the requirement for heating less massive structures (and in order to gain the advantages of the skin effect produced by higher frequencies) high frequency motor generator sets and high frequency vacuum tube units were employed (usually with the current being induced into the work by means of an inductor). The high frequency heating current was employed for operations such as heat treating, brazing, and soldering. This equipment has been adapted to many of the welding applications that were formerly reserved for low frequency resistance and arc welding methods.

PRINCIPLES OF OPERATION

CONTINUOUS HIGH FREQUENCY RESISTANCE WELDING

Continuous high frequency resistance welding is generally performed by introducing current into the work at about 400,000 Hertz by means of small sliding contacts. The parts to be joined are brought together in a "V" of about 4 to 7 degrees. The high frequency current follows a "V"-shaped path down one edge of the "V", and up the other, from one contact to the other. The two edges to be welded are resistance heated by the high frequncy current at a shallow depth, thus creating a high effective resistance. Speed and power level are adjusted so that the two facing edges are brought together at welding temperature, and then squeezed with forging pressure to produce the weld. Metal and impurities are squeezed out into two external upsets, which may be cut off, leaving smooth surfaces. Figure 45.1 shows configurations for butt welding the seam in a continuously-moving tube.

Another form of continuous high frequency welding utilizes 10,000 Hertz for a variation of low frequency seam welding. By use of the depth of current penetration possible with high frequency welding, in combination with the current-confining principle of the proximity effect, lap and butt welds are readily made (joints may also be made with this process by welding the lips of two pieces together). Two or more layers are heated in a confined line, and then squeezed together to form a continuous high-speed weld. This is called high-frequency current penetration welding.

FINITE-LENGTH HIGH FREQUENCY RESISTANCE WELDING

Techniques have been devised for bringing the ends of two strips together, and passing a high frequency current through the joint area. The high frequency current is confined to the joint area by means of proper positioning of a return, or proximity conductor, over the weld. By selection of the proper frequency, the depth of penetration of the current will heat the joint all the way through. When the joint is at welding temperature, pressure is applied and upset automatically takes place. Joints with small upsets are made in this fashion at very high rates of speed.

CONTINUOUS INDUCTION WELDING

Continuous induction welding can only be used in cases where there is a short-circuit path (or closed loop) wholly in the work, so that the induced current may circulate in the weld area. Typical is butt welding of tubing. In induction butt welding of tubing, the tube's edges are brought together in a 4- to 7-degree "V"; just downstream of the weld point. At the open end of the "V", an inductor encircles the tube. High frequency current in the inductor

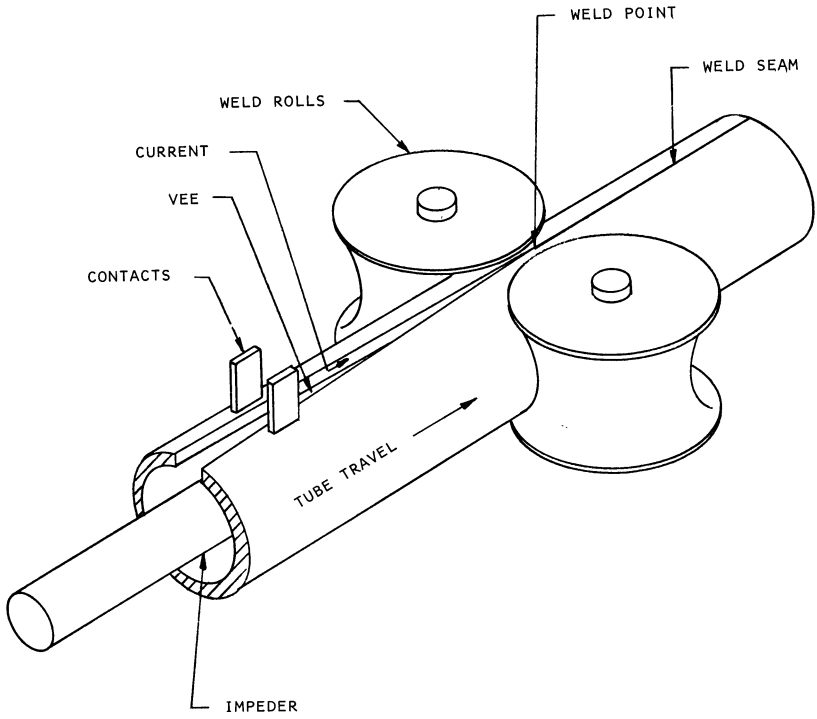


Fig. 45.1.—Continuously butt welding a tube seam by high frequency resistance welding.

induces a circulating current around the back of the tube and in the "V" produced by the convergence of the edges of the tube. The current heats the edges; by controlling the speed and power level, the edges are brought together at the proper welding temperature. Squeeze rolls press the edges together, producing a weld with liquid metal and impurities being squeezed out into an upset. This upset is then cut off, leaving a smooth surface. This technique of tube welding is advantageous for coated metals. Figure 45.2 is a representation of the induction butt welding of continuous tubing.

INDUCTION WELDING OF DISCRETE PIECES

Induction welding of individual pieces is also performed when there is a closed circuit path permitting the circulation of induced high frequency current in the piece. Typical of these applications are the butt welding of pipe, or tube ends, in which the two ends are pressed against one another with a force sufficient to produce a weld when welding heat is reached. An induction coil surrounds the joint under pressure and induced current circulating in the butted pipes causes the ends to become heated to welding temperature very rapidly. At welding temperature, the pressure causes a solid-phase forge weld with no liquid metal formed; an upset is produced and it is usually left in place.

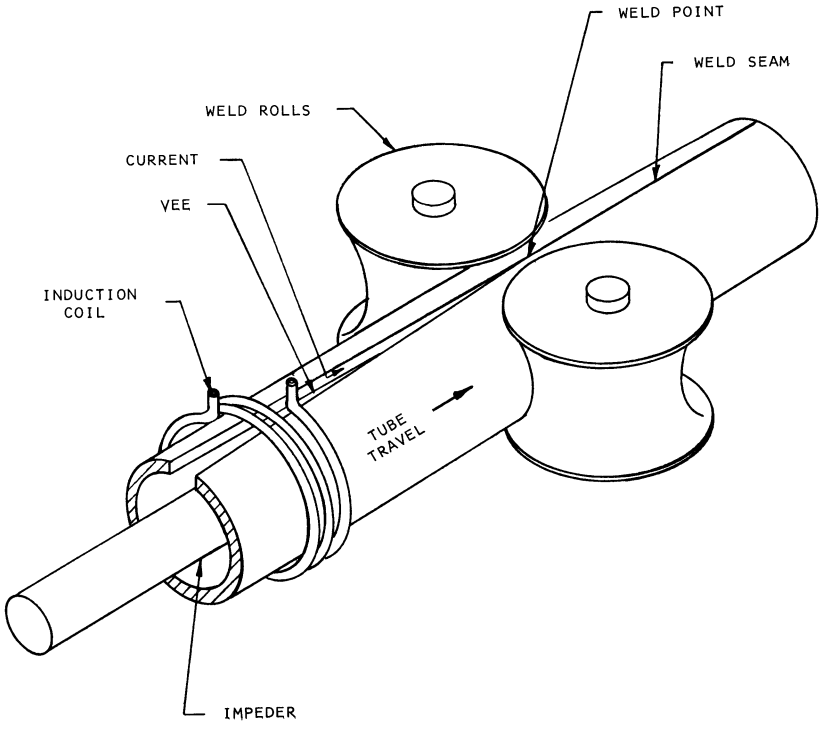


Fig. 45.2.—Continuously butt welding a tube seam by high frequency induction welding.

Figure 45.3 shows induction butt welding of 7-in. O.D. x ¼-in. wall pipe in a trench. Welding time is less than 1 minute.

In certain cases in induction welding, a circular joint may be made by melting the two edges of the lip together with an induced current. Surface tension of the liquid metal causes the two edges to flow smoothly together. Figure 45.4 shows typical cross sections of three of these joints.

Another very recent form of induction welding of individual pieces is performed by induction heating a joint, such as a lap joint, between two pipes. After the parts are at welding temperature, a very large extra pulse of current in the inductor produces magnetic forces in the work that press and forge the hot parts together to make the weld.

EQUIPMENT USED

POWER SOURCES

Power generators for high frequency continuous welding (either by high frequency resistance or induction) above 10,000 Hertz are usually restricted to vacuum tube oscillators. Figure 45.5 illustrates the basic circuit in use for high frequency RF generators. Section R represents schematically the mercury-



Fig. 45.3.—Output transformer, work coil, pipe alignment jig and hydraulic clamps in place around a 7 in. pipe ready for on-site welding.

tube rectifier used to convert the plant input voltage into the high-voltage direct-current utilized by the oscillator circuit, Section S. Solid-state rectifiers are now coming into use as a substitute for the tube rectifier. Section T is the output portion of the circuit. An induction coil (or inductor) surrounding the metal to be heated is shown.

The inductor can also be placed adjacent to the metal, when it is not practical to surround the parts being welded. This type of output is used where there is no contact with the material being welded, and is an arrangement widely employed by industry for such processes as heat treating, brazing, and soldering.

Section TT is the alternate output circuit, used when there is contact with the materials being welded, as in high frequency resistance welding of tubing.

High Frequency RF generators range from 1 to over 600 KW output to handle the wide range of materials and production requirements called for in welding.

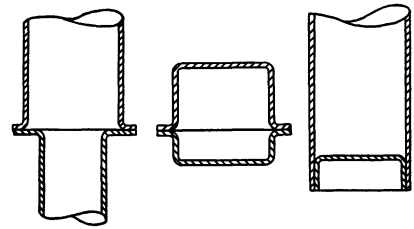


Fig. 45.4.— Typical joint types for induction welding.

For frequencies in the range of 3,000 to 10,000 Hertz, used for some continuous high frequency welding applications and also for some individual parts or pieces, high-frequency welding power is generally produced by motor generators or by solid-state inverters.

The motor generators used for this purpose usually consist of a high-frequency alternating-current single-phase alternator driven by an induction motor.

The inverters usually consist of a solid-state rectifier that converts three-phase alternating current to direct current. The direct current, in turn, is converted by a controlled solid-state device to high-frequency alternating current with frequencies up to 4,000 Hertz. Higher frequencies up to 10,000 Hertz are expected to be available shortly.

MATCHING DEVICES

Vacuum-tube oscillators inherently have high output impedances and should be fed into a high impedance load. Since the inductors and the contacts used for high frequency resistance welding are both low impedance loads, some impedance matching device is necessary in order to transfer energy efficiently from the generator to the work. This device is basically a transformer connected directly to the generator output; it is placed close to the welding operator, who is often a distance from the generator.

The transformer, or impedance matching device, is generally of simple construction. It consists of a primary winding composed of multiple turns of water-cooled copper tubing surrounded by a secondary of one or several turns of water-cooled copper tubing. The transformer is designed to provide the best possible coupling of primary to secondary while maintaining electrical isolation between primary and secondary.

The secondary of the transformer, together with the inductor coil or contact system, forms the low-voltage high-current circuit. It is desirable to maintain the lowest possible impedance in the leads connecting the inductor coil or contacts to the transformer. This is accomplished by using short connections, usually flat plates closely spaced to each other. A minimum spacing of flat leads is maintained, consistent with the voltage requirements. The losses in poorly designed leads or incorrectly matched transformers will often prevent successful performance of a high frequency welding operation. On most installations, capacitors are used across the primary of the transformer to improve the load match.

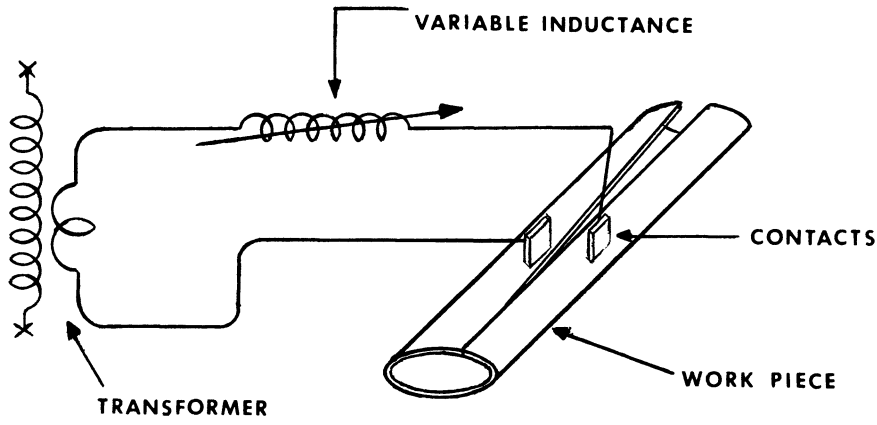


Fig. 45.5.—Typical electrical circuits for high frequency welding.

In motor generator and solid-state low-frequency power sources, the output of the device is normally fed through high-current cables to the primary of a transformer that is somewhat like a 60 Hertz transformer utilizing a laminated iron core. Capacitors are connected in parallel with the primary of the transformer in order to improve the power factor of the high inductance load so that the generator or inverter is operated as close to unity power factor as possible. The output of the transformer is at low voltage and high current; it feeds an induction coil or contact system through very short and closely spaced leads. The transformer ratio must be selected to give optimum power transfer between the output of the generator and the welding load.

CONTACTS

Contacts are means through which high frequency current is conducted into the workpiece for high frequency resistance welding. The material used for high-frequency contacts, either fixed or sliding, is usually of the copper-silver group of alloys. The contacts are required to carry rather large currents, so that it is necessary in most instances to provide water cooling for the contacts and mounts. The force of the contacts on the material being welded is generally low. It is usually in the order of 5 to 50 lbs. on continuous welding, and 5 to 100 lbs. on static welding operations. The forces required are dependent upon the thickness and condition of parts being joined, as well as on the current density.

The contacts have a relatively long life on continuous welding of nonferrous materials — they last as much as several hundred thousand feet of tubing before having to be replaced. Life on ferrous metals, which are clean or have tight scale, is around 50,000 to 100,000 feet of tubing, or more. On static welding operations the contacts will last for many thousands of operations before requiring dressing or replacement.

Contacts are silver brazed to heavy copper mounts so that replacements can be made by replacing the mount and contact tip assembly. Repairs can be made easily by rebrazing new contact tips on the mount.

INDUCTION COILS (INDUCTORS)

The induction coil is the means through which the high frequency alternating current flows to set up the alternating magnetic field required for the high frequency induction heating of a workpiece. They are generally formed from copper tubing, copper bar, or copper sheet, and are water cooled internally. The life of induction coils is usually dependent on whether physical damage occurs.

The coil can be of the single- or multiple-turn variety, with the geometry conforming to the workpiece or to the area to be heated. Although the inductor usually surrounds the workpiece, it is not a requisite in all cases. The efficiency is highest with the surrounding inductor. However, when the shape of the workpiece or the work to be heated precludes using a surrounding coil, other coil shapes, which have lower efficiency, are made and placed adjacent to the workpiece. The magnetic field, which induces the heating current in the workpiece, diminishes rapidly as the space between the coil and the work is increased. The sharpness with which the heated pattern in the workpiece mirrors the shape of the coils is increased with frequency and with the closeness of the coil to the surface of the workpiece. Thus, the coils in most instances are placed as close to the workpiece as practical, consistent with voltage requirements and variations in the shape of the part being welded.

IMPEDERS

In tube or pipe welding with either high frequency resistance or high frequency induction, there is a wasted current flowing around the inside surface of the tube. This current is in parallel with the welding current and is of no value. Therefore, in many tube welding installations, a magnetic core called an impeder is placed inside the tube in the weld area. This core increases the inductive reactance of the current path inside the tube and reduces the inside current significantly. This, in turn, makes more power available for heat in the weld zone with a corresponding increase in welding speed for a given power input.

CONTROL DEVICES

INPUT VOLTAGE REGULATORS

High frequency welding is by nature a mass-production system. Only a few hundredths to a few thousandths of a second when traveling at 350 fpm are required to bring the metal from room temperature to welding temperature. Thus, it is important that the power source be automatically and continuously regulated. Several systems of regulation are used, the choice being dependent upon the in-plant conditions, the welding requirements, and the size of the

high frequency generator. The most commonly-used regulators are:

1. Motor generator with high inertia to provide a constant output voltage, installed for one or a group of machines, but specifically devoted to feeding and controlling the high frequency equipment.
2. Electromechanical regulators, such as an induction regulator, installed on the individual equipment or on a group of machines. These regulators are considered sufficient where the in-plant conditions do not cause large variations in the power surges. (Nearby equipment demanding heavy current, operating intermittently, may cause large voltage changes that are beyond the reaction speed or range of this type of regulator).
3. Electronic and saturable core reactor regulators are employed mostly on high frequency equipment in the lower capacity ranges. (They are now becoming available for the larger capacity units. Electronic and saturable core reactor type regulators have faster response than induction regulators, but cannot isolate the high frequency equipment from short duration power line peaks in the way a motor generator does. Electronic regulators include silicon-controlled rectifier types that can be used with solid-state rectifiers).

All three types of regulators can include power level control. Electronic and saturable types, in addition, can include overload protection, system fault detection devices, and monitoring systems for the associated handling machinery employed in the welding operation.

HIGH FREQUENCY GENERATOR POWER CONTROLS

It is general practice to utilize a high frequency generator of greater capacity than called for by the application; thus it is desirable to have a control for raising and lowering the level of high frequency power to meet the individual demands of the welding operations. There are numerous types of high frequency power controls; all basically perform the function of lowering or raising the current flowing in the contacts or the inductor coil.

Thyratron, or phase-shift control, using a simple phase shifting of the voltage applied to the grid of the thyratron, is effective in raising and lowering the high frequency power level. Controls are available that permit automatic or manual power level setting.

Saturable reactor control placed in the circuit before or after the main plate transformer provides a smooth power control. By the addition of a magnetic amplifier and instrumentation, automatic controlling can be accomplished. Line voltage regulation can also be obtained with accessory circuits such as silicon-controlled rectifier units, if power line fluctuations do not occur too rapidly.

Variable impedance control is accomplished by connecting a variable impedance in series with the secondary winding of the welding transformer, and the inductor, or contacts. This is the most direct method of raising or lowering the high frequency power level. It does not alter the basic characteristics of the high frequency generator. Generally, this control is manually adjusted for the desired power level.

Another recent innovation in control is the use of a system utilizing a controllable vacuum tube device as a variable resistor placed in series with the d-c output of the power supply to the oscillator.

In continuous high frequency welding operations, it is considered essential that the welding power be continuous and ripple free, particularly for high-speed light non-ferrous metal welding. For heavy ferrous metal welding, this is of much less importance. In high-frequency motor generator power sources, power control is performed manually or automatically by varying the d-c field on the high frequency generator.

TIMING CONTROLS

For finite-length or individual piece high frequency resistance or induction welding, duration of the time of welding may be controlled by motor-driven timers or electronic timers that actuate the main contactors. In very high speed work in vacuum tube equipment, it may be desirable to key the grids of the oscillator tubes by use of direct current grid voltages. Very short pulsing times may be produced and controlled by this means. In certain cases, movement of the workpieces in the course of upsetting the weld is sensed and used to turn off the welding current.

APPLICATIONS

The number of applications for high frequency welding is growing at a rapid rate. Industry acceptance of the process is now general throughout the world, particularly for continuous welding operations. Equipment manufacturers have been working steadily on the process, and with new developments in technology, users of high frequency equipment have begun to seek out other applications.

The process is one of high efficiency. Well-designed installations use as much as 60% of the energy drawn from the power line; this appears as useful heat in the work. Practically all high frequency welding machines use a balanced three-phase power system.

The metals that can be welded with the continuous process include almost every carbon and alloy steel, hot-rolled, pickled, and cold-rolled steel; aluminum alloys with various tempers; copper alloys, and many others. Even dissimilar metals can be joined in many cases.

Metals that require inert atmospheres (such as argon) can also be welded with the high frequency process. Static high frequency welding processes are generally applicable to steels and stainless steel, and in the future it is expected that they will be suitable for some of the nonferrous materials.

As the time required in high frequency welding is short and the heat localized, there is minimum oxidation, discoloration, heat-affected zone, and distortion of the parts. Containers, which cover materials that would normally be damaged by excessive heat, can be high frequency welded. Included in the latter is the continuous welding of electrical cable sheaths, with the cable inside the sheath while it is being welded.

High frequency welding has been successfully employed for joining steels with thicknesses ranging from 0.004 to ¾-in., both continuously and statically.

Most nonferrous materials may be continuously joined in thicknesses up to ⅛-in. and more. Figure 45.3 shows an installation for static high frequency induction butt welding of steel pipe in the field. The pipe is mild steel, 7-in. diam., ¼-in. wall thickness. The pipe ends are machined square and pressed together hydraulically. The induction coil heats the mating ends simultaneously while they are under pressure. Argon gas is directed under the inductor into the heated area, and additional argon is carried to the inside joint area to prevent oxidation during heating. It requires about 60 seconds to make one joint with this 10,000 Hertz mobile equipment. Ten thousand Hertz is used because of the large depth of current penetration in the pipe wall (0.2-in.).

Figure 45.6 shows a pressure fixture for induction butt welding the ends of pipe in a plant. The spatter and flash encountered with conventional flash welding are not present with static high frequency butt welding.

The welding operation can be performed in a normal atmosphere, inert atmosphere, or a vacuum, depending upon the metal employed or the specific requirements of enclosed materials.

At present, static high frequency resistance welding may be used for butt or lap welding finite-length longitudinal seams up to 36-in. long. For example, in joining coil ends together in steel, a butt joint is made by shearing square both ends of the coils to be joined, and pressing the ends together with sufficient pressure to produce a weld when the parts are heated. The parts are placed on a metallic anvil, with a high-frequency proximity conductor arranged over the top of the seam, as shown in Figure 45.7. High-frequency current in the 10,000 Hertz range is passed through the system. The current flows through the proximity conductor, into the anvil, across the anvil, and then up into the joint. It flows in the joint in a narrow line because of the proximity conductor above, then back into the anvil, and thence to the source. When the butted edges are heated, the pressure will cause a forge weld to occur between the two ends.

A typical operation is the butt welding of two 10-in. wide x 1/16-in. thick steel pieces. Welding time could be as low as ¾ second, with a small amount of upset produced. This process is called "high frequency bar butt current penetration welding".

HIGH FREQUENCY TUBE WELDING

One of the major applications of continuous high frequency welding is the butt welding of tube and pipe, in which the longitudinal seam is continuously butt welded at high rates of speed. This process has produced a significant percentage of the world's output of pipe and tube. It is usable for the manufacture of nonferrous and ferrous tubing, as well as heavy-wall pipe.

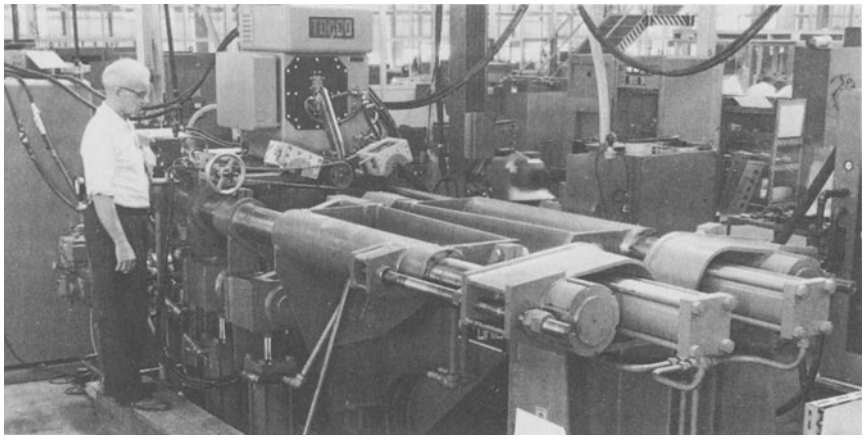


Fig. 45.6.—In-plant heavy-wall tube end butt welding.

The process uses continuously-formed tube made in the conventional manner from strip stock. After the tube is formed, but while still in a slightly open state, the edges are brought together at a weld point, generating a small "V", with the apex or the root of the "V" (weld point) occurring approximately where final squeezing pressure is produced.

High frequency resistance and high frequency induction welding are both used. High frequency resistance welding is used for all diameters up to 48 in., and for wall thicknesses up to ⅝ in. High frequency induction welding is usually used for diameters less than 8⅝ in., and thicknesses less than 7/16 in.

With high frequency resistance welding, the contacts are placed upstream from the weld point, on both sides of the "V" produced by the edges of the tube. High-frequency current flows in through the contacts, and thence along the sides of the "V". This heats the two edges to welding temperature, so that they may be forge welded together. The principle is shown in Figure 45.1.

With high frequency induction welding, the same forming method is utilized, and a high-frequency inductor is arranged to surround the tube without touching it. The inductor induces a current in the tube that flows in the "V" area, in a similar fashion to that of high frequency resistance welding. In addition, the current flows all around the back side of the tube, making it a closed circuit. Figure 45.2 shows the arrangement of the tube and coil.

The penetration of heat beyond the butt faces is only a few thousandths of an inch. Any heating much beyond the surface of the faces is by thermal conduction. There is so little time required and so little heat produced in the weld area that in some metals very little grain change takes place. It is almost impossible to find the weld in a cross section of the area. Welding speeds for tube and pipe lie in the 50 to 1,000 fpm range.

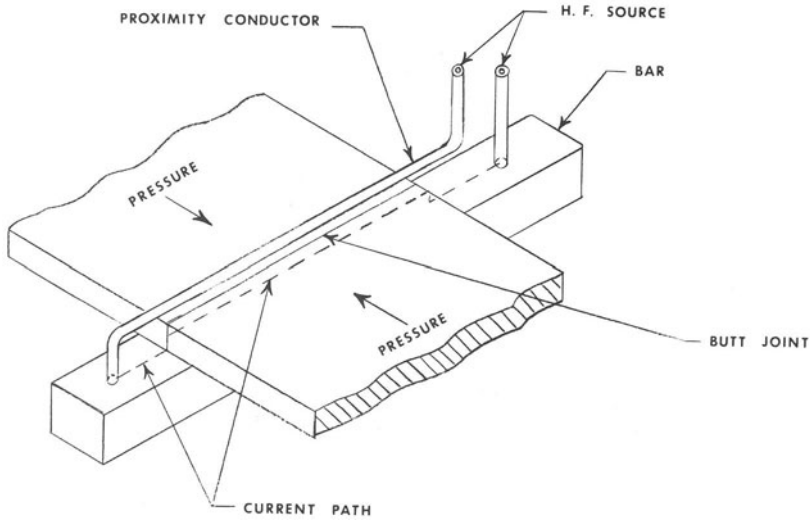


Fig. 45.7.—Joining coil ends together using static high frequency resistance welding. Note proximity conductor arranged over the top of the seam.

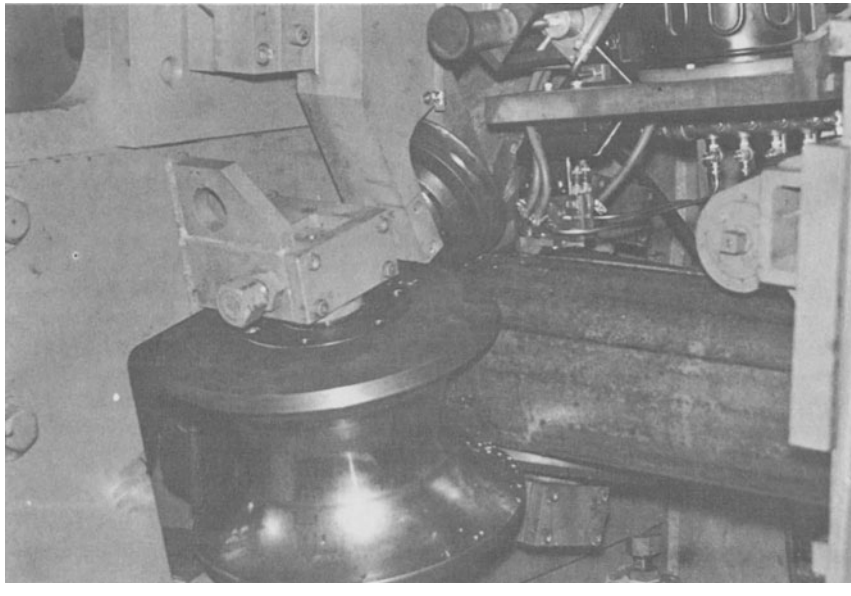


Fig. 45.8.—Close-up view of contact pipe butt welding on 16-inch diameter pipe.

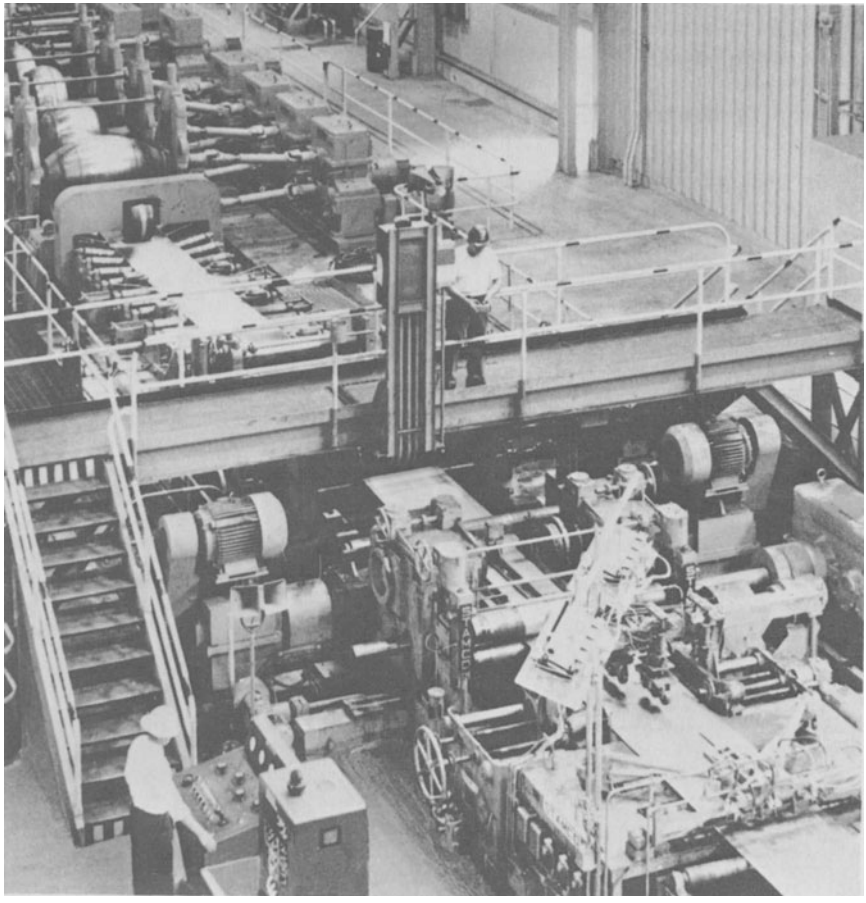


Fig. 45.9.—Mill for high frequency resistance welding 24-inch diameter pipe.

TUBE WELDING

The high frequency power source, and associated output and control devices used for tube and pipe welding, is the same vacuum-tube type as those previously described. The high frequency welding process can be used on almost any existing tube mill after conversion. A wide range of new, continuous tube forming equipment specifically designed for high frequency welding is available. Sizes range from the smallest, handling tubing up to 1 in., to those that form diameters up to 48-in., with wall thicknesses up to ⅝-in.

Figure 45.8 shows a close-up view of the tube forming operation of large-diameter hot-rolled black steel pipe welding.

Figure 45.9 shows a large mill for the production of 24-in. diam. pipe, with a wall thickness of ½ inch. Tubes are formed to diameter, and fed into the high frequency resistance welding station.

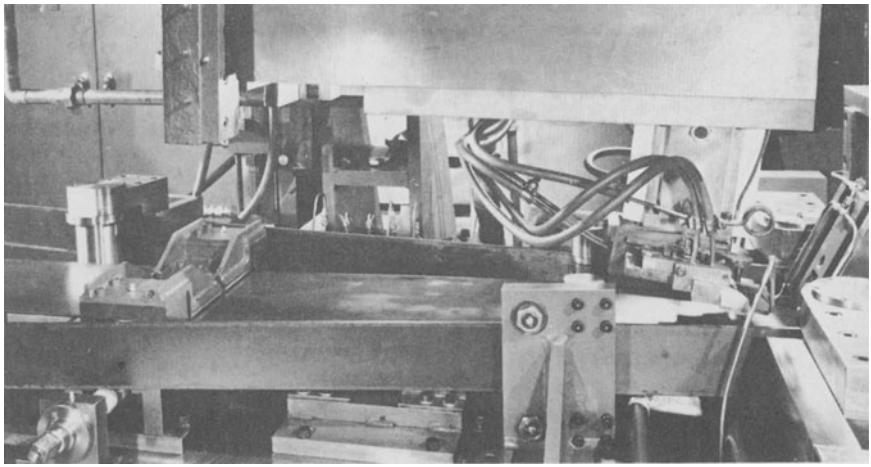


Fig. 45.10.—High frequency resistance welding of 12-inch H-beam.

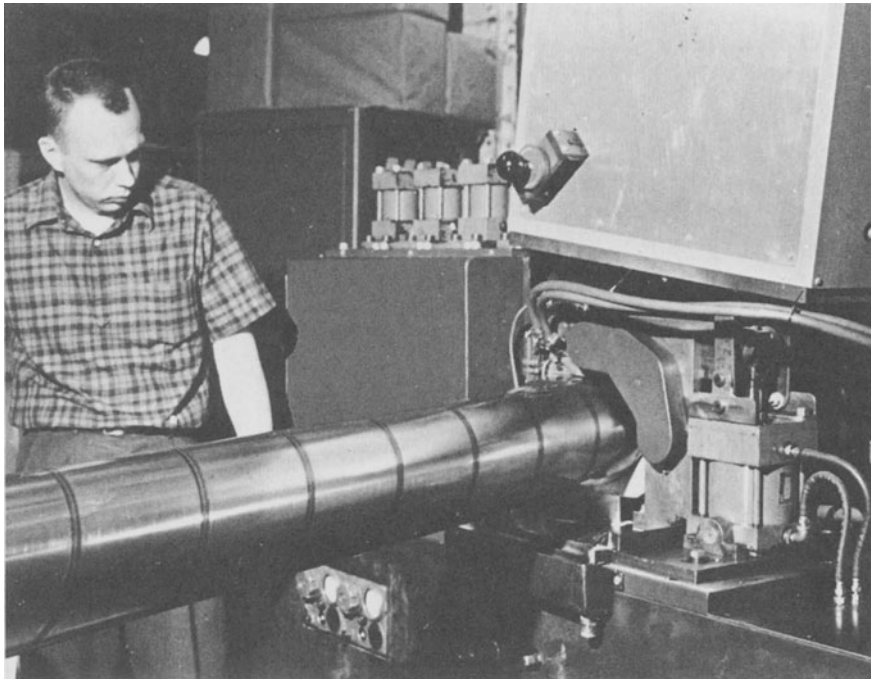


Fig. 45.11.—Spiral high frequency lap welding of 6⅝ inch diameter pipe.

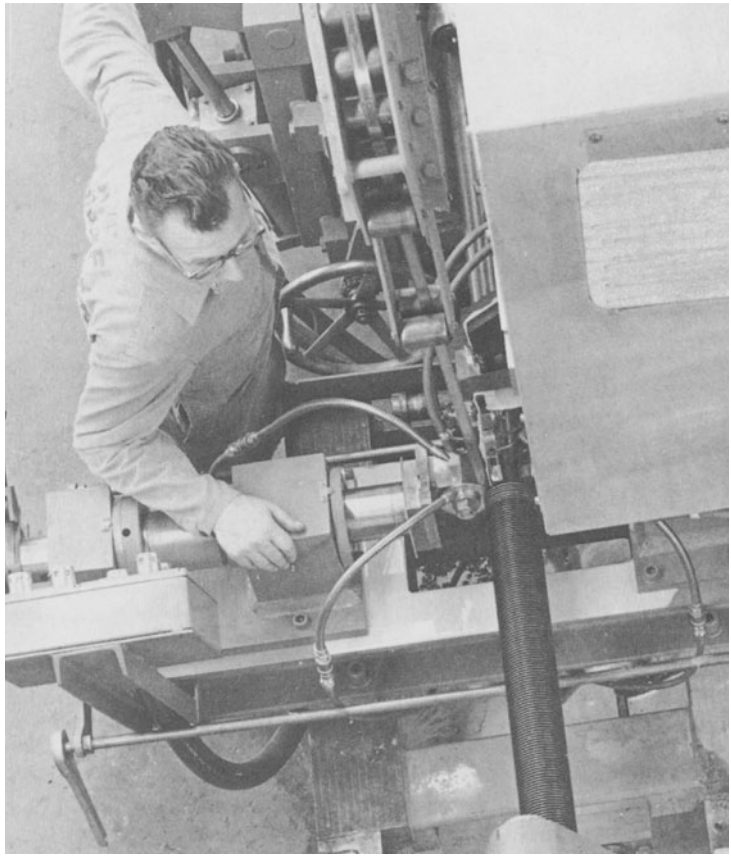


Fig. 45.12.—High frequency resistance welding zone for spiral fin to tube.

OTHER APPLICATIONS

Continuous high frequency resistance welding is not limited to tubing, but may also be used for joining strips of dissimilar metal, either in a butt or a lap joint. Typical applications are in the joining of galvanized mild steel to Type 430 polished stainless steel, for use as molding in automobiles. The galvanized mild steel acts as the mount, and the stainless is visible externally.

Another use is the joining of a small edge of high-speed tool steel to a carbon steel back-up strip, for use as band saw blades. The small amount of high-speed tool steel is utilized for the teeth, and the cheaper and better fatigue-resistant back-up material would be the carrier. The process is adaptable for joining very thin strip or sheet ranging from 0.004-in. up. With thin materials, where it is not practical to align or register the edges, a lap weld is used. The heavier materials can be welded with either lap or butt seams.

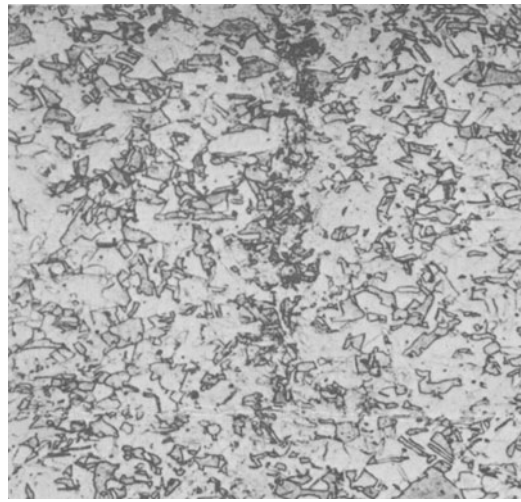


Fig. 45.13.—Photomicrograph of high frequency weld in electrolytic copper, 150X (etchant $Na_2Cr_2O_7$)

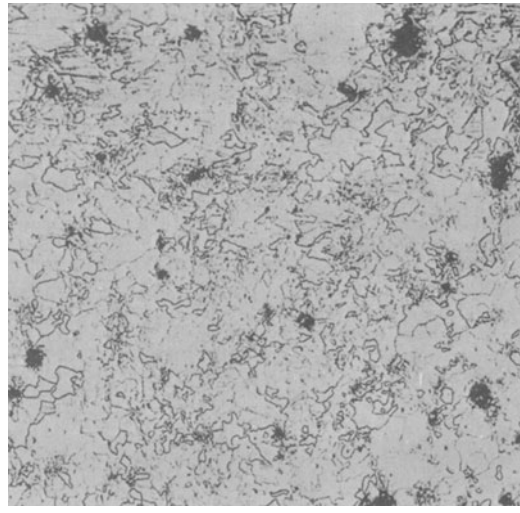
High frequency resistance welding is used for the production of structural shapes such as I- and H-beams, in sizes up to 20 in., with webs ⅜-in. thick. In this type of operation, three strips from coils are fed into a mill, and two high frequency resistance welders make the two T-joints simultaneously. Welding speeds lie in the 25 to 200 fpm range. This process is used in competition with conventional rolling techniques, but it has the advantage that it permits the manufacture of structural shapes that cannot be rolled, or shapes in different combinations of metals (such as high-tensile flanges, mild-steel webs, or stainless steel flanges with a mild-steel web). Figure 45.10 shows the welding area of an H-beam setup, utilizing high frequency resistance welding.

Spiral pipe and tube are also manufactured by high frequency resistance welding. In this case, continuous strip is fed into a mill and is formed into a tube as though it were a barber pole. Thin strip may be lap welded; thick materials are butt welded. Figure 45.11 shows a mill producing 6⅝-in. diam. spiral pipe from mild steel.

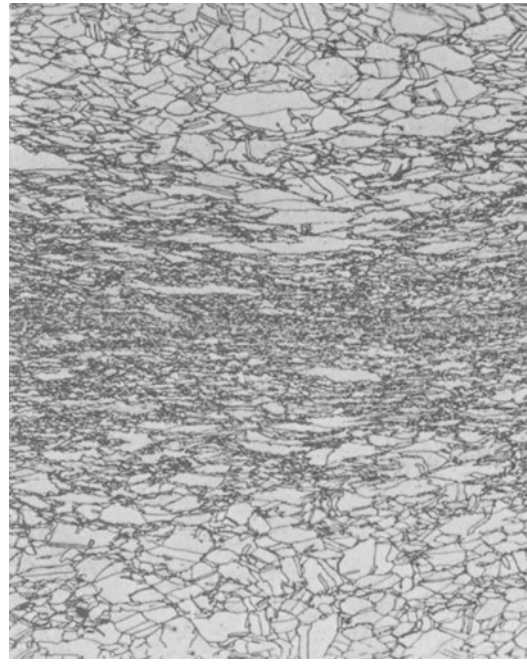
Diameters up to 96 in. with corrugations are welded commercially. Spiral and longitudinal fins are applied to tubing for heat exchangers, and for ease of assembly by means of high frequency resistance welding. Figure 45.12 shows tubing being finned spirally at about 100 feet per minute.

UPSET PRODUCED BY HIGH FREQUENCY WELDING

Almost all high frequency welding techniques employ a combination of heat and pressure, and different materials require different pressures to produce a sound weld. Generally, considerably lower pressures are required for high frequency welding than for low frequency resistance welding. In both static and continuous processes, an upset or bulging of metal occurs in the weld area.



(A) hot rolled, unscaled European steel;



(B) type 302 stainless steel.

Fig. 45.14.—Microstructures of high frequency welded joints in steels:

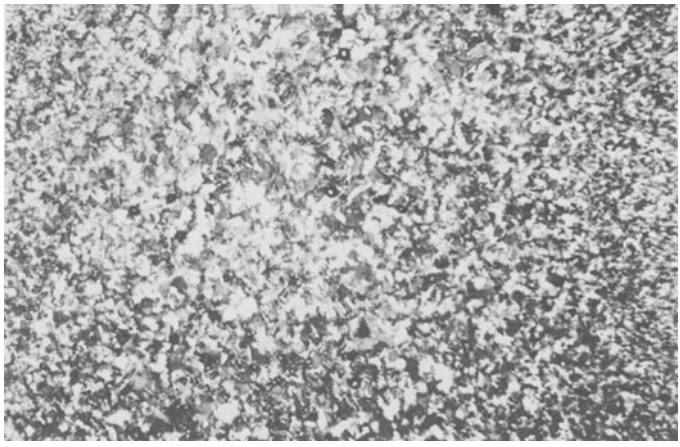


Fig. 45.15.—Microstructure of high frequency welded zircaloy tubing (50X).

Generally, in static welding this upset is left in place and the part is used as welded. In continuous welding such as in tubing, the upset produced is continuously scarfed, or cut off, on one or both sides of the weld, as part of the manufacturing operation. This leaves the surface of the weld smooth on one or both sides, with the appearance of the parent metal (except for some discoloration in some materials).

METALLURGICAL STRUCTURE

Aluminum and copper have low resistivity and high thermal conductivity, but with high frequency welding these properties are not a disadvantage. A large variety of aluminum tubing made of various alloys is being successfully welded in diameters from ½ to 16 in., with walls up to ¼-in. thick. Copper, having a conductivity as high as 101%, is successfully welded without change in grain size at or near the weld. Figure 45.13 shows the microstructure of a weld in copper.

Brass, normally difficult to weld due to its natural tendency to lose zinc when hot, can be joined with high frequency welding without a shielding atmosphere. The high resistivity of brass makes it weldable at very high speed.

Steel is very well suited to high frequency welding. Scaled hot-rolled steel can be welded without difficulty; hot-rolled, pickled and cold-rolled steels are also easily welded. Stainless steels in the 300 and 400 series are also welded by the high frequency process. Photomicrographs of various welds in steels are shown in Figure 45.14.

Zirconium and zircaloy have been welded successfully with a protective argon atmosphere. Figure 45.15 shows the structure of the weld area of zircaloy welded at fairly high speed to keep the heat-affected zone at a minimum. Many other materials such as bronze, silicon bronze, German silver, and Inconel are welded successfully with both the continuous high frequency resistance and high frequency induction welding processes.

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CHAPTER 46

SOLDERING

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CHAPTER 46

SOLDERING

FUNDAMENTALS OF PROCESS

DEFINITION AND GENERAL DESCRIPTION

Soldering is defined as a group of joining processes wherein coalescence is produced by heating to a suitable temperature and by using a filler metal having a liquidus not exceeding 800°F (427°C) and below the solidus of the base metals. The solder is usually distributed between the properly fitted surfaces of the joint by capillary attraction.

The bond between solder and base metal is more than adhesion or physical attachment although this does contribute to the strength. Rather the essential feature of the soldered joint is that a metallurgical bond is produced by a metal solvent action. The solder dissolves (not melts) a small amount of the base metal to form a layer of an intermetallic compound. Upon solidification, the joint is held together by the same attraction between adjacent atoms that holds a piece of solid metal together. The ease of wetting is related to the ease with which this solvent action occurs.

SOLDERING PROCESS CONSIDERATION

To achieve a sound soldered joint, the following requirements must be considered and applied.

Base Material Selection

The metals to be joined dictate to a great extent the flux, solder and heating methods to be used. The base metals are usually selected for specific properties, such as electrical conductivity, light weight or corrosion resistance. The ease with which a metal, alloy or coated metal may be soldered is often indicated by the mildness of the flux that can be used. As the metal becomes more difficult to solder, it is necessary to increase the activity of the flux or resort to special fluxes and solders. Where a choice of flux is available, the solder, flux, cleaning and heating methods chosen are governed by the end use of the product.

Table 46.1 indicates the relative ease, based on flux requirements, with which a number of alloys and metals may be soldered.

Joint Design

Joints should be designed with the requirements of the assembly and the limitations of the solders in mind, and should be shaped so that they fit together properly.

Precleaning

The metal surfaces that are to become a part of the joint must be cleaned thoroughly before assembly to facilitate the wetting of the base metal by the solder. Fluxes are not a substitute for precleaning.

Fluxing

A flux is applied to the precleaned areas to remove all traces of surface tarnish and to prevent formation of new surface film before and during the soldering operation.

Solder Selection

The solder to be used is selected to provide the desired properties in the finished product.

Heating Method

The heating method should be selected to provide the proper soldering temperature, heat distribution and rate of heating and cooling based on the properties of the base metal or metals and the requirements of the finished product.

Table 46.1—Flux requirements for metals, alloys and coatings

Base Metal, Alloy Or Applied Finish	Flux Type				Soldering Not Recommended*
	Noncorrosive	Intermediate	Corrosive	Special Flux and/or Solder	
Aluminum	—	—	—	X	—
Aluminum-bronze	—	—	—	X	—
Beryllium	—	—	—	—	X
Baryllium-copper	X	X	X	—	—
Brass	X	X	X	—	—
Cadmium	X	X	X	—	—
Cast Iron	—	—	—	X	—
Chromium	—	—	—	—	X
Copper	X	X	X	—	—
Copper-chromium	—	—	X	—	—
Copper-nickel	X	X	X	—	—
Copper-silicon	—	—	X	—	—
Gold	X	X	X	—	—
Inconel	—	—	—	X	—
Lead	X	X	X	—	—
Magnesium	—	—	—	—	X
Manganese-bronze (high tensile)	—	—	—	—	X
Monel	—	X	X	—	—
Nickel	—	X	X	—	—
Nickel-iron	—	X	X	—	—
Nichrome	—	—	—	X	—
Palladium	X	X	X	—	—
Platinum	X	X	X	—	—
Rhodium	—	—	X	—	—
Silver	X	X	X	—	—
Stainless steel	—	X	X	—	—
Steel	—	—	X	—	—
Tin	X	X	X	—	—
Tin-bronze	X	X	X	—	—
Tin-lead	X	X	X	—	—
Tin-nickel	—	X	X	—	—
Tin-zinc	X	X	X	—	—
Titanium	—	—	—	—	X
Zinc	—	X	X	—	—
Zinc die castings	—	—	—	—	X

* With proper procedures, such as precoating, most metals can be soldered quite easily.

Alignment

The parts to be joined are assembled in their proper position in such a manner that movement cannot take place during the heating and cooling. Special fixtures or jigs may be necessary, or the units may be crimped, riveted or otherwise held together.

Post Cleaning

All flux residues should be removed. Where rosin base fiuxes are used, their removal depends upon the product requirements.

JOINT DESIGN

The selection of a joint design for a specific application will depend largely on the service requirements of the assembly. It may also depend on such factors as the heating method to be used, fabrication techniques prior to soldering, number of items to be soldered and the method of applying the solder.

When service requirements of a joint are severe, it is generally necessary to design so that the strength of the joint is equal to or greater than the load-carrying capacity of the weakest member of the assembly. Solders as structural materials are weak when compared to the metals which they are generally used to join: therefore, the soldered joint should be designed to avoid dependence on the strength of the solder. The necessary strength can be provided by shaping the parts to be joined so that they engage or interlock, requiring the solder only to seal and stiffen the assembly.

There are two basic types of joint design used for soldering: the lap joint and the butt joint. Figure 46.1 illustrates a butt joint, a lap joint and a lap joint applied as a pipe joint.

The lap type of joint should be employed whenever possible since it offers the best possibility of obtaining joints with maximum strength. It should be used where sealing is required. Lap joints are a modification of butt joints, and the problems involved are similar.

An important factor in joint design is the manner in which the solder will be introduced into the joint. The designer should know what soldering process will be used or he must deside what process can be employed.

Normally, when joints are being soldered, the solder is face fed into the joint and little or no problem exists other than that the joint be accessible. When the production rate is sufficient to warrant the use of automatic equipment for soldering, or where a special problem exists, the solder may be preplaced in the form of wire, shims, strip, powder, a precoat or solder flux-paste. Of these forms, wire and strip are generally used.

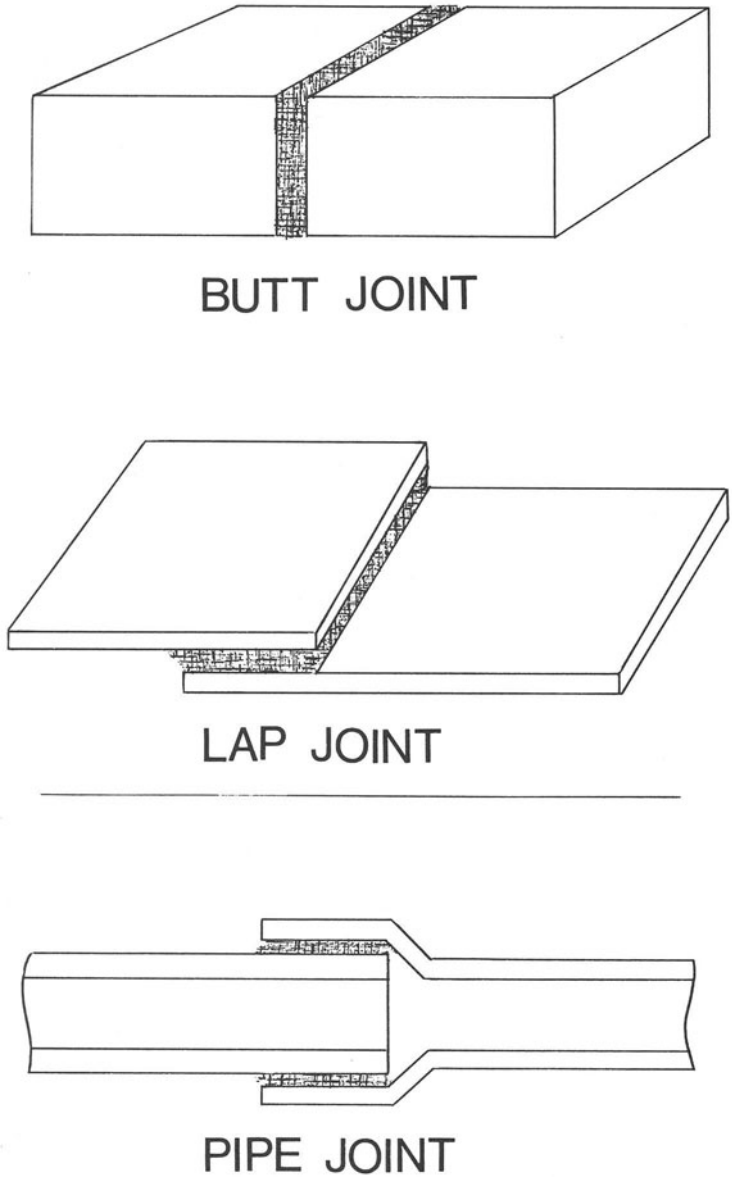


Fig. 46.1.—Typical joint design used for soldering

PRECLEANING AND SURFACE PREPARATION

The soldering process involves the wetting or alloying of the solder with the base metal. Any foreign material can interfere with the soldering. An unclean surface does not permit the solder to flow, making soldering difficult or impossible and contributing to the formation of a poor joint. All foreign materials such as oil, grease, paint, pencil markings, drawing or cutting lubricants, general atmospheric dirt, oxide or rust films must be removed before soldering. The importance of cleanliness cannot be overemphasized to ensure sound soldered joints as well as a rapid production rate.

The two general methods of cleaning are chemical and mechanical.

CHEMICAL CLEANING

Degreasing

Either solvent or alkaline degreasing is recommended for the cleaning of oily or greasy surfaces. Of the solvent degreasing methods, the vapor condensation of the trichlorethylene-type solvents probably leaves the least residual film on the surface. In the absence of vapor degreasing apparatus, immersion in liquid solvents or in detergent solutions is a suitable procedure. Hot alkali detergents are widely used for degreasing. All cleaning solutions must be thoroughly removed by steam or water before soldering. Residue from hard water may interfere with soldering.

These cleaning methods are especially designed for substantial production soldering applications and should be investigated thoroughly as to their suitability for a particular application.

Acid Cleaning

The purpose of pickling or acid cleaning is to remove rust, scale and oxides or sulfides from the metal so as to provide a clean surface for soldering. The inorganic acids (hydrochloric, sulfuric, phosphoric, nitric and hydrofluoric), singly or mixed, all fulfill this function, although hydrochloric and sulfuric are the most widely used. The pieces should be washed thoroughly in hot water after pickling and dried as quickly as possible.

MECHANICAL CLEANING

Abrasion and Shaving

Abrasion is the most commonly used and simplest method of cleaning and includes:

1. Grit or shotblasting.
2. Mechanical sanding or grinding.
3. Filing or hand sanding.
4. Cleaning with steel wool.
5. Wire brushing or scraping.

For best results, cleaning should extend beyond the joint area. Shot or steel

gritblasting is very effective and preferable to sandblasting because it avoids the embedding of silica particles on the surface which would interfere with the flow of solder. On the softer metals, such as copper, blast cleaning is not recommended.

PRECOATING

The coating of the base metal surfaces with a more solderable metal or alloy prior to the soldering operation is sometimes desirable to facilitate soldering. Coatings of tin, copper, silver, cadmium, iron, nickel and alloys of tin-lead, tin-zinc and tin-copper are used for this purpose. The advantages of precoating are twofold: (1) soldering is more rapid and uniform and (2) strong acidic fluxes are avoided at the assembly. The precoating of metals which have tenacious oxide films, such an aluminum, aluminum bronzes, highly alloyed steels and cast iron, is almost mandatory. Precoating of steel, brass and copper, although not entirely essential, is of great value in some applications.

Precoating of the metal surfaces may be accomplished by a number of different methods. Solder or tin may be applied with a soldering iron, an abrasive wheel, by an ultrasonic soldering iron, immersion in molten metal, electrodeposition or by chemical displacement.

Hot dipping may be accomplished by dipping the parts, one at a time, in molten tin or solder of any composition. Small parts are placed in a wire basket, cleaned, dipped in the molten metal and rotated in a centrifuge to remove excess metal. Coating by hot dipping is applicable to carbon steel, alloy steel, cast iron, copper and certain copper alloys and, to a lesser extent, brass and aluminum.

Precoating by electrodeposition may be done in stationary tanks, conveyorized plating units or in barrels. This method is applicable to all steels, copper alloys, nickel alloys, zinc-base die castings and aluminum. The coating metals are not limited to tin and solder. Copper, cadmium, silver, precious metals, nickel, iron and alloy platings such as tin-copper, tin-zinc and tin-nickel are also in common use.

Certain combinations of electrodeposited metals (duplex coatings), where one metal is plated over another, are becoming more popular as an aid to soldering. A coating of 0.0002 in. of copper plus 0.0004 in. of tin is particularly useful for brass. The solderability of aluminum is assisted by a coating of 0.00005 in. of nickel followed by 0.0003 in. of tin or by a combination of zincate (zinc), 0.0002 in. copper and tin. An iron plating followed by tin plating is extremely useful over a cast iron surface.

Immersion coatings or chemical displacement coatings of tin, silver and nickel may be applied to most of the common base metals. These coatings are usually very thin and generally have poor shelf life.

The shelf life of a precoating is defined as the ability of the coating to withstand storage conditions without impairment of solderability. Hot tinned and flow-brightened electrotin coatings have excellent shelf life; inadequate thicknesses of electrotinned coatings have limited shelf life. Coating thicknesses of 0.0002 in. to 0.0003 in. of tin or solder are generally recommended to assure maximum solderability after prolonged storage.

FLUX

A soldering flux is a liquid, solid or gaseous material which, when heated, is capable of promoting or accelerating the wetting of metals with solder. The purpose of a soldering flux is to remove and exclude small amounts of oxides and other impurities from the joint being soldered. Anything interfering with the attainment of uniform contact between the surface of the base metal and the molten solder will prevent the formation of a sound joint. An efficient flux removes tarnish films and oxides from the metal and solder and prevents re-oxidation of the surfaces when heated. The flux should be readily displaced by the molten solder.

A functional method of classifying fluxes is based upon the nature of their residues. They are classified into three main groups: highly corrosive, intermediate (moderately corrosive) and noncorrosive fluxes. Good soldering practice requires the selection of the mildest flux that will perform satisfactorily in a specific application.

HIGHLY CORROSIVE FLUXES

The highly corrosive fluxes consist of inorganic acids and salts. Corrosive fluxes are used to best advantage where conditions require a rapid and highly active fluxing action. They can be applied as solutions, pastes or dry salts. They function equally well with torch, flame, oven, resistance or induction soldering methods since they do not char or burn.

Fluxes in this classification can be formulated which are stable over the entire soldering temperature range. They are more versatile in this respect than the less corrosive fluxes.

The corrosive fluxes have one distinct disadvantage in that the residue remains chemically active after soldering. This residue, if not removed, may cause severe corrosion at the joint. Adjoining areas may also be attacked chemically by residues from the spray of flux and from flux vapors. Fluxes containing ammonium salts may cause stress corrosion cracking in the soldering of brass.

INTERMEDIATE (MODERATELY CORROSIVE) FLUXES

Fluxes of this type, as a class, while weaker than the inorganic salt types, are effective at soldering temperatures from 200 to 600°F (93 to 316°C). They consist mainly of organic acids and bases and certain of their derivatives such as hydrohalides. They are active at soldering temperatures, but the period of activity is short because of their susceptibility to thermal decomposition. Their tendency to volatize, char or burn when heated limits their use with torch or flame heating. They are useful, however, in quick spot soldering operations. When properly used, the residue is relatively inert and easily removed with water.

Intermediate fluxes are particularly useful in applications where minimum controlled quantities of flux can be applied and where sufficient heat can be applied to fully decompose or volatilize the corrosive constitutents. Caution is necessary to prevent undecomposed flux from spreading to insulating sleeving. Care must also be taken when soldering in closed systems where corrosive fumes may deposit in cold areas or on critical parts of the assembly.

NONCORROSIVE FLUXES

Rosin Fluxes

Water white rosin dissolved in a suitable organic solvent is the closest approach to a noncorrosive flux. Rosin fluxes possess important physical and chemical properties which make them particularly suitable for use in the electrical industry. The active constituent, abietic acid, becomes mildly active at soldering temperatures. Its function as a flux is largely protective. It melts readily and is active between 350°F (117°C) and 600°F (316°C). The residue is hard, nonhygroscopic and electrically nonconductive and does not cause corrosion. These characteristics outweigh its weak fluxing action.

Activated Rosin Fluxes

Because of the slow fluxing action of rosin on anything but clean or precoated metal surfaces, activated rosins have been developed to increase the fluxing action without altering the noncorrosive nature of the residue. The activated fluxes depend on the addition of small amounts of complex organic compounds for their increased activity.

FLUX FORMS

The fluxes are available as a core in wire solder, or in liquid, paste and dry powder forms in most of the above categories. Also available are solder and flux combinations in either dry powder or paste form.

JOINT CLEARANCE

Clearance between the parts being joined should be such that the solder can be drawn into the space between them by capillary action, but not so large that the solder cannot fill the gap. Joint clearances of 0.003 to 0.005 in. are optimum but variations are allowable in specific instances. For example, when soldering precoated metals, a clearance as low as 0.001 in. is possible. Capillary attraction, as a force to fill gaps with solder, does not function with clearances greater than 0.010 inch.

SOLDERING METHODS

The proper application of heat is of paramount importance in any soldering operation. The heat should be applied in such a manner that the solder melts while the surface is heated to permit the molten solder to wet and flow over the surface. A number of tools are available as a heat source.

SOLDERING IRONS

The traditional soldering tool is the soldering iron with a copper bit which may be heated electrically or by oil, coke or gas. To lengthen the usable life of a copper bit, a coating of solder-wettable metal, such as iron, with or without additional coatings, is applied to the surface of the copper. The rate of alloy solution of the coating is substantially less than for copper. A good surface coated bit works as well as a plain one, showing less wear, oxidation and pitting.

The selection of soldering irons can be simplified by classifying them in four groups: (1) soldering irons for servicemen, (2) transformer-type, low-voltage pencil irons, (3) special quick-heating and plier-type irons and (4) heavy-duty industrial irons.

Regardless of the heating method, the bit performs the following functions:

1. It stores and conducts heat from the heat source to the parts being soldered.
2. It stores molten solder.
3. It conveys molten solder.
4. It withdraws surplus molten solder.

Table 46.2 provides a guide to the selection of the proper soldering iron. The performance of electrical industrial irons cannot be measured solely by the voltage rating of the heating element. The materials used and the design of the iron affect the heat reserve and temperature recovery of the copper bits.

The correct angle at which to apply the copper bit to the work is of importance in delivering the maximum heat. The flat side of the bit should be applied to the work to obtain the maximum area of contact. Flux-cored solders should not be melted on the soldering iron because this destroys the effectiveness of the flux and results in defective joints.

TORCH SOLDERING

The selection of a torch for soldering is controlled by the size, mass and configuration of the assembly to be soldered. The time available for performing the soldering operation will also have some bearing. Where fast soldering is necessary, a high flame temperature, together with a large flame and large tip size, may be required. Slower heating cycles may be obtained by using a lower flame temperature and, sometimes, smaller flames. Flame temperature is controlled by the nature of the gas or gases used. Any fuel gas burned with oxygen will give the highest flame temperature possible with that gas. The

Table 46.2—Selection of bit size

Work to Be Done	Electrically-Heated Irons		Externally-Heated Irons†
	Choice of Bit Dia., In.*	Heat Rating, Watts	Size of Bit, Lb
Printed circuit soldering	Up to 1/4	35 max.	1/4
Very light soldering on radios, telephones, electrical appliances, fuses, fine instruments, and for home use	1/4–7/16	44–52	1/2
Medium soldering on switchboards, telephones, radios, electrical appliances and light manufacturing	3/8–1/2	60–70	1
Fast soldering on radios, telephones, electrical appliances, jewelry, etc. For light medium jobs in home, factory and schools	3/8–9/16	85–100	1 1/2
High-speed soldering on radios and telephones. Medium light soldering on tinware, toy motors, type bars, fuses, etc., tinsmithing, plumbing and wiring	5/8–7/8	130–150	2
High-speed soldering on light tinware, art glass, toys, small metal patterns, organ pipes, etc.	5/8–1	170–200	2 1/2
Medium tinware, light roofing, gutters, ventilating flues, electrical, airplane and other medium manufacturing, shipboard repairs	7/8–1 3/8	225–250	3
Roofing, refrigerators, copper and galvanized iron, heavy tinware, metal patterns, ship, auto and airplane building	1 1/8–1 3/8	300–350	4
Heavy roofing and cornices, vats, tanks, ventilating flues, auto radiators, armatures, plumbing and shipbuilding	1 3/8–1 7/8	350–650	5
Extra heavy duty work	2	1250	10

* The bit diameters vary with the manufacturer of electrically-heated irons, and sizes used depend somewhat upon the working space available.

† Bits for externally-heated irons are usually furnished in pairs. Thus, a 1/2-lb bit is identified as "1 lb per pair."

lowest flame temperature is secured by burning the fuel gas with air. The highest flame temperatures are attainable with acetylene and lower temperatures with propane, butane, natural gas and manufactured (city) gas, roughly in the order given. The flame of the fuel gas burned with oxygen will be sharply defined; with air, the flame will be bushy and widespread.

Multiflame tips, or burners, of shapes suitable to the work are frequently used. They may be designed to operate on oxygen and fuel gas, compressed air and fuel gas, or bunsen-type torches.

In adjusting tips or torches, care should be taken to avoid adjustment which results in a "sooty" flame; the carbon deposited on the work will prevent the flow of solder.

DIP SOLDERING

When conducted properly, this method of heating may be very useful and economical inasmuch as an entire unit, comprising any number of joints, can be soldered merely by dipping the part in a bath of molten solder. It is necessary, however, to use jigs or fixtures to contain the unit and keep the proper clearance at the joint until solidification of the solder takes place.

The molten bath of solder supplies both the heat and solder necessary for completing the joint. The soldering pot used should be large enough so that at a given rate of production the units being dipped will not appreciably lower the temperature of the solder bath. Pots of adequate size allow the use of lower operating temperatures and still supply sufficient soldering heat.

OVEN SOLDERING

This method is not widely used, but there are many applications where it has been found to produce consistent and satisfactory soldering.

Oven heating should be considered under the following circumstances:

1. When entire assemblies can be brought to the soldering temperature without damage to any of the components.
2. When production is sufficiently great to allow expenditure for jigs and fixtures to hold the parts during the soldering.
3. When the assembly is complicated in nature, making other heating methods impractical.

Proper clamping fixtures are very important, since the assembly must be moved before and during solidification of the solder. Failure to clamp properly may result in a poor joint, since solder fails very easily when it is distributed near its solidus temperature.

Another important consideration is the flux to be used. All but the acid-type fluxes are subject to decomposition when maintained at elevated temperatures for an extended period of time. When a rosin-type or intermediate (moderately corrosive) type flux is used, the part must be brought rapidly to the liquidus temperature of the solder. It is sometimes beneficial to dip the parts in a hot flux solution before placing them in the oven. When using rosin-base flux, it is generally necessary to use a solder with a tin content of 50% or more.

The use of a reducing atmosphere in the oven does not allow joints to be made without flux, because the temperatures at which these atmospheres become reducing are far above the liquidus temperature of the solders. The use of inert atmospheres will prevent further oxidation of the parts but flux must be used to remove the oxide that is already present.

It is often advantageous to accelerate the cooling of the parts on removal from the oven. An air blast has been found satisfactory for this.

The ovens should be equipped with adequate temperature controls since the flow of solder is optimum at about 80 or 90°F (26.7 to 32.2°C) above its liquidus temperature. The optimum heating condition exists when the heating capacity of the oven is sufficient to heat the parts rapidly to the liquidus temperature of the solder.

SPRAY GUN SOLDERING

This method of heating is generally used when the contour of the part to be soldered is such that it is difficult to follow with a wiping or drop method, or where the part is placed in the assembly in such a way that the solder cannot be applied after the parts are assembled.

Gas-fired or electric heated guns are available and each is designed to spray a continuously fed solid solder wire on the work piece.

Two types of guns are used to spray solder. The first uses propane with oxygen or natural gas with air to heat and spray a continuously fed solid solder wire of approximately ⅛ in. diameter. About 90% of the solder wire is melted by the flame of the gun. The solder contacts the workpiece in a semiliquid form. The workpiece then supplies the balance of the heat required to melt and flow the solder. Adjustments can be made within the spray gun to deposit completely liquified solder or a series of fine drops.

RESISTANCE SOLDERING

In resistance soldering, the work is placed either between a ground and a movable electrode or between two movable electrodes to complete an electrical circuit. Heat is applied to the joint both by the electrical resistance of the metal being soldered and by conduction from the electrode, which is usually carbon.

Production assemblies may utilize multiple electrodes, rolling electrodes or special electrodes, depending on which will be advantageous with regard to soldering speed, localized heating and power consumption.

Resistance soldering electrode bits cannot generally be tinned and the solder must be fed directly into the joint. The flux and solder must therefore be in the proper position.

INDUCTION SOLDERING

The only requirement for a material that is to be induction soldered is that it be an electrical conductor. The rate of heating however, is dependent upon the induced current flow. The distribution of heat obtained with induction heating is a function of the induced current frequency. The higher frequencies concentrate the heat at the surface. Three types of equipment are available for induction heating: the vacuum tube oscillator, the resonant spark gap and the motor generator unit.

Induction soldering is generally applicable for operations with the following requirements:

1. Large-scale production.
2. Application of heat to a localized area.
3. Minimum oxidation of surface adjacent to the joint.
4. Good appearance and consistently high joint quality.
5. Simple joint design which lends itself to mechanization.

The induction technique requires that the parts being joined have consistently clean surfaces and that joint clearances be maintained accurately. High-grade solders are generally required to obtain rapid spreading and good capillary flow. Preforms often afford the best means of supplying the correct amount of solder and flux to the joint.

When induction soldering dissimilar metals, particularly joints composed of both magnetic and nonmagnetic components, attention must be given to the design of the induction coil in order to bring both parts to approximately the same temperature.

OTHER SOLDERING METHODS

Wave Soldering

In wave-soldering, as opposed to dipping on to a static bath (Fig. 46.2a), the solder is pumped out of a narrow slot to produce a standing wave or series of waves (Fig. 46.2b). The conveyor may be at a small angle to the horizontal to assist drainage of the solder and double waves or special wave forms may be used also for this purpose. In weir and cascade soldering (Fig. 46.2c), the solder flows down a trough by gravity and is returned by pump to the upper reservoir. These moving solder systems are excellent in that a virtually oxide-free surface is provided on the solder and dislodgement of flux and vapors is also encouraged by the flow of the solder.

All wave-soldering systems perform the same basic steps usually in integrated units: applying flux, drying and heating, soldering and cleaning. Each system has special features: the flux may be applied by passing through a wave of aerated flux, by spraying, rolling or dipping; several systems use oil mixed with solder to aid in eliminating the formation of icicles and bridging between conductor paths, wave size and shape are adjustable in all systems, dual waves flowing in opposite directions to the board travel are features of one system. With material of good solderability, there is no problem in obtaining capillary rise of solder through eyelets or plated through holes to make connections on the upper surface when the lower face is brought in contact with the solder wave in a period of 2 to 3 seconds.

Focused Infrared Soldering

Optical soldering systems are available which are based on focusing infrared light (radiant energy) on the joint by means of a lens. Lamps ranging from 45 to 1500 watts can be used for different application requirements. Low intensity lamps are used for soldering applications at 50°F (10°C) above the eutectic temperature on heat-sensitive devices. The device is usually programmed through a silicon-controlled power supply with an internal timer.

Hot Gas Soldering

The principle is to use a fine jet of inert gas, heated to above the liquidus of the solder. The gas acts as a heat transfer medium and as a blanket to reduce access of air around the joint.

Reflow Soldering

Multiple-lead soldering units are available based on the principle that pre-coated surfaces (tin or solder) will reflow at temperatures just above the liquidus to give a solder bond. Sufficient thickness of coating (0.002 to 0.004 in.) must be used on both surfaces to provide a fillet around the joint.

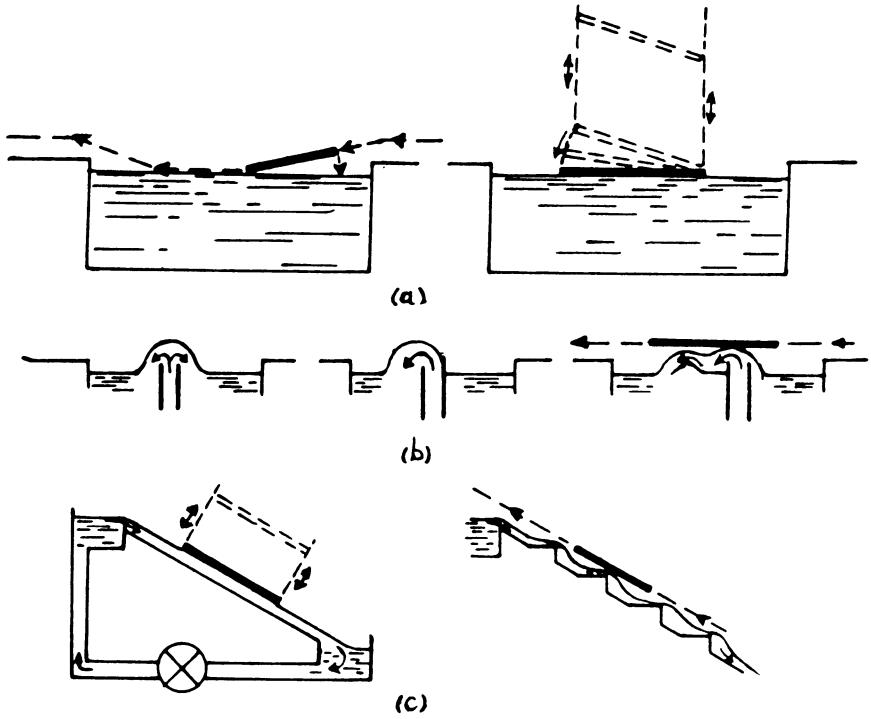


Fig. 46.2.—Some techniques for mass producing parts by soldering. (a) Dipping on to a static bath; (b) Wave soldering systems; (c) Weir and cascade soldering systems

Ultrasonic Soldering

This soldering method has limited use but ultrasonic hand irons and vibrating units are available for dip-soldering pots. A transducer produces high frequency vibrations which break up tenaceous oxide films on base metals such as aluminum, thereby exposing the base metal to the wetting action of the liquid solder. Untrasonic units are primarily useful in applying a solderable coating to difficult-to-solder metals.

Abrasion Soldering

Abrasion soldering is similar to ultrasonic soldering. The base metal is mechanically abraded to remove oxides, thus exposing the metal to the wetting action of the solder.

Abrasion soldering tools generally are fiberglass brushes, stainless steel brushes and stainless steel wool. Carbon steel brushes should be avoided since loose strands may accelerate corrosion. Abrasion soldering of aluminum may also be facilitated with a grinding wheel.

SOLDERS

TIN-LEAD SOLDERS

Solders of the tin-lead alloy system constitute the largest portion of all solders in use. They are used for joining most metals and have good corrosion resistance to most media. All cleaning and soldering processes may be used with the tin-lead solders. Fluxes of all types can also be used; the choice depends on the type of metal to be joined.

In describing solders it is customary to give the tin content first. A 40/60 solder, for example, is understood to be 40% tin and 60% lead.

The behavior of the various tin-lead alloys can best be illustrated by their constitutional diagram (Fig. 46.3).

In order to understand the diagram more fully, the terms used are defined as:

Solidus temperature is the highest temperature at which a metal or alloy is completely solid, curve ACEDB.

Liquidus temperature is the lowest temperature at which a metal or alloy is completely liquid, curve AEB.

Eutectic alloy is an alloy that behaves like a pure metal in that it melts at one temperature and not over a range, point E.

Pasty range is the temperature differential between solidus and liquidus in which the solder is partially melted, curve ACEDBEA.

As shown in the diagram, 100% lead melts at 621°F (327°C), point A, and 100% tin melts at 450°F (232°C), point B. Solders containing 19.5% (point C) to 97.5% (point D) tin have the same solidus temperature, which is 361°F (183°C). From the diagram it can be seen that the eutectic composition is approximately 63% tin and 37% lead, point E. This composition becomes completely liquid at 361°F (183°C). Any composition other than a eutectic composition will not become completely liquid until a higher temperature is reached. For example, 50/50 lead solder has a solidus temperature of 361°F (183°C), and a liquidus temperature of 417°F (214°C), or a pasty range of 56°F (13.3°C), the difference between the solidus and liquidus.

Melting characteristics of the tin-lead solders are shown in Table 46.3.

The 5 grade solder is a relatively high melting temperature solder with a short pasty range. Its wetting and flow characteristics are poorer than the higher tin content solders, necessitating extra care in surface preparation. This high lead solder has better strength properties at 300°F (149°C) than solders containing more tin. The high soldering temperature limits the use of organic base fluxes, such as rosin or those of the intermediate type. This solder is particularly adaptable to torch, dip, induction or oven soldering. It is used for sealing precoated containers, coating and joining metals and for moderately elevated temperature uses.

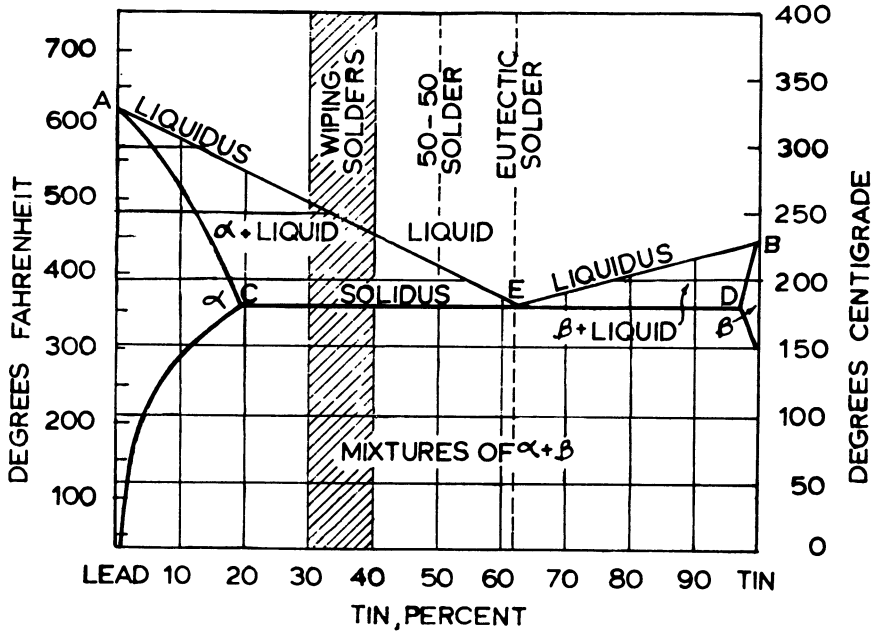


Fig. 46.3.—Constitutional diagram for the tin-lead alloy system

The 10, 15 and 20 grade solders have lower liquidus and solidus temperatures but wider pasty ranges than the 5 grade solder. The wetting and flow characteristics are also better. Extreme care must be taken, however, to avoid movement of the solder during solidification to prevent hot tearing. Fluxes of all types and all soldering methods are applicable. These solders are used for sealing cellular automobile radiators, filling joints and dents in automobile bodies, and for the coating and joining of metals.

The 25 and 30 grade solders have lower liquidus temperatures than all previously mentioned alloys but have the same solidus temperature as the 20 grade solder. Therefore, the pasty range is narrower. All standard cleaning, fluxing and soldering techniques can be used with these solders. Machine and torch soldering are widely used.

The 35, 40 and 50 grade solders have liquidus temperatures low enough to be easily worked. The solidus temperature is the same as the 20 to 30 grade solders and the pasty ranges are narrower. Solders of this group have the best combination of wetting properties, strength and economy, and for these reasons are widely used. They are the general purpose solders being used extensively on sheet metal work. They are used as a rosin-cored wire for radio and television applications.

The 60 grade solder is used wherever temperature requirements are critical, such as in delicate instruments. The composition is close enough to that of the eutectic tin-lead alloy to have an extremely narrow pasty range. All methods of cleaning, fluxing and heating may be used with this solder.

Table 46.3—Tin-lead solders

ASTM* Solder Classification	Composition, Weight %		Temperature, °F/°C		
	Tin	Lead	Solidus	Liquidus	Pasty Range
5	5	95	572/300	596/314	24/
10	10	90	514/268	573/301	59/33
15	15	85	437/225	553/290	116/65
20	20	80	361/183	535/280	174/97
25	25	75	361/183	511/267	150/84
30	30	70	361/183	491/255	130/72
35	35	65	361/183	477/247	116/64
40	40	60	361/183	455/235	94/52
45	45	55	361/183	441/228	80/45
50	50	50	361/183	421/217	60/34
60	60	40	361/183	374/190	13/7
70	70	30	361/183	378/192	17/9

* ASTM solders Grade A are considered high-purity solders and obtain 0.12% antimony, maximum. ASTM solders Grade B contain 0.2% antimony, minimum; 0.5% maximum.

The 70 grade solder is a special-purpose solder used where high tin content is necessary. It is intended for soldering zinc and for coating other metals. All soldering techniques are applicable.

TIN-ANTIMONY-LEAD SOLDERS

Antimony may be added to a tin-lead solder as a substitute for some of the tin. The addition of antimony up to 6% of the tin content increases the mechanical properties of the solder with but slight impairment to the soldering characteristics.

Joint clearances for these solders should be from 0.003 to 0.005 in; 0.010 in. is a practical maximum to obtain capillary flow. All standard methods of cleaning, fluxing and heating may be used. Their use is not recommended on aluminum, zinc or zinc-coated material, such as galvanized iron. When solders containing antimony are used on zinc or zinc alloys, they form an intermetallic compound of zinc and antimony causing the solder to become brittle.

TIN-ZINC SOLDERS

A large number of tin-zinc solders, some of which are listed in Table 46.4 have come into use for the joining of aluminum. Electrogalvanic corrosion of soldered joints in aluminum is minimized if the metals in the joint are close to each other in the electrochemical series. Alloys containing 70 to 80% tin, with the balance zinc, have been recommended. The addition of 1 to 2% aluminum or an increase of the zinc content to as high as 40% improves corrosion resistance. However, the liquidus temperature rises correspondingly, and they are therefore more difficult to apply. The 91/9 and 60/40 tin-zinc solders may be used for high temperature applications (above 300°F/149°C) while the 80/20 and the 70/30 tin-zinc solders are generally used as precoating solders.

Table 46.4—Tin-zinc solders

Composition, Weight %		Temperature °F/°C		
Tin	Zinc	Solidus	Liquidus	Pasty Range
91	9	390/199	390/199	0/0
80	20	390/199	518/269	128/70
70	30	390/199	592/311	202/112
60	40	390/199	645/340	255/141
30	70	390/199	708/375	318/176

LEAD-SILVER SOLDERS

These solders have solidus temperatures high enough to make them useful where strength at moderately elevated temperatures is required. Although lead melts at 621°F (327°C) just slightly higher than the lead-silver solders, it cannot be used as a solder because it does not normally wet steel, cast iron or copper and its alloys. The addition of silver to lead results in alloys which will more readily wet steel and copper. Flow characteristics, however, are very poor. The lead-silver solders are susceptible to humid atmospheric corrosion in storage, and may become unusable as solders. The addition of 1% tin increases their wetting and flow characteristics and in addition reduces their susceptibility to humid atmospheric corrosion. The addition of tin to a lead-silver alloy containing more than 1.75% silver causes the segregation of tin-silver intermetallic crystals. It is therefore general practice to limit the silver content to 1.5% when tin is to be added. The tensile, creep and shear strengths of those solders at temperatures up to 350°F (177°C) are good. Their fatigue properties are considerably better than those of solders which do not contain silver. The lead-silver solders require higher soldering temperatures and special fluxing techniques. The use of a zinc chloride base flux on uncoated metals is recommended. Rosin fluxes are readily decomposed at the soldering temperature and can be used only when the soldering time is relatively short.

Table 46.5—Cadmium-silver solder

Composition, Weight %		Temperature °F/°C		
Cadmium	Silver	Solidus	Liquidus	Pasty Range
95	5	640/338	740/393	100/55

CADMIUM-SILVER SOLDERS

The 95 cadmium-5 silver solder has melting characteristics as shown in Table 46.5. Its primary use is in applications where service temperatures will be higher than permissible with lower melting solders. At room temperature, butt joints in copper can be made to produce tensile strengths of 25,000 psi. At 425°F (218°C) a tensile strength of 2600 psi can be obtained. Joining aluminum to itself or to other metals is possible with this solder. Improper use of cadmium-silver solders may lead to health hazards and care should be taken in their application, particularly with respect to fume inhalation.

CADMIUM-ZINC SOLDERS

These solders are useful for soldering aluminum. Their characteristics are given in Table 46.6. The cadmium-zinc solders develop joints with intermediate strength and corrosion resistance when used with the proper flux. The 40 cadmium-60 zinc solder has found considerable use in the spot soldering of aluminum lamp bases. Improper use of this solder may lead to health hazards.

ZINC-ALUMINUM SOLDERS

This solder, shown in Table 46.7 is specifically for use on aluminum. It develops joints with high strength and good corrosion resistance. The solidus temperature is high, which limits its use to applications where soldering temperatures in excess of 700°F (371°C) can be tolerated. The heated aluminum surface is stroked with the solder stick and wetting is accomplished without a flux.

FUSIBLE ALLOYS

Bismuth—containing solders, the so-called fusible alloys, are useful for soldering operations where a soldering temperature below 361°F (183°C) is required. The melting characteristics and compositions of a representative group of fusible alloys are given in Table 46.8.

These low melting temperature solders have applications in cases such as: soldering heat-treated surfaces where higher soldering temperatures would result in the softening of the part; soldering joints where adjacent material is very sensitive to temperature and would deteriorate at higher soldering temperatures, step soldering operations where a low soldering temperature is necessary in order to avoid destroying a nearby joint that has been made with a higher melting temperature solder, and on temperature-sensitive devices where the failure of a soldered joint is required at relatively low temperature.

Many of these solders, particularly those containing a high percentage of bismuth, are very difficult to use successfully in high-speed soldering operations. Particular attention must be paid to cleanliness of metal surfaces. Strong, corrosive fluxes must be used in order to make satisfactory joints on uncoated metal surfaces such as copper or steel. If a plated surface, such as tin, silver or cadmium, can be provided for soldering, noncorrosive rosin fluxes may be satisfactory, but they are not effective below 350°F (177°C).

INDIUM SOLDERS

These solders possess certain properties which make them invaluable for some special applications. Their usefulness for any particular application should be checked with the supplier. Melting characteristics and compositions of a representative group of these solders are shown in Table 46.9.

A 50-indium-50 tin alloy adheres to glass readily and may be used for glass-to-metal and glass-to-glass soldering. The low vapor pressure of this alloy makes it useful for seals in vacuum systems.

Indium solders do not require special techniques during use. All of the soldering methods, fluxes and techniques used with the tin-lead solders are applicable to indium solders.

COMMERCIAL FORMS OF SOLDERS

Solders are commercially available in various sizes and shapes which can be grouped into about a dozen classifications. These major groups are listed below, along with the weights and sizes of the solders that fall into each group. This listing is by no means complete, inasmuch as any desired size, weight or shape is available on special order.

Pig	Available in 50 and 100 lb. pigs.
Slabs	Weight 15 to 35 lb. Common sizes are 36x3x1 in., 24x3x¾ in., and 18x3x¾ inch.
Cakes or ingots	Rectangular or circular in shape, weighing 3, 5 and 10 lb.
Bars	Available in numerous cross sections, weights and lengths. Some of the more common dimensions are given in Table 44.14.
Paste	Available as a mixture of powdered solder and suitable flux in paste in quantities of 1 lb. or more.
Ribbon or tape	Thicknesses of 1/16 to 3/16 in., 1/8 to 1 in., in width, on reels or spools and in 12 in. lengths.
Segment or drop	Triangular bar or wire cut into any desired number of pieces or lengths, up to 500 pieces per pound.
Pulverized or powdered	Screen sizes from 50 to 200 mesh.
Foil	Thicknesses from 0.00125 in. on rolls 5 to 18 in. wide, weighing 20 to 30 lb.
Sheet	Thicknesses from 0.010 to 0.100 in. in sizes not larger than 24 x 36 in.
Wire, solid	Diameters of 0.010 to 0.30 in. on spools weighing 1, 5, 10, 20, 25 and 50 lb. The flux may be incorporated with the solder in single or multiple hollows or in external parallel grooves.
Preforms	Unlimited range of sizes and shapes to meet special requirements.

Table 46.6—Cadmium-zinc solders

Composition, Weight %		Temperature °F/°C		
Cadmium	Zinc	Solidus	Liquidus	Pasty Range
82.5	17.5	509/265	509/265	0/0
40	60	509/265	635/335	126/70
10	90	509/265	750/399	241/134

Table 46.7—Zinc-aluminum solder

Composition, Weight %		Temperature °F/°C		
Zinc	Aluminum	Solidus	Liquidus	Pasty Range
95	5	720/382	720/382	0/0

Table 46.8—Typical fusible alloys

Alloy	Composition, Weight %				Temperature, °F/°C		
	Lead	Bismuth	Tin	Other	Solidus	Liquidus	Pasty Range
Lipowitz	26.7	50	13.3	10 Cd	158/70	158/70	0/0
Bending (Wood's Metal)	25	50	12.5	12.5 Cd	158/70	165/74	7/4
Eutectic	40	52	...	8 Cd	197/91	197/91	0/0
Eutectic	32	52.5	15.5	...	203/95	203/95	0/0
Rose's	28	50	22	...	204/96	225/107	25/11
Matrix	28.5	48	14.5	9 Sb	217/102	440/227	223/125
Mold and pattern	44.5	55.5	...	...	255/124	255/124	0/0

Table 46.9—Typical indium solders

Composition, Weight %			Temperature, °F/°C		
Tin	Indium	Lead	Solidus	Liquidus	Pasty Range
50	50	—	243/117	257/125	14/8
37.5	25	37.5	280/138	280/138	0/0
—	50	50	356/180	408/209	52/29

SOLDER SPECIFICATIONS

Specifications for solders have been published by the American Society for Testing Materials (ASTM Designation B-32-*Solder Metal,* and ASTM Designation B-284-*Rosin Flux Cored Solder*) and by the United States Government (Federal Specification QQ-S-571-*Solders*).

FLUX RESIDUE TREATMENT

After the soldered joint is completed, flux residues that are liable to corrode the base metal or otherwise prove harmful to the effectiveness of the joint must be removed. The removal of flux residues is especially important where joints must be subjected to humid environments.

The corrosive type flux residues containing inorganic salts and acids should be removed completely. The intermediate type fluxes may be composed of the very mild organic acids, such as stearic, oleic and ordinary tallow, or the highly corrosive combinations of urea plus various organic hydrochlorides. If the composition includes some of the more active acids the flux residue should be removed completely. If no indication of the composition of these intermediate fluxes is given, the safest procedure is to treat them as if they are of the more corrosive type.

Noncorrosive flux residues, generally having a rosin base, may remain on the joint unless appearance is the prime factor or if the joint area is to be painted or otherwise coated.

The activated rosin fluxes have a rosin base with small additions of complex organic compounds. These can generally be treated in the same manner as the non-corrosive fluxes for structural soldering, but should be removed for critical electronic applications.

Where flux residue removal procedures are not practical and the nature of the soldered assembly is such that flux corrosion would either interfere with its operation or substantially shorten its life, the use of zinc chloride or other corrosive fluxes must be prohibited. This does not preclude the use of this type flux in precoating operations where flux residues can be removed before the parts are assembled.

Zinc-chloride base fluxes leave a fused residue that will absorb water from the atmosphere to the extent that droplets of a highly corrosive water-zinc-chloride mixture will form around the soldered joint. Removal is best accomplished by thorough washing in hot water containing 2% of concentrated hydrochloric acid per gallon of water, followed by a hot water rinse. The acidified water removes the white crust of zinc oxychloride which is insoluble in water. Complete removal may also require washing in hot water containing some crystals of washing soda (sodium carbonate) followed by a clear water rinse. Occasionally some mechanical scrubbing may also be required.

Acidified rinse water, when used on copper articles, may build up in copper salt content and cause unsightly darkening of the soldered joints. When this occurs, the acidified rinse may be regenerated with a small amount of potassium ferrocyanide which precipitates the copper salts from the solution.

The residues from reaction-type fluxes used on aluminum usually respond to a rinse in warm water. If this does not remove all traces of residue, the joint may be scrubbed with a brush and then immersed in 2% sulfuric acid followed by immersion in 1% nitric acid. A final warm water rinse removes all acidic compounds.

The residues from the intermediate or self-neutralizing organic fluxes are usually quite soluble in hot water. Double rinsing in warm water is always advisable.

Oily or greasy flux paste residues are generally removed with an organic solvent.

Soldering pastes are usually emulsions of petroleum jelly and a water solution of zinc-ammonium chloride. Because of the corrosive nature of the acids contained in the flux, residues must be removed if no corrosion can be tolerated. In some cases, the presence of petroleum jelly may inhibit corrosion, but if the jelly is removed by solvent action, the remainder of the flux must also be removed.

If rosin residues must be removed, alcohol, chlorinated hydrocarbons and most common organic solvents may be used. Certain rosin activators are soluble in water, but not in organic solvents. These flux residues require removal by organic solvents followed by a water rinse.

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CHAPTER 47

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CHAPTER 47

ELECTRON BEAM WELDING

FUNDAMENTALS OF PROCESS

DEFINITION AND GENERAL DESCRIPTION

Electron beam welding is a process wherein coalescence is produced by the heat obtained from a concentrated beam composed primarily of high velocity electrons impinging upon the surfaces to be joined. The process derives its name from these basic particles of matter (electrons), which are characterized by a negative charge and very small mass.

Electron beam welding usually has taken place in an evacuated chamber, in which the beam generating and focusing devices, as well as the workpiece, are in this vacuum environment. Welding in a chamber imposes several limitations; but at the same time provides one of the outstanding advantages of the process: namely, the potential for a pure and inert environment in which the metal may be welded without fear of chemical contamination.

At the time of its invention, electron beam welding was strictly a high-vacuum* process. Today the process has a much wider scope, being also practiced at medium vacuum** and at atmospheric pressure. In each of these three operational modes, however, the beam is always generated in a high vacuum. It is the workpiece that may be at the same pressure as the beam generator or at a higher pressure.

* High vacuum = pressure of 10^{-6} to 10^{-3} torr (commonly called a "hard" vacuum). A torr is a unit of low pressure equal to 1/760 of a standard atmosphere, or 1340 dynes per cm^2. The torr is almost identical with the "millimeter of mercury" or "mm Hg"; the difference between the two units amounts to about 1 part in 10 million.

** Medium vacuum = pressure of 10^{-3} to 25 torr (commonly called "soft" or "partial" vacuum).

Another outstanding feature of electron beam welding is its ability to make exceedingly narrow, deeply penetrated welds. The weld width, for example, in a butt joint weld in 0.500-in. thick steel plate may be as little as 0.060-in. This stands in remarkable contrast to the fusion pattern in arc and gas welds, and is attributable to the unique penetration mechanism of the electron beam. Conventional arc and gas heating sources melt little more than the surface, and further depth of penetration comes solely by conduction of heat in all directions from this molten surface spot; hence, the fusion zone is at least as wide as it is deep.

By contrast, the electron beam can produce such intense local heating that it almost instantly vaporizes a hole through the entire joint thickness. The walls of this hole are molten and as the hole is moved along the joint, the metal on the advancing side of the hole throughout its depth is melted. The metal flows around the bore of the hole and solidifies along the rear side of the hole to make the weld.

The heart of the process is the electron gun. In the electron gun, electrons are emitted from a cathode, with speed and direction imparted to these electrons by their attraction to a positively charged anode. Usually the electrons are generated from a heated filament, and a precisely shaped cathode electrode surrounding the filament electrostatically shapes the electrons into a converging beam.

In early equipment, the workpiece was sometimes used as the accelerating anode, but this had several disadvantages. Welds could not be made into deep recesses because the upper edges of the workpiece attracted the electron beam, reducing process control. Weld tooling, not being insulated from the workpiece, was also positively charged and exerted a similar influence on simple butt welds. As a result, the accelerating anode was incorporated into the electron gun, making the beam completely independent of the workpiece (Figure 47.1).

The converging beam of electrons, accelerated to speeds in the range of 30,000 to 120,000 miles per second, passes through a small hole in the center of the anode and continues toward the workpiece. After the beam leaves the anode, the mutual repulsion of the electrons causes the beam to diverge as it travels. To counteract this effect, an electromagnetic lens system is used to reconverge the beam and thereby control the size of the beam focal spot at the workpiece. This beam convergence and divergence is gradual, so the useable length of the beam (depth of focus) for most welding applications may be several inches.

Heat input for welding is controlled by four basic parameters: the number of electrons per second impinging on the workpiece (beam current), the speed of the electrons (accelerating voltage), the diameter of the electron beam at the surface of or within the workpiece (beam spot size), and the speed with which the workpiece or electron gun is being translated (welding speed).

A fundamental characteristic of an electron beam, which can help to define its welding capability, is the electron beam's power density at the workpiece; this factor, obviously, is dependent upon the basic gun parameters of beam power (current x voltage) and beam spot size. Power densities in electron beam welding can exceed 10^7 W/cm^2, and electron beam welding devices capable of producing power densities in the range of 10^5 — 10^8 W/cm^2 have been manufactured. Even at the lower end of this range, the power densities are almost twice those produced by shielded arc welding processes.

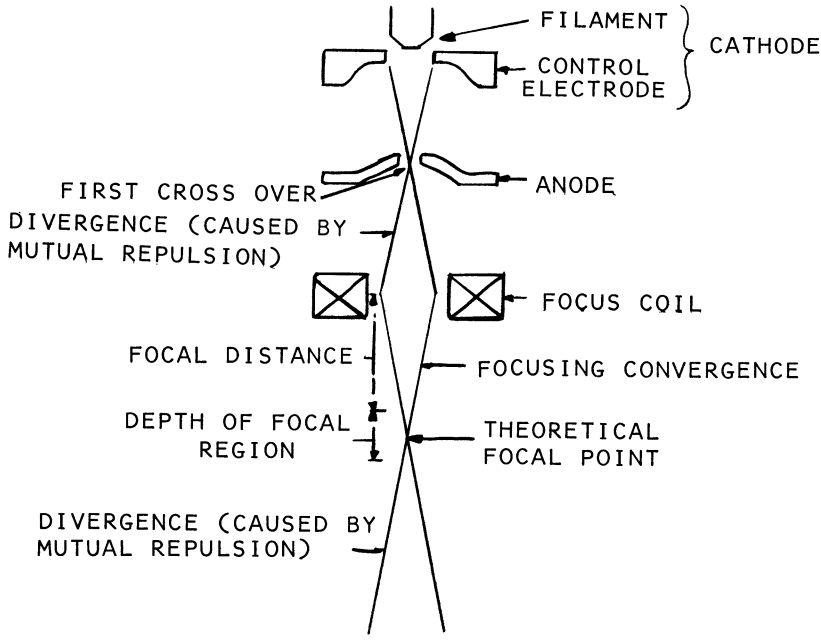


Fig. 47.1.—Geometry of electron beam in unobstructed space

AREAS OF UTILIZATION

Not only is electron beam welding generally applicable to the same kinds of fabrication as the more conventional fusion welding processes, but the unique performance capabilities of electron beam welding permit the solution of a wide range of joining problems that cannot be handled by any other method. Environment, exceptional power densities, and outstanding control capabilities make this possible. A brief summary of some of the principal attributes and application areas of electron beam welding is given below:

1. Electron beam welding permits the narrowest known fusion zones and the highest known depth-to-width ratios. The ability to produce either of these characteristics decreases as one goes from high to medium to nonvacuum electron beam welding, and is dependent on beam spot size and beam power density. This process — and in particular its high vacuum mode — have made possible the joining of dissimilar metals, and repair welds previously deemed impossible. The significantly lower heat input that is possible in electron beam welding noticeably reduces distortion in joining. Here again, the high mode is the most advantageous; although the other two modes also offer some notable advantages over the gas-shielded arc welding processes.

2. Lower heat input means much narrower heat-affected zones and, as a consequence, better properties in these zones for some materials. Statistical data indicate that unstabilized austenitic stainless steel can often be welded without sensitization. High-strength steels can often be welded after heat treatment without significant lowering of tensile properties.
3. Reactive and refractory metals, whose properties are detrimentally affected by gaseous contaminants (such as oxygen, nitrogen, and hydrogen) in the range of a few to several hundred parts per million, may be welded without introducing these contaminants. Metals which fall into these classifications include tungsten, molybdenum, columbium, tantalum, zirconium, titanium, and hafnium. The high-vacuum mode is most suitable for joining these materials; the other two methods offer decreasing performance capabilities (although they still permit satisfactory operation in a number of cases).
4. Welds having depth-to-width ratios of 25:1 are possible in some metals. The welding of heavy sections in a single pass, using a simple square butt joint geometry, is practical and has been demonstrated for aluminum plate up to 9 in. in thickness. While some problems remain in the joining of such heavy cross-sections, production experience to date extends up to 6 inches. The higher-pressure modes do not have such extensive penetration capabilities; in the non-vacuum mode, the maximum penetration is less than 1 in.
5. Grain size, both in fusion and heat-affected zones, is smaller than in fusion welds made by other processes. Such a grain structure has inherently better metallurgical properties in most materials. The best results are obtained with the high vacuum mode; there is mild degradation in the higher pressure modes.
6. Multiple welds may be made in a single pass. For example, honeycomb sections with skins separated by as much as 3 in. vertically, have been successfully butt welded in a single pass.
7. Welding can be performed satisfactorily in all positions, although some change in the geometry of the fusion zone may be expected.
8. Components sealed by electron beam welding in high- or medium-vacuum retain an internal vacuum.

HISTORY

In 1938, M. von Ardenne suggested the use of electron beams as a working tool. In 1940, J. R. Pierce described rectilinear electron flow in beams, as well as the guns for employing them. In 1948, K. H. Steingerwald developed a telefocus gun, and became interested in the use of electron beams as a heat source to perform precision machining operations. In 1953, Stuttgarter Nachrichten suggested the possibility of using electron beams for welding in air. In 1957, J. A. Stohr, of the French Atomic Energy Commission, published the results of electron beam welding studies that he had initiated in 1954.

Another early researcher in electron beam welding was W. L. Wyman, who, working independently, developed a work-accelerated gun and successfully welded zirconium alloys for nuclear applications in 1957. The next year, in Germany, an electron beam drilling machine was successfully adapted for welding operations.

Following these initial activities, considerable effort and involvement by a number of U.S. and foreign corporations led to the development of viable electron beam welding equipment, and to the gradual acceptance of the process on a commercial basis.

In 1962, efforts aimed at removing the confines of the vacuum chamber led to the development of non-vacuum and inert atmosphere electron beam welding installations. The year 1966 saw the introduction of the medium-vacuum welding process, also referred to as the partial or commercial-vacuum process. This advance was prompted by the realization that air at pressures in the vicinity of 10^{-1} torr has purity comparable to purified argon.

THE ELECTRON GUN

In the early days of the process, a rather futile controversy developed between proponents of so-called high- and low-voltage guns. The high-voltage advocates (equipment up to 150 KV) emphasized focusing capabilities; the low voltage proponents (equipment up to 60 KV) attempted to undermine this position by calling attention to radiation danger, etc.

The controversy ended after it was demonstrated that the real concern should be for power density, i.e., beam power and beam spot size. The operational voltage of the gun is unimportant, so long as it produces the needed beam power and beam density at the workpiece.

Besides acceleration voltage, a broad range of conditions must be satisfied if an electron gun is to be able to deliver the required power and power density. Design, configuration, cathode, total power capabilities, and focusing provisions all contribute to optimum gun characteristics. Thus, for a given material and weld depth, characteristically narrow welds will result if sufficient total beam power is available to permit rapid welding speeds, and if the beam power density is great enough to develop and maintain a hole equivalent to the depth of the weld as the weld progresses.

An electron gun generates, accelerates and, to some extent, focuses a beam of electrons. The constituents of an electron gun logically divide themselves into two categories: (1) the elements necessary for the generation of free electrons, i.e., the filament or cathode element; and, (2) the field-shaping elements necessary for the production of a useful beam, i.e., the cathode or control electrode, and the anode electrode. Although major design effort must be given to providing the proper electrode configuration, and hence beam shaping, careful attention also must be paid to the cathode/filament element to be sure usefulness of the final design is not hampered. The cathode may be a current-carrying or self-heating filament, or a solid block indirectly heated by radiation from a filament (or in some cases, by an electron beam from another cathode). The method by which the cathode is heated, either directly or indirectly, affects the resulting beam only in detail.

There are many electron beam gun designs that could be considered for either general use or for specific applications in electron beam welding, including work-accelerated type guns in which the workpiece is the gun anode. But, in practice, only self-accelerated type guns such as the Pierce gun and the

telefocus gun are used. This is because of their superior focusing and power handling capabilities, and the fact that they permit placing the gun (anode) and workpiece at the same electrical potential (namely, earth-ground).

The Pierce gun is designed to operate with a space-charge-limited cathode and to produce a uniform current density over the beam cross section. When properly designed, the primary focal point will occur beyond the anode, and thereafter, the beam will diverge uniformly. Aside from design ease, the principal advantage of the Pierce gun is its high power capability and its high efficiency.

The telefocus system also has a high efficiency, and is designed to produce a primary gun focus at a relatively large distance from the anode. The long-focus effect is due to the hollow shape and negative bias of the grid electrode.

As pointed out earlier, these guns are all focused to their final spot size by means of electromagnetic lenses. Furthermore, their beams can be oscillated, interrupted, or deflected by suitable controls.

Oscillation and deflection have been particularly useful in welding. With the beam oscillating transversely to the weld, the fitup of the butt joint is made less critical. Deflection, likewise, aids in seam tracking, since non-linear seams can be traced effectively by electromagnetic control of beam position. Oscillations of beam spot of 0.25-in. about the neutral position are easily obtained. Interruption (or pulsing) of the electron beam has been useful in certain applications, but has not been utilized extensively in welding.

The field of electron optics was well developed before electron beam welding equipment became commercially available. As a result, early electron gun designs for welding were based on guns developed for use in electronics, electron microscopy, and electron irradiation. Most electron guns used in electronics work operate in the 10 to 60 KV range, while those used in electron microscopy and electron irradiation operate at 50 KV and above. Some welding guns were similar in appearance to guns previously used in electronics work, and operated at 60 KV or below; these were designated "low voltage welding guns." Others resembled electron microscopes, and operated at voltages in excess of 60 KV; these were designated "high voltage welding guns."

The 60 KV boundary is an arbitrary limit that presently separates two types of equipment of substantially different design. It is, however, indicative of usage rather than of a significant technical barrier between the two classes of apparatus.

EQUIPMENT

INTRODUCTION

The original and still principal class of electron beam welding equipment is the high vacuum type (Fig. 47.2). However, the limitation imposed by welding inside a chamber has led to the development of techniques for bringing the beam outside the chamber. Nonvacuum welding equipment is not satisfactory

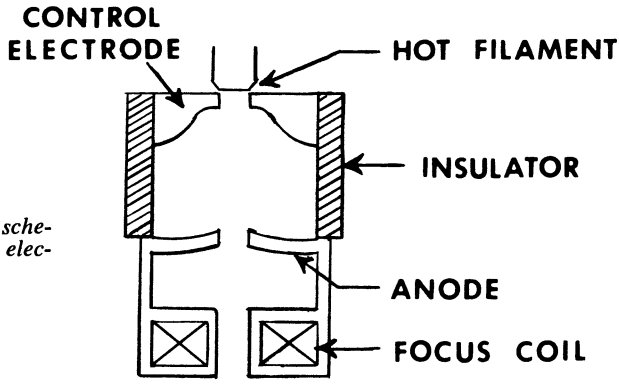


Fig. 47.2.—Mechanical schematic of hard vacuum electron beam gun.

for all applications; it yields welds that are wider and shallower than welds made with equal power in vacuum. The medium-vacuum welding machine was developed to retain most of the advantages of high vacuum — the deep, narrow, low distortion weld — with improved production rates.

The medium-vacuum operation takes the beam as generated in high vacuum and brings it to an ambient 10^{-1} torr (Fig. 47.3). This is accomplished through an orifice of special design that is large enough to pass the beam, but too small to allow significant back-diffusion of gases into the gun chamber. In non-vacuum electron beam welding equipment, the beam is also generated in high vacuum but then it is brought out through a series of orifices in differentially-pumped chambers into the pressure environment in which the weldment is located (Fig. 47.4). Each of these three modes have specific operating capabilities.

HIGH VACUUM WELDING

High vacuum (10^{-3} torr or less) is the natural environment for all electron guns. Although special devices enable the electron beam to be brought into an environment of higher pressure, the gun itself cannot operate effectively at pressures greater than 10^{-3} torr. Welding in a high vacuum is the first form of electron beam welding from which all others have evolved.

The principal advantages which accrue as a result of welding in high vacuum are:

1. Maximum weld penetration and minimum weld width can be achieved.
2. Maximum weld purity is possible due to the absence of atmosphere and contaminating gases.
3. Weld shrinkage and distortion are the minimum obtainable with any fusion welding process.
4. The relatively long gun-to-work distances possible with this method enhance the ability to observe the welding process.

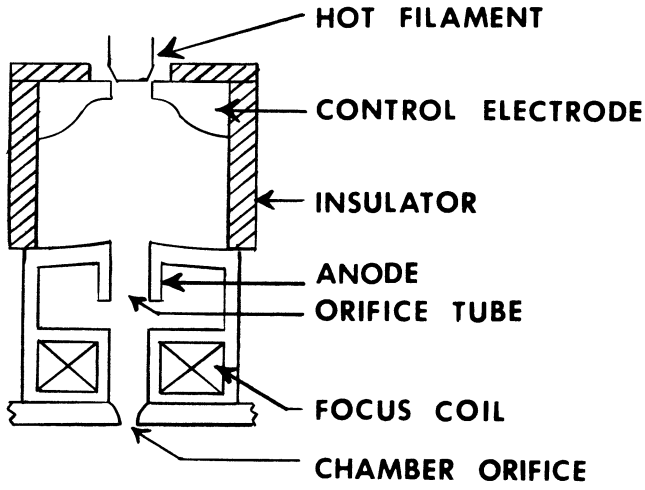


Fig. 47.3.—Mechanical schematic of soft vacuum electron beam gun

LOW VOLTAGE SYSTEMS

All electron beam welding systems in the low-voltage class have many characteristics in common. In addition to operating at accelerating voltages up to 60 KV, the gun of the low-voltage machine can be located wholly within the welding chamber. Power up to 50 KW is provided to the gun through a special high-voltage terminal in the top of the chamber. Inside the chamber, the movable electron gun is connected to this terminal by means of a flexible high-voltage cable. This arrangement provides the low-voltage welding machine with one of its greatest assets — gun mobility. While the more common installations do not include all forms of motion, it is possible to arrange the chamber so that the gun may be moved along all three rectilinear (x, y and z) axes. In addition, the gun may be tilted, rotated or automatically controlled to follow an irregular path. Generally, however, the gun is provided with y and z axis motion, and x axis motion is provided by the workpiece carriage.

Low-voltage welding guns are generally operated in the space-charge-limited condition. They can be classed into two types: (1) those in which only the accelerating voltage is varied to control power, and (2) those in which the accelerating voltage and beam current are varied to control power. The former type is sometimes referred to as a "diode type" gun because it is primarily a two-element device that is electronically similar to a diode; the latter is termed a "triode type" gun. In either type of guns, if the gun is operated in the space-charge-limited condition, the beam current produced at any value of accelerating voltage is proportional to the 3/2 power of the accelerating voltage ($I = kV^{3/2}$), where the constant of proportionality (k) is a function of gun geometry.

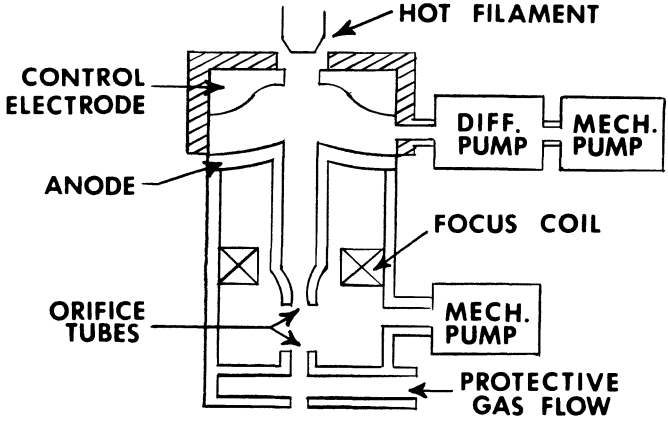


Fig. 47.4.—Mechanical schematic of non-vacuum electron beam gun

In the diode gun, when a change in beam current is desired at a given voltage, the adjustment is accomplished by mechanical change of the cathode-to-anode spacing of the gun, thereby changing the proportionality constant of the gun. These gun spacers as supplied by the manuafcturer provide a wide range of operating conditions. Selection of the proper spacer permits the operator to work in a current range in which adequate beam power and beam spot size are available, and control sensitivity is ample.

The triode type gun is similar to the diode gun, except that the "cathode" is now provided with a variable negative voltage relative to the filament. This makes it possible to control the electron beam current at any operating voltage; thus, both the accelerating voltage and beam current can be developed independently when establishing welding parameters.

Low voltage guns can also be operated in the temperature-limited condition. In this case, the beam current at a given voltage is determined by the temperature of the electron emitter. Control is effected by means of the filament current.

Work chambers provided with low-voltage electron beam welding machines are characteristically rectangular in shape, and are made from heavy-gage carbon steel plate. The thickness of this carbon steel provides both adequate x-ray protection (making lead shielding unnecessary) and the structural strength necessary to prevent deflection of the flat surfaces under the external load of atmospheric pressure. The weldment inside the chamber may usually be observed by direct viewing through lead glass windows; however, the effectiveness of this technique depends on the distance between the operator and the work and the shape of the work. Therefore, an optical viewing system which permits the operator to obtain a magnified "beam's eye" view of the weld and/or seam

is an integral part of the welding system. It is used for setup operations, inspection of the weld, aligning of the workpiece in relation to the gun travel, and positioning the gun to locate the electron beam focal point at the center of the weld seam.

Computer control and numerical control are available for automatic programming of power and welding speed as a function of gun position.

HIGH VOLTAGE SYSTEMS

High-voltage electron beam systems generally operate above 60 KV. Most modern equipment in this class is actually designed to operate at voltages up to 150 KV, with beam power of up to 30 KW available. The electron guns of high-voltage electron beam welding machines are housed in an external vacuum chamber mounted to the top of the welding chamber by either a stationary or a sliding vacuum seal. In the latter case, motion of the gun is limited to the y axis, with x axis motion provided by the weldment carriage. Other motions, such as z axis movement, are provided by special jigging. Automatic seam tracking and computer-programmed welding are also available.

Electron guns in this class include all of the triode type in which both accelerating voltage and beam current are independently controlled. The external location of the gun reduces its maneuverability, but provides ready access to the gun components (for service). In addition, the reduced mobility considerably enhances the feasibility of incorporating sophisticated weldment viewing systems into the welding machine.

Full control of beam current by the bias voltage permits rapid changes in beam current. Electronic switching circuits in some equipment permit the rapid pulsing of the beam. This is necessary for electron beam drilling, and offers beneficial characteristics to some applications by minimizing heat input, while still producing deep weld penetration.

Immediately below the electromagnetic lens is a set of magnetic deflection coils that permit deflection of the electron beam in the x and y directions. Simultaneous use of both sets of coils allows the formation of the classical Lissajous figures on the work surface. Sinusoidal deflection perpendicular to the direction of weld travel permits broadening of the weld to simplify the manual tracking of the weld seams. Circular and elliptical deflection tends to reduce weld porosity by enlarging the welding crater, and thereby facilitating the escape of evolved gases.

Work chambers provided for this equipment are usually heavy-walled rectangular carbon-steel boxes with an external cladding of lead, to attenuate the "hard" x-rays generated by the high-voltage beam. In chambers requiring weldment turnover, a cylindrical chamber of somewhat reduced wall thickness is provided.

The external mounting of the high-voltage gun provides the most desirable condition for weldment viewing. In addition to the direct viewing that is available with all high-vacuum welding apparatus, this arrangement also allows viewing the weld through optics that are coaxial with the electron beam, and unimpaired by the presence of lead glass. (The radiation hazard is eliminated by bends in the optical system.)

A further improvement is available in the form of closed-circuit television, which may have both a light source and a television camera mounted in a serviceable location outside the chamber. Only the optics protection system is mounted inside to protect the viewing media from metal splatter and metal vapor deposition. Use of the closed-circuit television system permits continuous monitoring of welds with minimum operator fatigue, and minimum exposure to the intense visible light of the weld spot.

WORK HANDLING EQUIPMENT

With electron beam welding, as with other welding processes, it is important that the relative positions of the heat source and the weld joint be established accurately prior to initiation of the welding cycle. This requirement is somewhat more complicated with electron beam welding because, in general, the weldments produced are relatively narrow, and the workpiece is usually contained in a vacuum chamber, making visual alignment of the heat source and the workpiece difficult. As previously mentioned, in order to meet this requirement, most electron beam welding machines are equipped with a telescopic viewing system that permits the operator to view the welding area and establish the correct position of the electron beam in relation to the weldment. Fig. 47.5 shows a typical operator's sighting on an electronic component.

In the welding of long, slightly irregular seams, the use of automatic seam tracking equipment is desirable. Direct optical viewing of welding and manual correction for deviation of seam position while welding can be difficult due to slowness of human response, although some equipment is utilized in this manner.

There are two means of maintaining the beam on a seam of changing position. The first involves programming by analog means or continuous path numerical controls. This method is only applicable if the parts have been machined precisely to some given contour, and are located in position with extreme accuracy.

A second means of maintaining the beam on the seam is by a self-adaptive seam tracking control. This implies that the weld seam is followed exactly by a tracking device, so that for a given change in location of the joint the tracker will maintain the beam on the seam. Both tracking devices listed below employ the same electrical circuitry and are quickly interchanged to accomplish the various tracking requirements:

1. Stylus Type Seam Tracker
2. Contour Tracker

The stylus type seam tracking system is based on a probe, or stylus, that rides in the joint, e.g., linear butt joints or girth seams. The lateral cross seam movements of the probe, resulting from the seam misalignment, are converted by a transducer to electrical signals that drive the cross seam positioning servomotor to maintain the preset alignment of the seam-to-gun locus. The electrical signals from this system define: a right-error, a left-error, and the null — the latter indicating correct gun position. Alternately, the beam's position can be deflected electronically to accommodate changes in the location of the weldment.

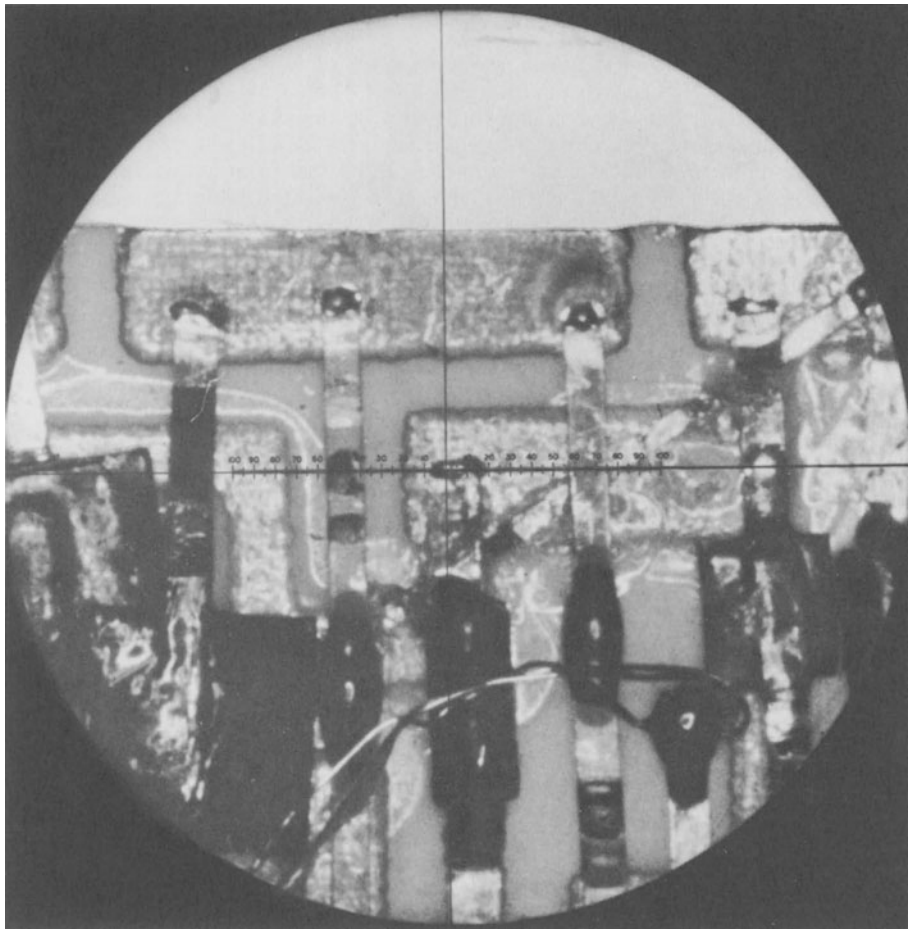


Fig. 47.5.—A typical operator's sighting on an electronic component

A simple modification of the stylus type seam tracking system permits the edge welding of certain types of assemblies by using the weldment as a cam. A preloaded ball-type stylus is used, which rides against the edge of the weldment being rotated or driven linearly. In some cases, the device may also be employed to trace a replica of a given weldment. As a proximity control to accommodate the eccentricities, or rises and fall, of nonlinear welds, the system is modified to maintain a constant gun-to-work distance by applying the tracking signal to a servo on the z axis.

Recently, an electronic tracking system has been developed whereby proper alignment between the electron beam and the weld joint can be attained. It is a two-step method, the first of which involves optical viewing to verify that the weld joint and weld travel direction are parallel after the workpiece has been clamped into position.

Then the vacuum chamber is closed and pumped down to the welding level, a focused low-energy electron beam is aimed at the weld joint. The beam oscillates across the joint at 60 Hertz. Intermittently, a pulser circuit interrupts the scanning circuit, allowing the undeflected beam to be projected upon the workpiece. An oscilloscope displays the weld joint pattern relative to the electron beam location.

From the oscilloscope display, the operator can tell quickly and precisely the position of the electron beam with respect to the joint. Weld joint gapping and runout are also easily detectable with this system.

Once the relative positions of the heat source and the weld joint have been established, it is important that this relationship be maintained during the entire welding operation. Therefore, the weld motion mechanisms must be accurate and well defined, requiring design and manufacture in accordance with good machine tooling practices. Ruggedness, repeatability, smoothness, and accuracy are prime requirements. Since welding speed affects weld geometry, it is important that this parameter be controlled accurately and be repeatable. In general, electric motor drives having an accuracy of about $\pm$ 2% of set speed are adequate.

Most electron beam welding machines provide standard mechanisms for linear and rotary motion of the workpiece relative to the electron beam. Linear motion in the horizontal plane usually is provided by movement of a heavy-duty table. Linear motion in the perpendicular direction is provided either by movement of an auxiliary table, or by movement of the electron gun. Rotary motion about a vertical axis is achieved with a motor-driven horizontal rotary table. Machines can be equipped with a runout platform so that the work table plus any added work handling mechanisms can be removed from the vacuum chamber for ease of loading and fixturing.

Fig. 47.6 shows a typical electron beam welding machine with an x-y work table on its external platform. On the table is mounted a horizontal rotary table with an auxiliary electric power drive attached. Rotary motion about the horizontal axis is accomplished through the use of a head and tailstock, the headstock being power driven. Fig. 47.7 shows such a unit. In this case, the headstock can be tilted to any angle from horizontal to vertical so that it can be used as a rotary positioner. With these mechanisms, simple linear, rotary, and circular welds can be made.

Often it is desirable to load several parts into the vacuum chamber at one time. In this case the components are arranged in a systematic array on a flat table, which oscillates in a circular manner. The diameter of the circles can be changed by a simple adjustment of the oscillating table. Each piece in turn is placed into position, and the circular weld motion made with the aforementioned table motion. Programmed indexing from piece to piece can be added quite easily. The eccentric table is also useful for single circular welds in large or odd-shaped pieces where it is inconvenient or difficult to rotate the entire piece about the centerline of the weld.

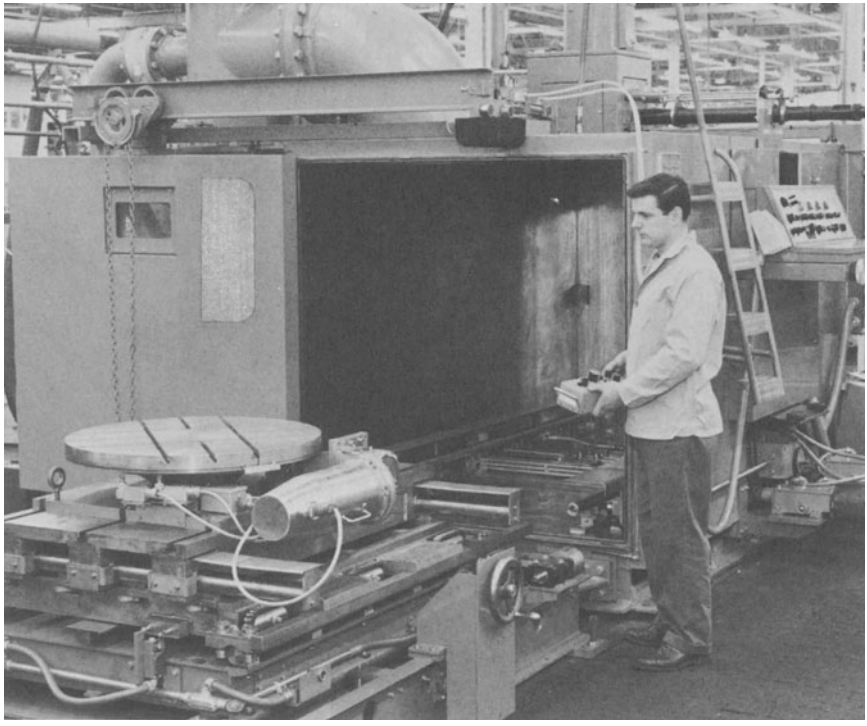


Fig. 47.6.—A typical electron beam welding machine with an x-y work table on its external platform

Beam deflection using a variable frequency generator also can be used to make welds similar to those described for the eccentric table. This is particularly true when the part is very heavy or of a shape or structure which makes it desirable to keep the piece stationary. When using circular beam deflection, the frequency is adjusted to obtain the desired linear welding speed for the diameter of circle involved.

Multiple-spindle rotary fixtures frequently are used for making rotary welds on a group of similar parts. The rotary weld on the part can be positioned by linear movement of the main table in the machine on which the rotary fixture is mounted. It is possible to automate the entire operation. An example of a special purpose rotary fixture is shown in Fig. 47.8. Other special tooling and fixturing devices can be designed to meet specific welding needs.

Since all operating parameters of electron beam welding are machine-controlled, this process is very readily adaptable to complete numerical control. Weld motions, beam power, focus, deflection, etc., can be included in the program.

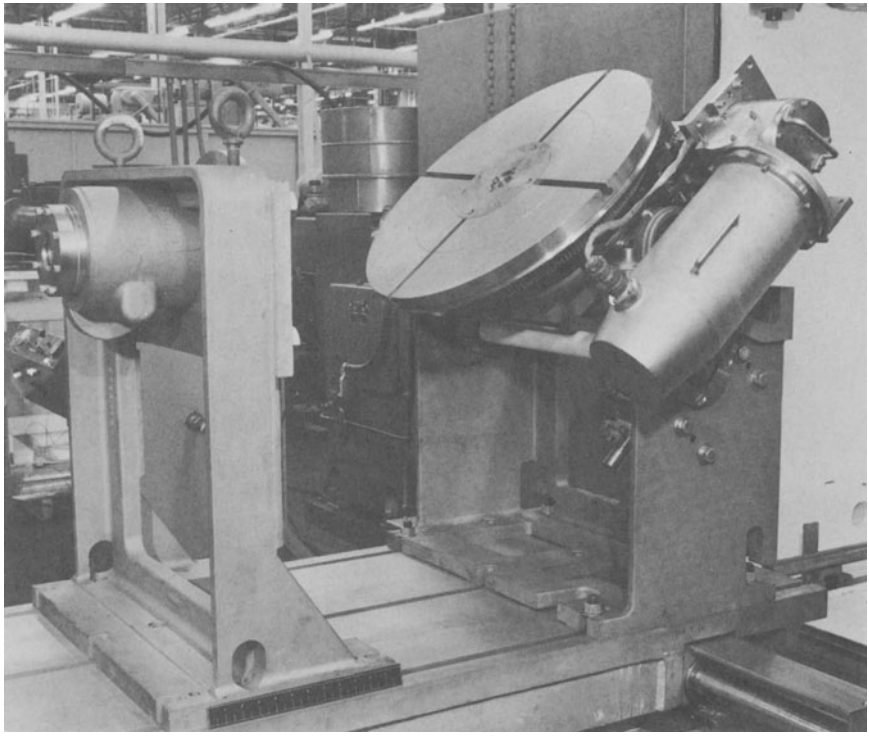


Fig. 47.7.—A head and tailstock unit

As with most manufacturing processes, it is necessary with electron beam welding to have good and adequate tooling and work handling mechanisms in order to obtain maximum benefits from the process.

MEDIUM VACUUM WELDING

The realization that air even at medium vacuum can have a purity level equal to or better than purified argon led in 1966 to the introduction of the medium vacuum electron beam mode. As previously mentioned, this mode of welding is also called the soft, partial, or commercial vacuum welding mode. Table 47.1 illustrates the relative contamination levels. The higher density at the increased pressure scatters the beam's electrons and diffuses them somewhat. The ambient higher density also causes the working distance, as well as the penetration capabilities of the beam, to be less than in the high vacuum mode. The higher voltage machine can obtain longer working distances in medium vacuum. For example, the beam can be deflected for 12 in. at a 36 in. working distance.

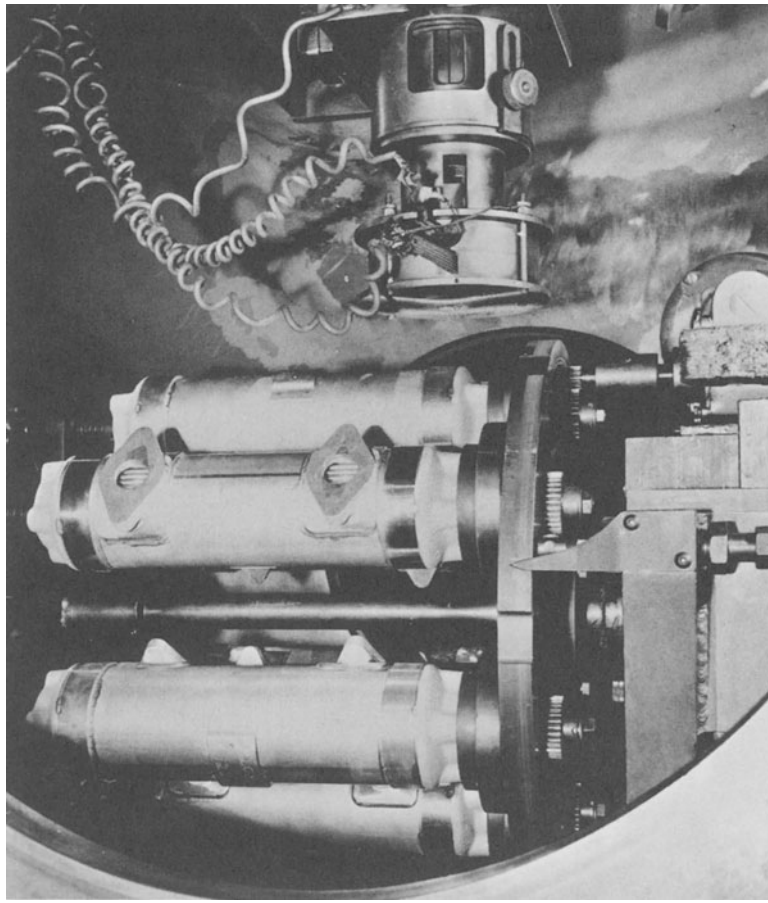


Fig. 47.8.—Loaded heat exchanges welding fixture in location beneath the electron beam gun

Equipment for medium vacuum electron beam welding that operates in the range of 0.010 to 0.100 torr is basically a modification of standard high-vacuum equipment. A diffusion pumping port with an orifice for the beam is inserted in the beam column. In this manner, a hard vacuum of 10^{-4} torr or better is maintained in the beam generating and forming section of the gun; the beam impinges on the workpiece in the medium vacuum. Both 60 KV and 150 KV installations are produced for this operational mode.

A principal asset of the medium vacuum welding mode is the fact that its pumping requirements can be met without diffusion pumping the work chamber. Pumping times, typically, are a matter of seconds. In terms of commercial and economic processing, this is of major importance. This mode appears the most ideally suited for the manufacture of large numbers of equivalent parts, and where repetitive production tasks are involved. Gears

and shafts, for example, can be medium vacuum electron beam welded successfully in their final or machined condition with no subsequent finishing needed (Fig. 47.9). Close tolerances can be maintained — gear eccentricity of only 0.0015 in. and face runout of 0.0006 in., in the as-welded condition.

Although general purpose machines (Fig. 47.10), which can be employed advantageously in short production runs are offered, the principal development is in special purpose machines tooled for particular parts. Fig. 47.11 illustrates some typical medium-vacuum tooling concepts. Note that in each case the work chamber and tooling are an integral assembly, specially designed for and limited to a single weld design.

A large number of medium vacuum welding machines have been produced. For example, a machine with a single welding station and dual loading stations, can have production capability in the range from 50 to 150 parts per hour. A dual gun, dual welding station machine, on the other hand, could increase the production capability up to and perhaps above 240 parts/hr. It should be stated that the production rates in the final analysis are dependent on the design of the parts.

The medium-vacuum mode of welding has found wide acceptance in the automotive industry. A particularly interesting recent introduction has been the combination of parts handling by means of a dial feed table (Fig. 47.12) and medium vacuum welding. Utilizing a labyrinth sliding-seal technique to provide a guard vacuum before and after the separately pumped welding chamber, this concept enables the full realization of the well-known high production capability of the dial feed table, which can range from 500 to 1500 parts per hour.

NONVACUUM WELDING

Because electrons have very small mass, they are deflected upon impact with gas molecules of much greater mass. As a result, an electron beam passing through a gas at atmospheric pressure very quickly becomes diffuse, and its effectiveness as an intense heat source is lost.

Two basic technical problems had to be solved in order to produce a practical non-vacuum electron beam welding system. First, a technique had to be developed which permitted the electron beam to escape from the vacuum environment in which it was formed into a region of gas at atmospheric pressure without significant loss of power. Second, the electron beam characteristics have to provide a reasonable working distance external to the gun structure before the scattering of electrons reduced the power density of the beam to a level too low for metalworking.

The first problem was solved by staging the vacuum over a very short length, using an orifice system through which the electron beam could pass. The second problem was solved by using a beam of relatively high-speed electrons, that is, a beam generated at relatively high voltage. About 175 KV are required for a practical working distance between the final orifice and the workpiece.

Fig. 47.13 is a schematic of a non-vacuum electron beam optical column and orifice system. The electron gun is typical of those used for other types of electron beam welding. Working voltages are in the range of 150 to 175 KV;

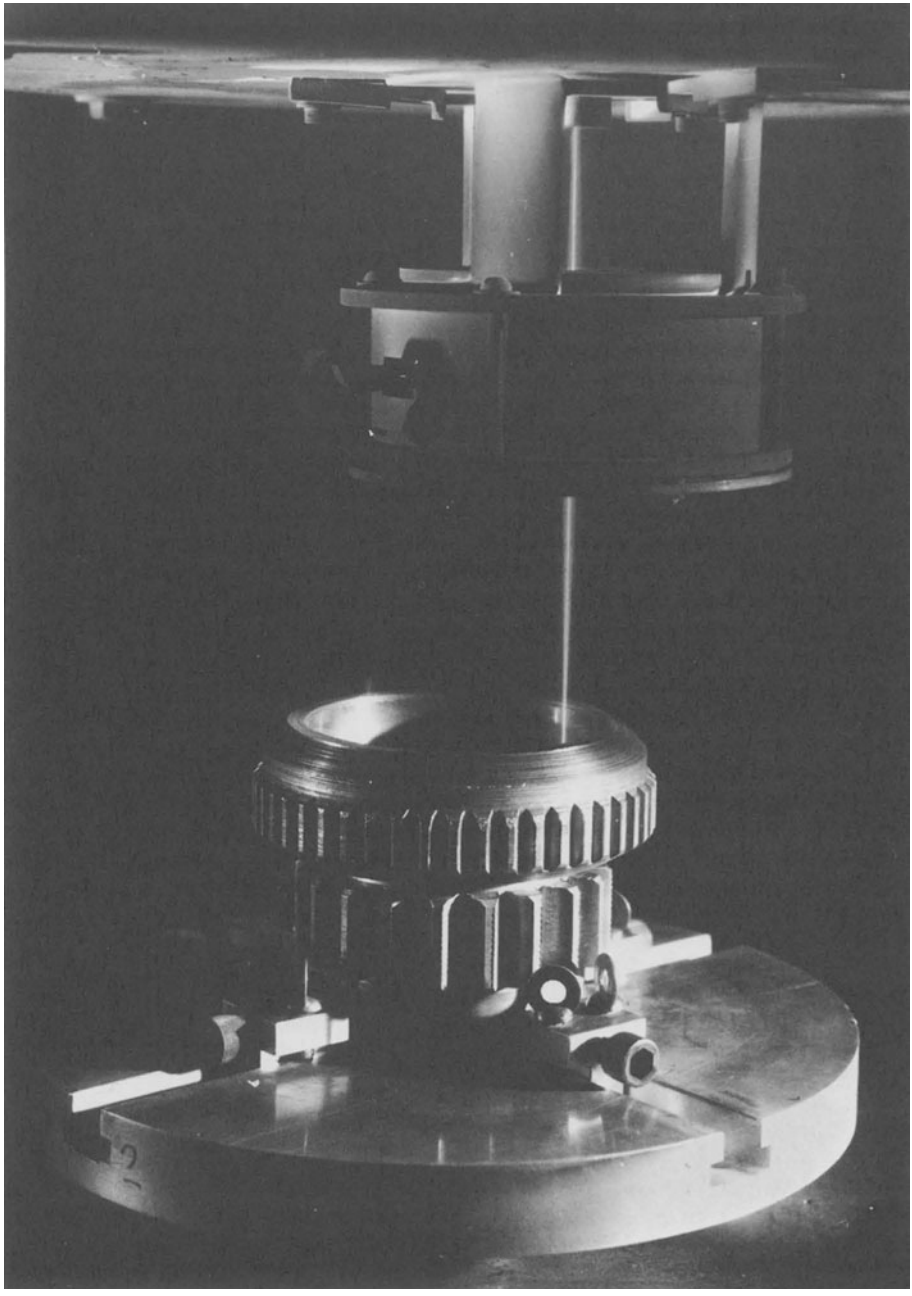


Fig. 47.9.—Gear welding in soft vacuum

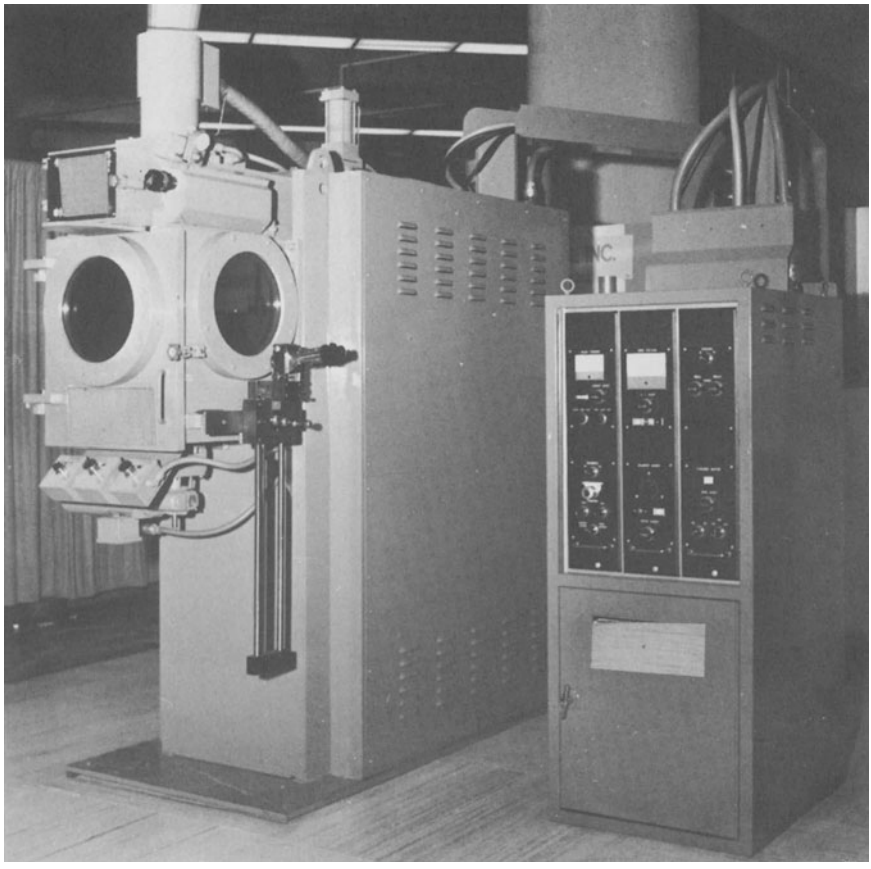


Fig. 47.10.—One general purpose machine for short production runs.

beam current and thus power are controlled by the bias voltage on the grid of the gun. The beam is focused by an electromagnetic lens to a minimum diameter by the orifice system shown in the lower part of the diagram. It emerges from the vacuum environment into gas at atmospheric pressure through the final orifice, where inert gas shielding can be added, if desired. The workpiece is placed near this final orifice. A high vacuum is maintained continuously in the gun area during operation with the aid of an oil diffusion pump. Higher pressures (but still well below atmospheric pressures) are maintained in the orifice system by means of mechanical pumps.

Fig. 47.14 shows one of the two basic types of non-vacuum electron beam welding machines. In most cases, the work is moved under the electron column in the overhung region using suitable tooling and fixturing. The point of welding must be shielded to prevent external x-ray radiation.

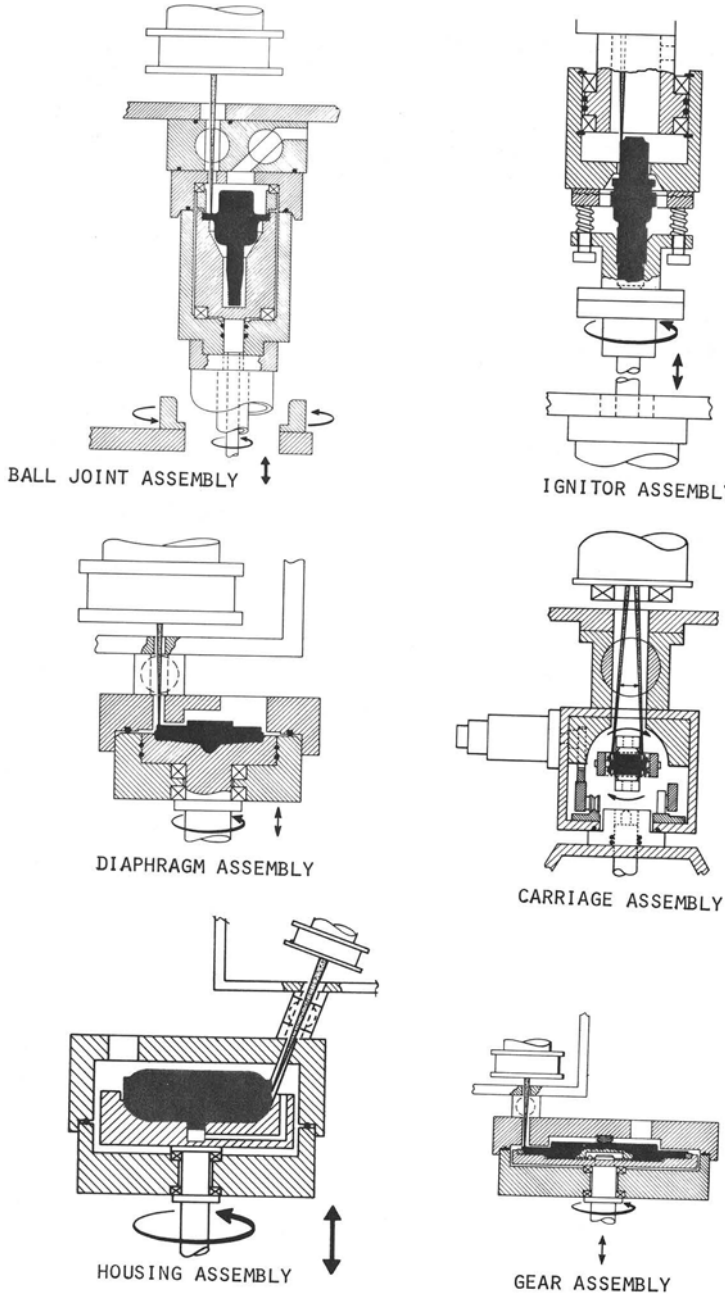
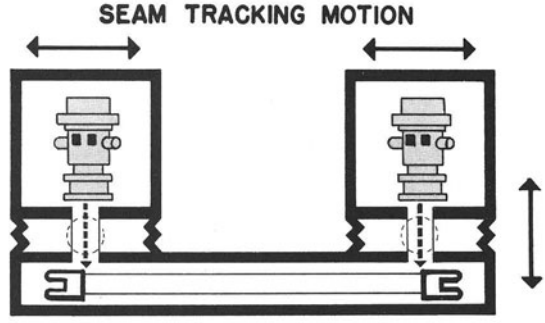
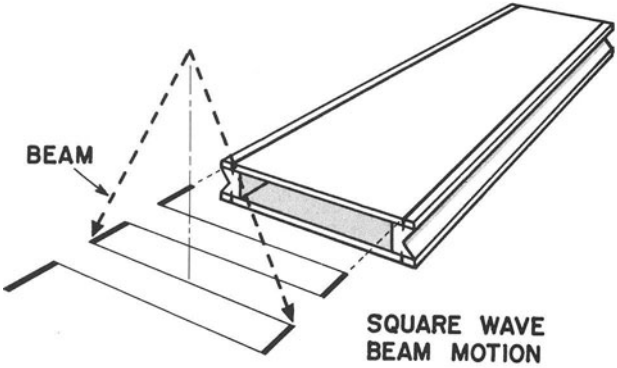


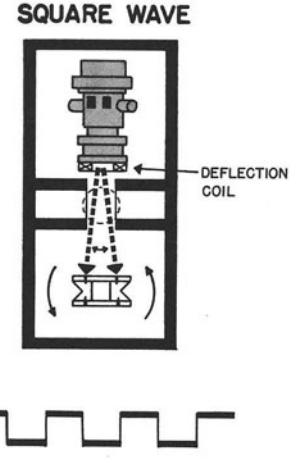
Fig. 47.11.—Some typical tooling concepts in special purpose machines tooled for particular parts (this page and next)

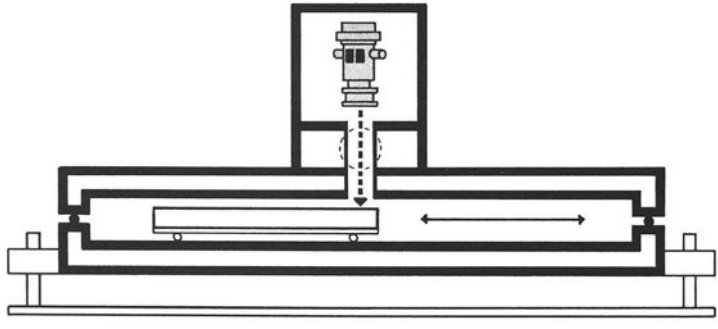


TWO GUNS WELD BOTH SHORT SIDES OF A PART 24 X 144 INCH IN ONE PASS, FLEXIBLE MOUNTING OF GUNS ON THE WELDING CHAMBER PERMITS THEM TO MOVE INDEPENDENTLY OF EACH OTHER IN RESPONSE TO INDIVIDUAL SEAM TRACKERS.



SHORT-WAVE CURRENT CONTROL OF THE DEFLECTION COIL PRODUCES A BEAM WITH A SQUARE-WAVE MOTION. WELDING ACTION OCCURS ONLY ALONG THE SIDES OF THE SQUARE WAVE, WHICH ARE VERY SHORT, SO THAT THEY BLEND TO PRODUCE TWO PARALLEL WELDS WITH ONE GUN.





SHUTTLE TOOLING FOR LINEAR WELDS, MOTION OF THE SHUTTLE CAN BE CONTROLLED EXTERNALLY.

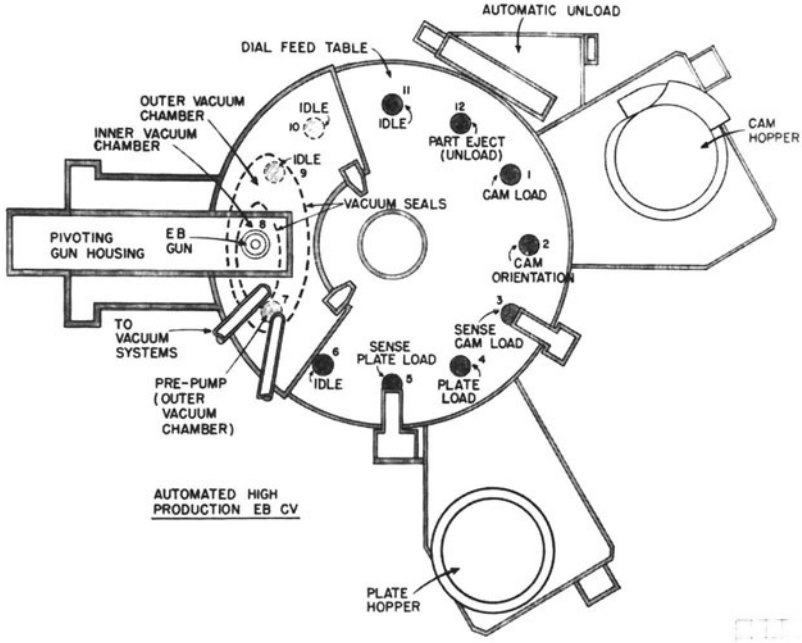


Fig. 47.12.—A dial feed table

With the 25 KW equipment available today, it is possible to produce single pass welds in many materials to depth exceeding ¾ in. at relatively high speeds. Fig. 47.15 is a cross section of such a weld in Type 302 stainless steel. Fig. 47.16 is a typical plot of weld penetration versus speed in stainless steel. These curves are valid for operation at a working distance of ¼ inch. Penetration decreases as the working distance is increased. If a gas of lower density than air, such as helium, is used, electron scattering is reduced and depth of penetration increased.

Obviously, non-vacuum electron beam welding has the very significant advantage of not placing a limitation upon the size of the part being welded. It also simplifies work handling in high-production applications. It does impose a limitation upon the shape of the workpiece, since the contour of the workpiece must be reasonably smooth so that the point of beam impingement remains within 1 in. of the welding structure, to avoid excessive beam diffusion. In general, somewhat wider fusion zones are produced than with high vacuum electron beam welding techniques, and in some cases these can resemble gas tungsten-arc welds.

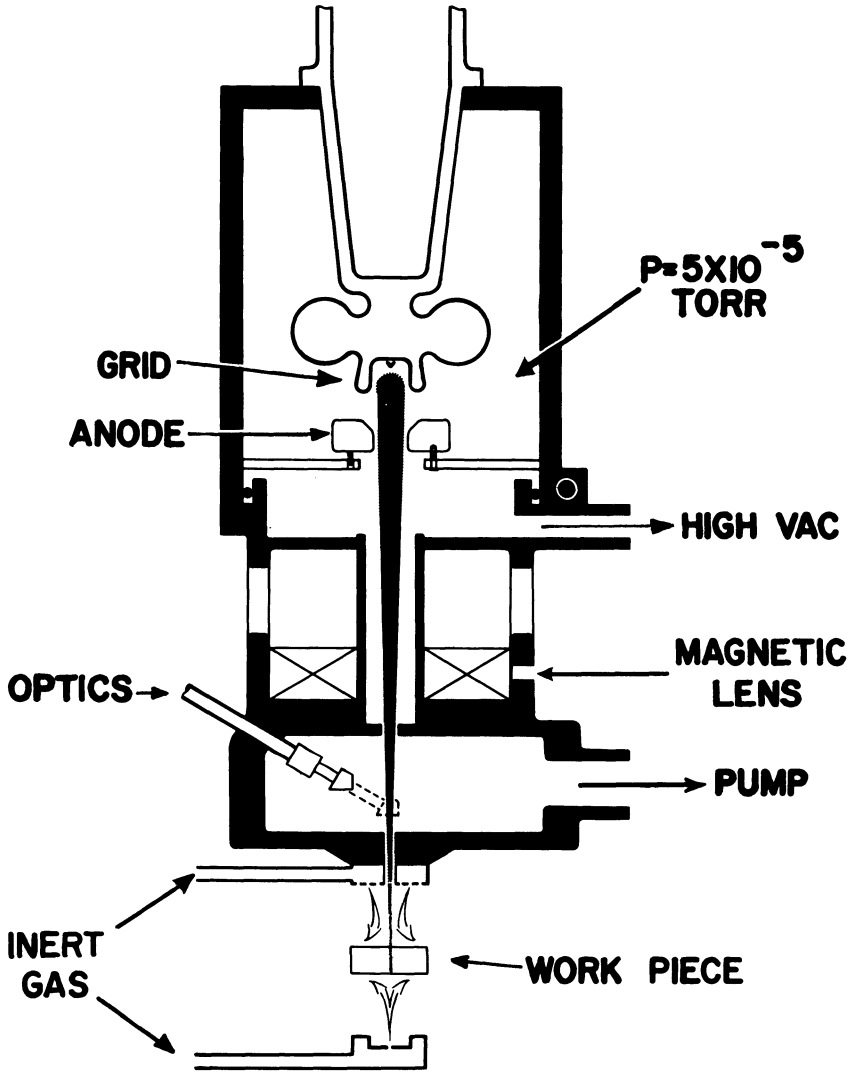


Fig. 47.13.—A non-vacuum electron beam optical column and orifice system

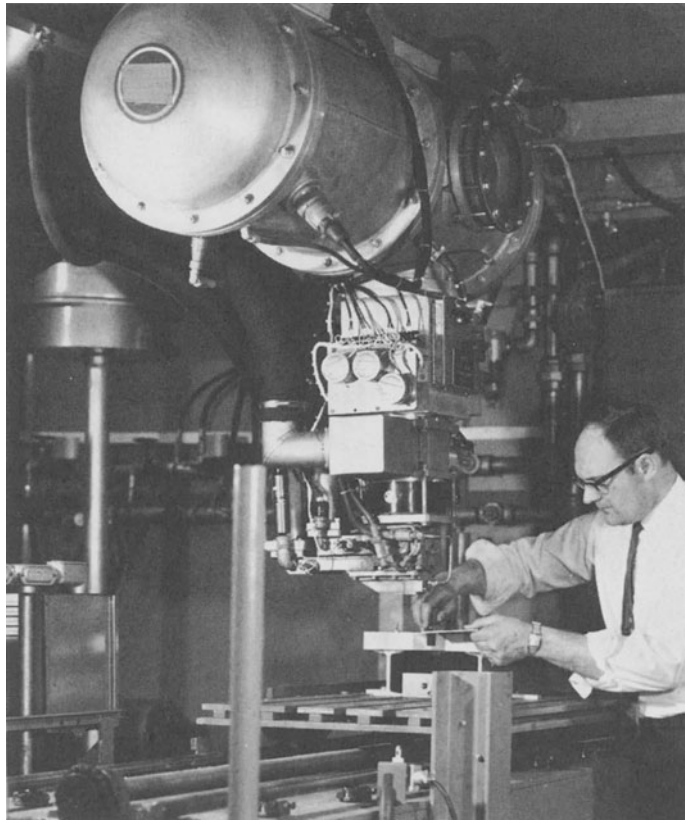


Fig. 47.14.—One of the two basic types of non-vacuum electron beam welding machines

Many materials have been welded successfully using the non-vacuum technique. They include carbon steels, alloy steels, stainless steels, high temperature alloys, refractory alloys, copper and its alloys, and aluminum alloys. Some of these materials are welded in air, while others require inert gas protective atmospheres because of their chemical and metallurgical characteristics.

Non-vacuum electron beam welding has found its major application in high production industrial use. For example, steel companies and metal fabricators are using this technique in the manufacture of welded tubing. Several units, integrated with tube mills, weld tubing on a production basis at speeds up to 100 feet per minute.

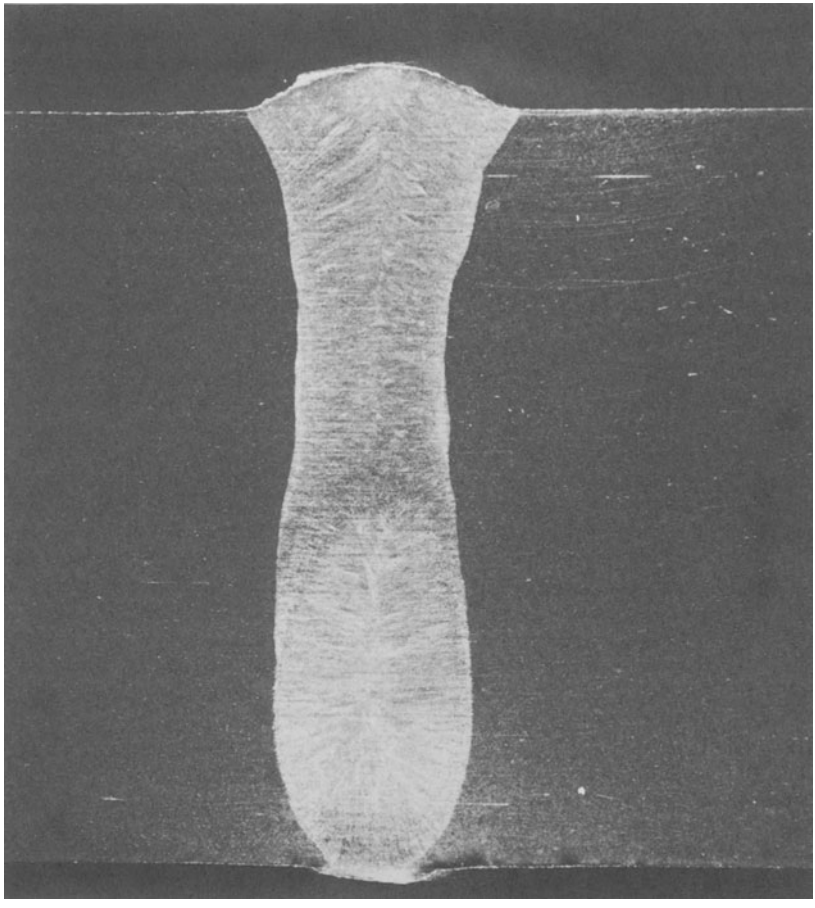


Fig. 47.15.—A cross section of a single pass weld in type 302 stainless steel

POWER SUPPLIES

GENERAL DESCRIPTION

The term high-voltage power supply, as applied to an electron beam welding machine, is commonly understood to refer to an assembly of at least one main high voltage dc power supply plus one or several auxiliary supplies, all operating at the high voltage (cathode) potential of the gun, and all of them responsible in some manner for producing and maintaining the electron beam. Depending upon the type of gun used, whether a diode type or a triode type, the high-voltage power supply consists of at least two, or respectively, three of the following:

1. A main high-voltage dc power supply, which delivers the electron beam accelerating voltage and the total beam current.
2. A filament supply (cathode heater supply is a better term if the cathode is heated by other means) that can be either ac or dc, and provides the power required to heat the cathode to the temperature at which electrons are emitted in sufficient quantity.
3. A bias supply (or control voltage supply) which impresses a voltage between cathode and bias cup (grid cup, control electrode) to control and regulate the amount of beam current to the workpiece. This voltage also serves, in some measure, to shape and focus the beam. (As indicated above, the bias supply is not applicable to diode type guns.)
4. Special electronic supplies such as a "beam pulser," a "beam current regulator," etc., frequently are furnished, also working at high voltage potential. They are packaged with the other supplies in the high-voltage supply assembly, and may or may not be separated from the bias supply; they may require a triode type gun.

BASIC DESIGN

The main high-voltage dc power supply and the auxiliary supplies mentioned above are frequently placed together in a common oil-filled enclosure or tank. The oil, a high-purity electrical-grade mineral oil, serves both as an electrical insulating medium and as a heat transferring agent, cooling the electrical components and carrying the heat to the walls of the tank. The supplies, to facilitate access for repairs, are typically supported entirely from the cover plate of the tank so that by merely lifting the cover plate they are removed from the oil and become fully exposed. The oil, therefore, need not be removed except for periodic filtering or replacement, or when the need arises to clean the inside walls of the tank.

A relatively new development by one manufacturer is a high-pressure gas insulated (sulfur hexafluoride) high-voltage power supply for a 150 KV electron beam non-vacuum welding machine. This supply is considerably more compact and lighter in weight than an oil-insulated supply of the same rating. Cost and other considerations, however, appear to be in favor of the oil-insulated supply.

Air-insulated high voltage supplies, while physically feasible, are impractical due to space requirements.

The components used in the main high-voltage dc power supply and the auxiliary supplies are, primarily, transformers, diodes (rectifiers), capacitors and resistors. Electron tube diodes are still used by some manufacturers in the main supply, but the trend is toward solid state diodes, either selenium or silicon. Cost, regulation, physical size, and ability to absorb transients of voltage and current are some of the considerations affecting the choice of components.

ELECTRICAL CHARACTERISTICS

The Main High-Voltage DC Power Supply

1. *Power* — Since the early days of electron beam welding, when most machines were rated 3 KW or less, manufacturers have steadily increased the maximum power available with their machines. Maximum continuous-duty rating offered today is 50 KW, but the trend is toward still higher ratings. The most common rating, and the one that will satisfy most requirements, is in the range of 5 to 30 KW.

2. *Voltage* — Voltage ratings vary widely in accordance with the wide variety of electron beam welding guns available. A classification by voltage could be made as follows:

Low voltage machines	up to 60 KV
High voltage machines	up to 200 KV

Machines are available in both categories. However, non-vacuum operation is impractical at less than 100 KV, and medium vacuum is impractical at less than 25 KV.

3. *Current* — Beam current is determined from the rated power and rated voltage. Typical rating of machines presently available are:

KW	KV	MA
6	30	200
7.5	30	250
7.5	150	50
12	175	70
15	30	500
15	60	250
25	150	167
25	175	140
30	30	1000
30	60	500
50	50	1000

4. *Ripple* — Requirements vary, depending upon desired quality of beam focusing. Also, excessive ripple on the accelerating voltage is reflected in a ripple on beam current; hence also on beam power and penetration. Most specifications, therefore, allow a maximum ripple of 1% (rms) of the accelerating voltage (or the equivalent of 2.8% peak to peak).

5. *Voltage Regulation and Stability* — The inherent droop (regulation) of output voltage due to applied load is, typically, in the order of 15 to 20%. To compensate for this droop and to eliminate the effect of line voltage variation and transients, as well as the effects of temperature and other factors influencing the accelerating voltage, manufacturers offer a variety of controls and regulators. The more sophisticated of these are designed to eliminate all of the effects mentioned, and are capable of maintaining a stable accelerating

voltage to within 1% of the selected value. Other controllers eleminate only some of the effects, but are less costly and may be adequate for less critical applications. Some of the controllers offered, in approximate order of sophistication and performance, include:

1. Line voltage regulator (constant voltage transformer).
2. Servo-operated variable transformer with feedback from high voltage output.
3. Motor-generator with electronic exciter and feedback from high voltage output.

Filament Supply

Directly heated cathodes, or filaments, are typically of the "hairpin" type or the "ribbon" type. The heating current can be either ac or dc; but dc is preferred due to the influence of the magnetic field (created by the filament current itself) on the direction, or positional stability, of the electron beam. Using an ac filament current, the beam will not impinge on a fixed point on the workpiece, but will oscillate with a small but significant amplitude around that point. For the same reason, when dc heating is used, it is necessary to use a filter to reduce the ripple to an acceptable value of 3% (rms) or less. Current and voltage ratings of a filament supply depend, of course, on the type and size of the filament used. For a 0.020 in. diameter hairpin filament the supply would be rated 30 amps, 20 volts (approximately 90% of the voltage is used to cover ohmic resistance losses in cable and connectors). Ribbon type filaments, most frequently used for low voltage guns, are generally designed to provide a much larger emitting area, which can be realized using a hairpin type filament. The power supply for a 500 ma ribbon filament would be rated for 70 amps at 10 volts.

Cathodes, or emitters, heated indirectly by electron bombardment from an auxiliary filament, are not in common use. However, a trend is seen in this direction, particularly for high-current electron beam guns. Heating supplies, such as cathodes of emitters, differ only from the filament supplies discussed above in that, in addition to a filament supply, they include a dc power supply to impress a voltage between the auxiliary filament and the emitter. A typical rating for this supply would be on the order of 500 or 1000 volts, 100 or 200 milliamperes. The filament supply rating typically might be 30 amps, 20 volts.

Bias Supply

The bias supply for a triode type gun is usually designed to give complete control of beam current from cutoff to full load current. This means that the output voltage of the supply must be adjustable from the cutoff voltage, which is of the order of 1500 to 2500 volts, to a bias voltage corresponding to full load current, which is about 200 or 300 volts (minus on bias cup, plus on cathode). The bias current, often referred to as "grid current," is usually small — 1 to 10 milliamperes.

The bias supply voltage must be a well filtered dc voltage so as not to cause a ripple on the beam current. The maximum ripple is about 1%.

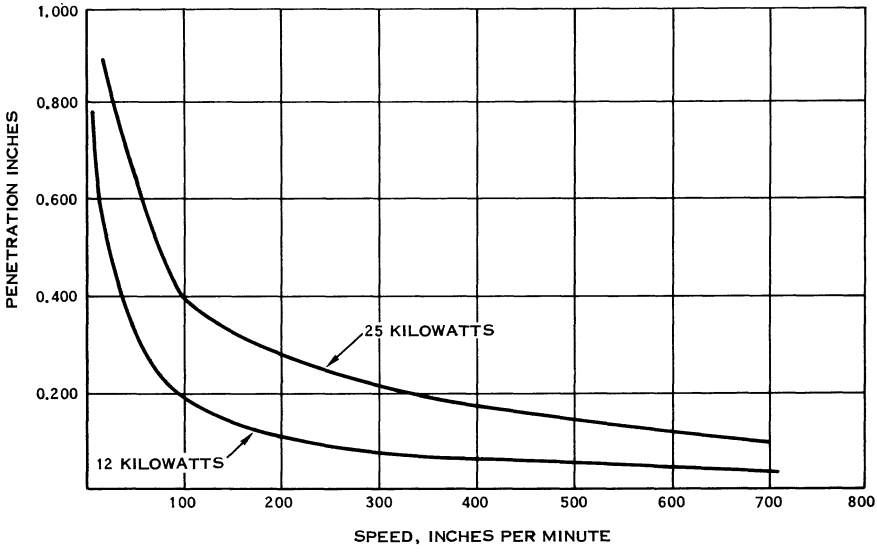


Fig. 47.16.—Non-vacuum electron beam welding: penetration vs. speed (in steel, using air as process gas) at ¼" working distance

One manufacturer employs a "self-biasing" system in which the bias is derived, partially from the main accelerating voltage through a voltage divider, and partially from the voltage generated by the beam current itself as it is forced to pass through a series resistor. This system, therefore, employs no actual bias supply *per se*.

Vacuum Equipment

All electron beam modes do not operate in a vacuum, but a vacuum is one of the integral parts of the process: All electron beams used for welding are generated in a high vacuum regardless of the environment in which they encounter the workpiece.

A vacuum is created by the transfer of the gas particles out of the chamber. Two basic types of vacuum pumps are used in electron beam welding machines. The first is a mechanical type used to effect a pressure reduction from 1 atmosphere to about 10^{-1} torr. (For medium-vacuum welding, these mechanical pumps are often operated in conjunction with Roots-type pumps, an alternative type of mechanical pump.) For pressures below 10^{-2} torr, an oil diffusion type pump is used to reduce the pressure to 10^{-4} torr or less. The sequencing of these pumps to produce the needed pressures can be accomplished either manually or by automatic means. In modern commercial electron beam welding equipment, automatic sequential programming is virtually standard.

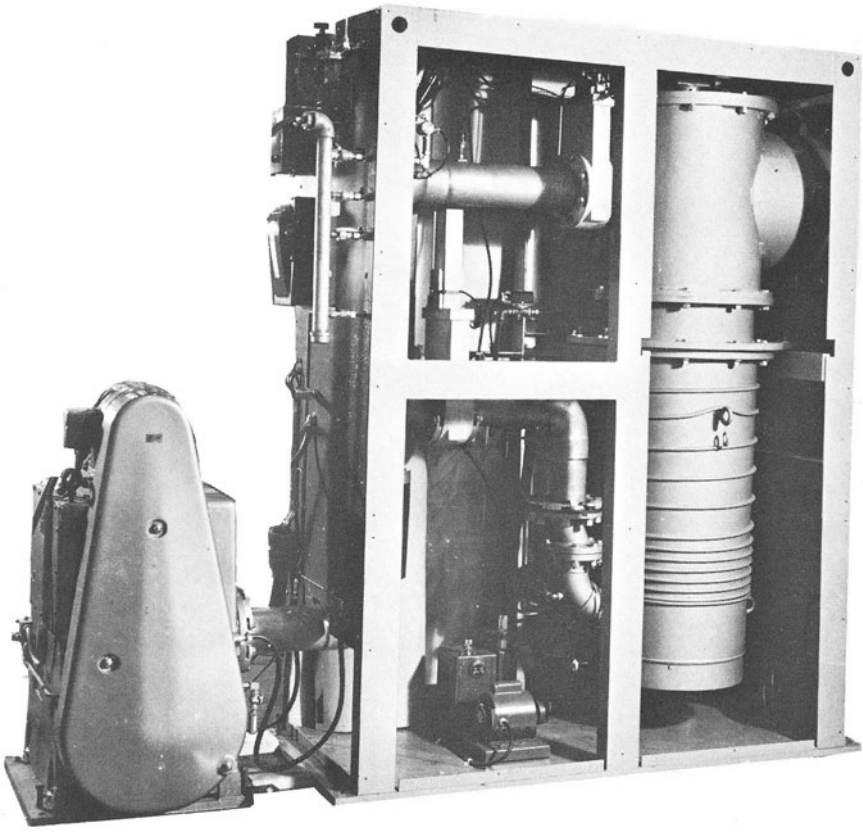
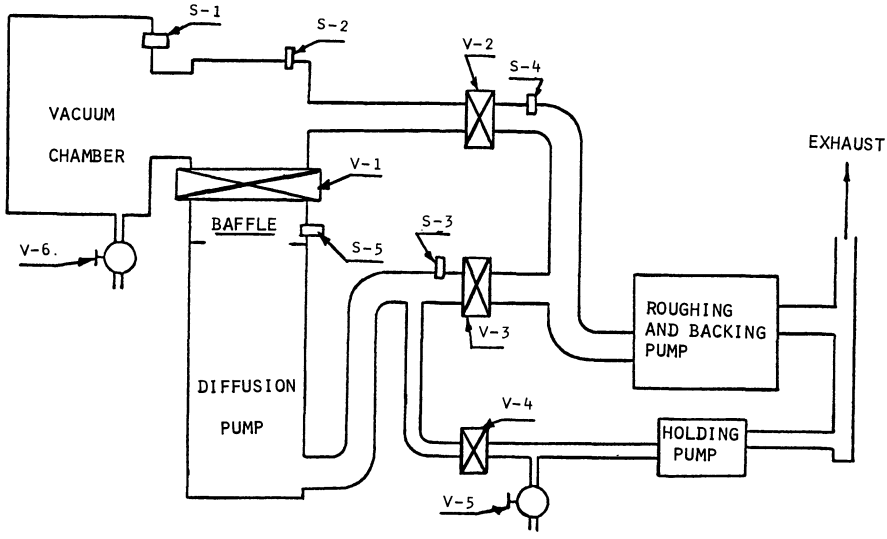


Fig. 47.17.—Vacuum pumping system

Table 47.1—Contamination levels of air at reduced pressure, and argon at atmospheric pressure

ARGON	
Purity Grade	Contamination Level, ppm
99.95% 99.995%	500 50
AIR	
Pressure, Torr	Contamination Level, ppm
380 x 10^{-3} 100 x 10^{-3} 38 x 10^{-3} 10 x 10^{-3} 1 x 10^{-3} 1 x 10^{-4}	500 132 50 13.2 1.3 0.1



VALVES

V-1—High Vacuum Valve, Poppet Type, Air-operated.*
V-2—Roughing Valve, Gate type, Air-operated.*
V-3—Backing Valve, Gate type, Air-operated.*
V-4—Holding Valve, Poppet type, Air-operated.*
V-5—Vacuum Release Valve, Ball-type, manual.
V-6—Vacuum Release Valve, Ball-type, manual.
* Air-operated valves are normally closed.

VACUUM SENSORS

S-1—ion type; Sensor & Port (Std.)
S-2—TC type; Sensor & Port (Std.)
S-3—TC type; Sensor (Optional), Port (Std.)**
S-4—TC type; Sensor (Optional), Port (Std.)**
S-5—ion type; Sensor (Optional), Port (Std.)**
** Port supplied with plug, if Sensor not ordered.

Fig. 47.18.—Vacuum pumping system

The vacuum pumping system is wholly located within an enclosure (with the exception of the mechanical roughing pump, which is mounted on a separate base at the rear of the machine to minimize transmission of vibration from the pump to the welding chamber (Fig. 47.17). The vacuum system consists of a mechanical roughing pump and a diffusion pump, both of which are attached to the chamber through a water-cooled optically-dense baffle (Fig. 47.18). A large diameter poppet valve closes off the diffusion pump during the roughing portion of the pumping cycle, so that the pump is not exposed to atmospheric pressure at any time. Another small mechanical pump acts to "hold" the diffusion pump at low pressure until the poppet valve is opened. The roughing and diffusion pumping periods are controlled by automatic sequence of the pneumatically operated valves.

The evacuation process and its rate depend upon the capacity of the pumps, the size of the chamber, and its total leak rate. Although the first two factors may vary over a large range, the "real" leak rate of a system for satisfactory operation should not exceed 1×10^{-8} atm cc per second. The magnitude of the "virtual" leakage is assessed by a rate-of-rise test. Here a customary acceptable limiting value is a rise rate of 5×10^{-3} torr per hour, averaged over a 10 hour rise time. This test is performed with the chamber valved off from the pumps, and is initiated immediately after a four-hour preparatory pumpdown of the chamber.

The automatic pumpdown cycles are accomplished by pumps interconnected through pressure-sensitive relays, which activate the system's valves and preprogrammed sequential operations. These operations are designed to protect the system in case of accidental loss of chamber vacuum.

Cryogenic traps, using liquid nitrogen (LN) for example, and thereby enabling attainment of less than 10^{-6} torr, are almost never required in electron beam welding systems.

PROCEDURE

JOINT PREPARATION

For electron beam welding, the faying surfaces should be machined square and true. Gapping, due to part fitup or machining, or both, should not exceed 0.005 in. for best results (see Fig. 47.19). For circular parts, annular welds and such, it is recommended that a light press fit be used in assembly. Typical electron beam weld joint types are shown in Fig. 47.20. The use of self-aligning joints, as shown in this figure, will be an aid in simplifying tooling.

In any welding process where high standards are to be met, cleanliness is a prime requisite. The particular requirement will depend on the end use of the welded product. Contamination of the weld joint is likely to cause porosity and/or cracking, and a deterioration of mechanical properties. In electron beam welding, failure to clean the weldments properly may increase the pumpdown time also.

Acetone is a preferred solvent for cleaning parts. Chlorinated hydrocarbon solvents should be avoided, because of chlorine's harmful effect on the diffusion pump oil. If heavy degreasing is needed and a chlorinated hydrocarbon solvent is used, such as a vapor degreaser, the parts should be washed in acetone after degreasing.

Surface oxides and other forms of contamination that are not removable with solvents should be removed by mechanical or chemical means. Flat surfaces in soft materials, such as magnesium, aluminum and copper, can be scraped by hand. Machining without coolant is good for all but very hard materials, where machine grinding must be used. For surfaces that cannot be machined, such as corrugations, pickling is used. Wire brushing is not recommended, generally, because it tends to embed the contaminants in the metal surface. Grit blasting and grinding are not recommended for softer materials, including non-hardened steels, because the grit becomes embedded in the surfaces.

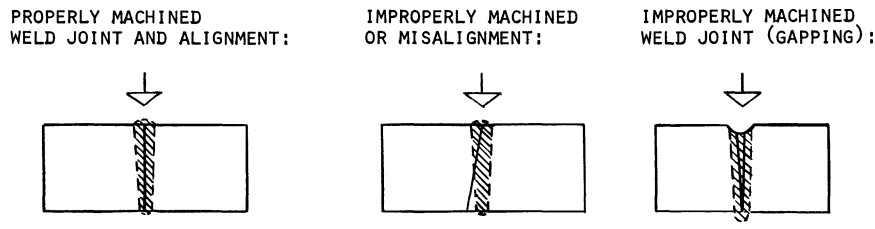


Fig. 47.19.—Gapping should not exceed 0.005 in.

If the above cleaning recommendations are followed, quality welds will be produced easily. If, however, materials are improperly cleaned, the resultant welds may contain internal defects, such as cracking, scattered to gross porosity, and possibly voids. External defects may also be produced, such as surface cavities, undercutting and, in general, a weld bead which has rough surfaces both top and bottom.

TOOLING

Generally speaking, for any specific weld joint design chosen, hold-down clamping of the workpiece is required to maintain the part in a fixed position. In some cases, such as square butt welds (either linear or circular), clamping can be supplemented by use of a sealing pass. The beam is run over the weld joint at low power, making a shallow penetration weld, thereby holding the two pieces together. The beam is then turned on at full welding power, making this weld at the proper penetration level. The tooling associated with electron beam welding is relatively simple and lightweight. Since welds are quite narrow, distortion is minimal and there is generally no need for very bulky heat-sinks or water-cooled tooling.

WELDING PARAMETER SELECTION

The expression most widely accepted in the welding industry for description of the rate of energy input to the workpiece is joules per inch. The equation for this expression is:

$$\text{Energy Input} = \text{Joules/inch} = \frac{60\,V\,I}{S} = \frac{60\,P}{S}$$

where V = beam accelerating potential in volts
I = beam current in amperes
P = beam power in watts
S = welding speed in inches per minute

The factor 60 arises in the conversion from "joules per second" to "joules per minute", to permit the result to be read in "joules per inch," using the speed factor of inches per minute.

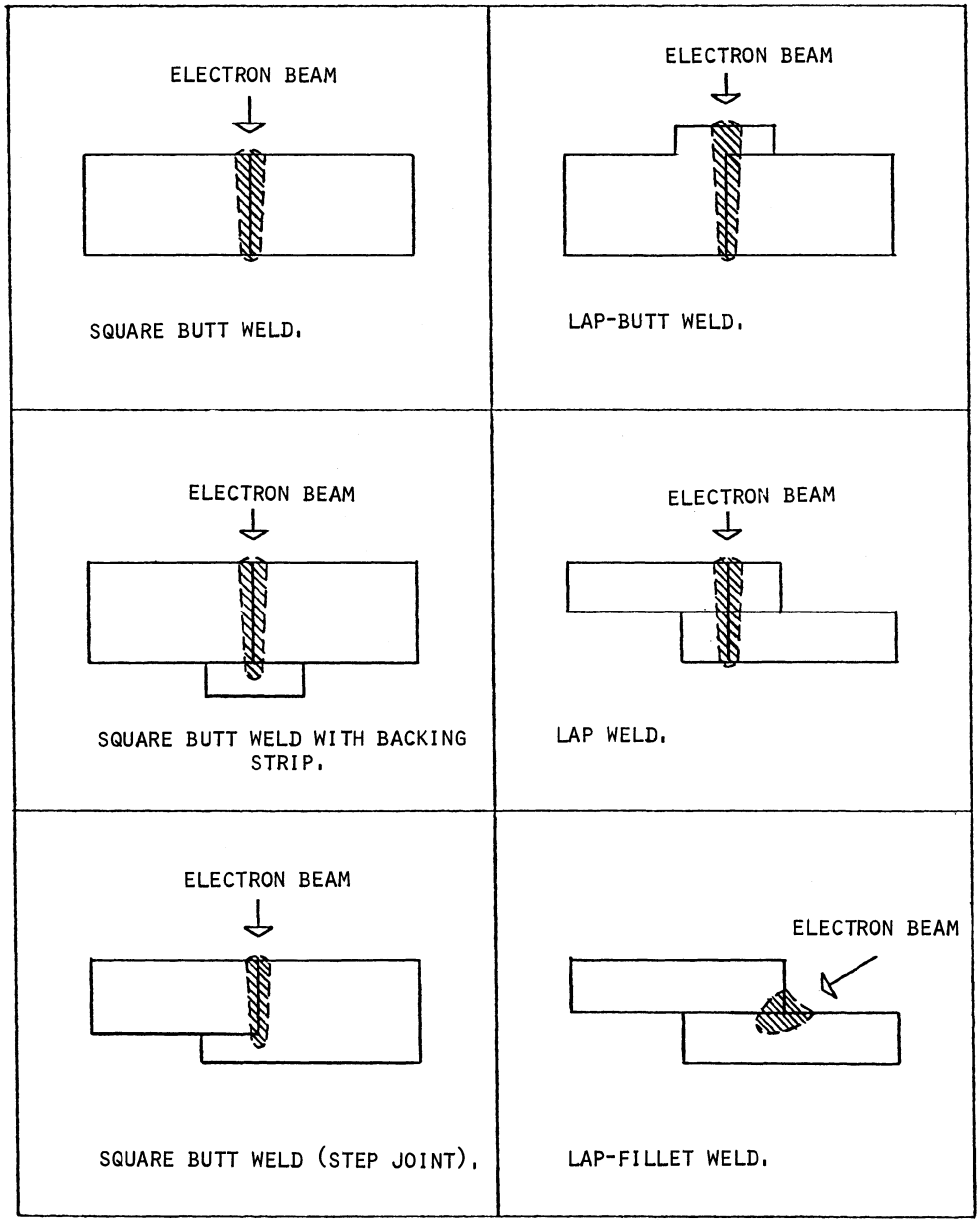
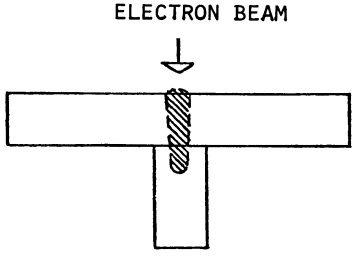
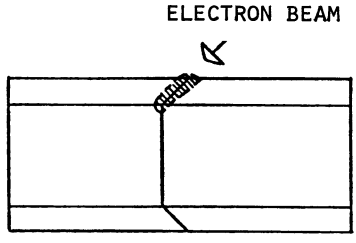


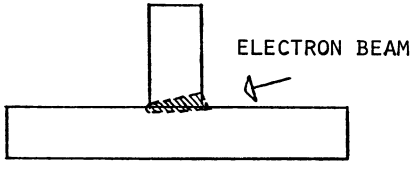
Fig. 47.20.—Electron beam weld joint types



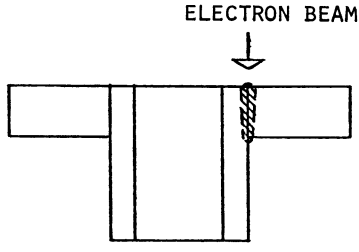
BURN-THROUGH "T" WELD.



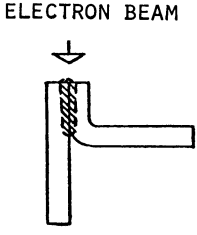
ANGULAR WELD.



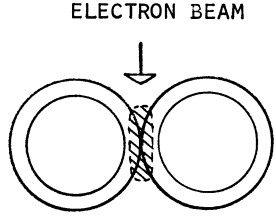
FILLET "T" WELD.



TUBE-TO-HEADER WELD.



EDGE WELD.



TANGENT TUBE WELD.

The above equation, along with information from weld data sheets (typical weld settings), allows interpolation of weld settings for a given alloy or material by plotting the thickness of the material *vs* the energy requirement in kilojoules per inch. This allows a few typical weld settings to establish a curve for a family of materials (Fig. 47.21). Such curves are quite useful for obtaining starting parameters. This is largely due to three important factors. First, the parameters that establish the weld setting are controlled by regulated closed-loop servo controls, which ensure stability and reproducibility. Second, the adjustment of each parameter is independently controlled, thus permitting flexibility in selection. Third, there are only four basic parameters to adjust: beam voltage, beam current, welding speed, and focus. These factors combine to make establishing of the weld schedule a relatively simple process.

Once the required energy input in kilojoules per inch is determined for a given material thickness, either the welding speed can be selected and the welding power thereby defined, or the power can be selected thereby defining the welding speed. Similarly, the beam voltage can now be selected, thereby defining the beam current.

The focus selected will be dependent upon the desired weld bead geometry. In order to maintain a fixed beam diameter at the surface of the workpiece, it is necessary to correspondingly increase the focus current as the accelerating voltage is increased, since the focus is a dependent function of the accelerating potential used. If, however, the accelerating potential (high voltage) is maintained constant, but the gun-to-work distance is increased, a corresponding decrease in focus current is necessary to maintain a fixed beam diameter at the surface of the workpiece.

Changes in individual weld parameters will affect the penetration and bead geometry as follows:

1. *Accelerating Potential* — As the accelerating potential is increased, the penetration of the weld bead will also increase. For long gun-to-work distances, or when narrow parallel-sided welds are desired, the accelerating potential should be increased so as to attain maximum beam density.

2. *Beam Current* — As the beam current is increased, penetration of the weld bead will also increase.

3. *Weld Speed* — As the weld speed is increased, the weld bead will become narrower, and the penetration will start to decrease. (The effects of weld speed are discussed further in the next section.)

4. *Focus* — Sharp focus will produce a narrow parallel-sided weld bead geometry, since the effective beam density is at its maximum (see Fig. 47.22). Defocusing the beam either by over-focusing or by underfocusing will increase the effective beam diameter, thereby causing the beam density to be reduced, which, in turn, will produce a shallow or more V-shaped weld bead.

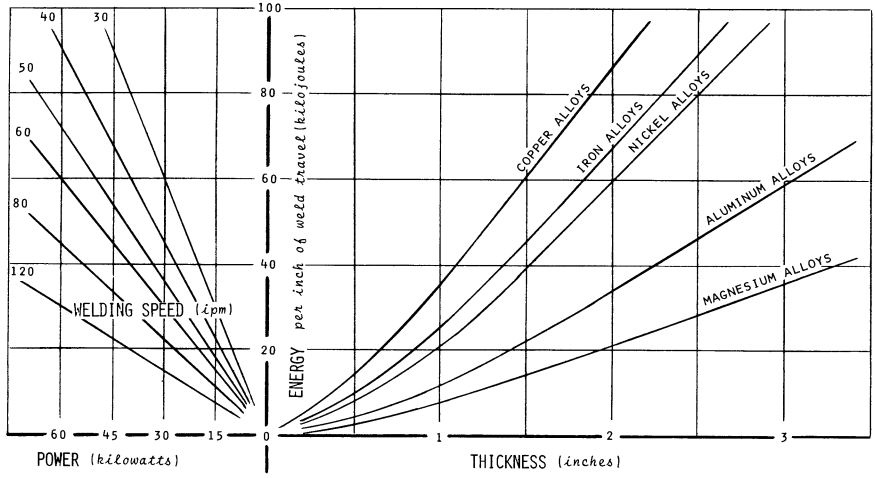


Fig. 47.21.—Hard vacuum electron beam welding energy requirements for full-penetration welding in several materials as a function of the joint thickness

OTHER TECHNIQUES

Electron beam welds (depending on the parameters chosen) are parallel-sided with a uniform crown or buildup of weld bead on the top surface (Fig. 47.23). At full (100%) penetration, welds will also have a uniform underbead, the width of which is dependent upon the welding parameters. In extremely heavy or thick sections of material (e.g., 3-in. stainless steel) the top and bottom surface condition is dependent upon the surface tension supporting the column of molten material which is being transported along the weld joint. As the welding speed is decreased, this material flow, due to insufficient surface tension and the action of gravity, will form an extremely heavy underbead, the "sag" of which causes the top surface to display severe underfill. Various techniques, such as the use of a backing strip, a step joint, or the use of "position" welding wherein the electron beam is used to produce horizontal or vertical welds, will tend to minimize this condition.

Use of starting and run-off tabs — The entry and exit of the electron beam tends to produce a loss of material from the terminal edge of the workpiece. In order to minimize or eliminate this defect, tabs of the same material as the workpiece are fitted tightly to the entry and exit surfaces. The beam is initiated on the starting tab, traversed across the weld joint, and terminated on the run-off tab. Later the tabs are removed by machining to the proper contour and dimension of the part.

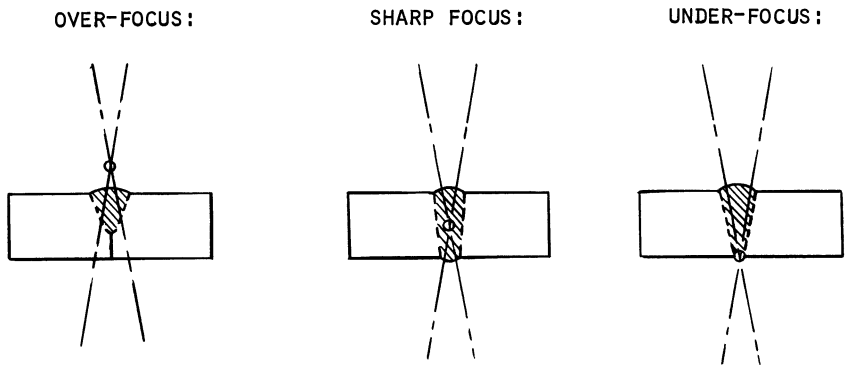


Fig. 47.22.—Focus

Use of Filler Blocks — Filler blocks are employed when an irregular cross section area is to be welded. Utilization of the filler block provides a constant thickness through which the weld can be made, thereby eleminating the necessity to make two weld passes, or to use some type of programming device. It should be noted that starting tabs and run-off tabs can sometimes be incorporated into the design of the filler block. Upon completion of the weld joint, this filler block material is machined away, leaving the part at proper contour and dimension. The filler blocks should be held securely in place and should have intimate contact throughout the contoured area.

Use of Filler Wire and Shims — No discussion of electron beam welding would be complete without consideration of the use of the electron beam to eliminate defects related to the inherent metallurgy of a system of alloys. There have been many attempts to eliminate microcracking in many alloys by the use of the electron beam wherein it was hoped that the smaller weld, the restricted heat-affected zone, and lower residual stress level would prove to be a solution. The electron beam can sometimes be of help, but it cannot improve metallurgically upon the base material. In many cases, an improvement in the alloy itself might obviate considerable experimentation.

In certain cases, unweldable materials or unweldable material combinations have been made weldable by the introduction of another metal, usually in the form of a shim. Table 47.2 lists several of these instances.

Whether or not two metals or alloys can be welded successfully depends on their physical properties, such as melting point, thermal conductivity, atomic size, coefficient of thermal expansion, etc., and is usually predicted by empirical experience in this line. A good idea of compatibility can be determined by examining the phase diagrams of the couples to be welded. If intermetallic compounds are formed by the two metals to be joined, the weld will be brittle.

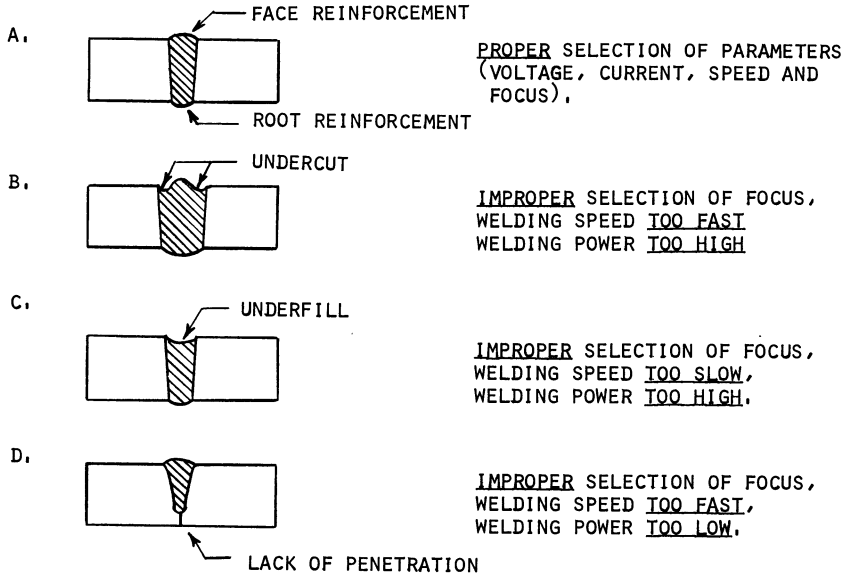
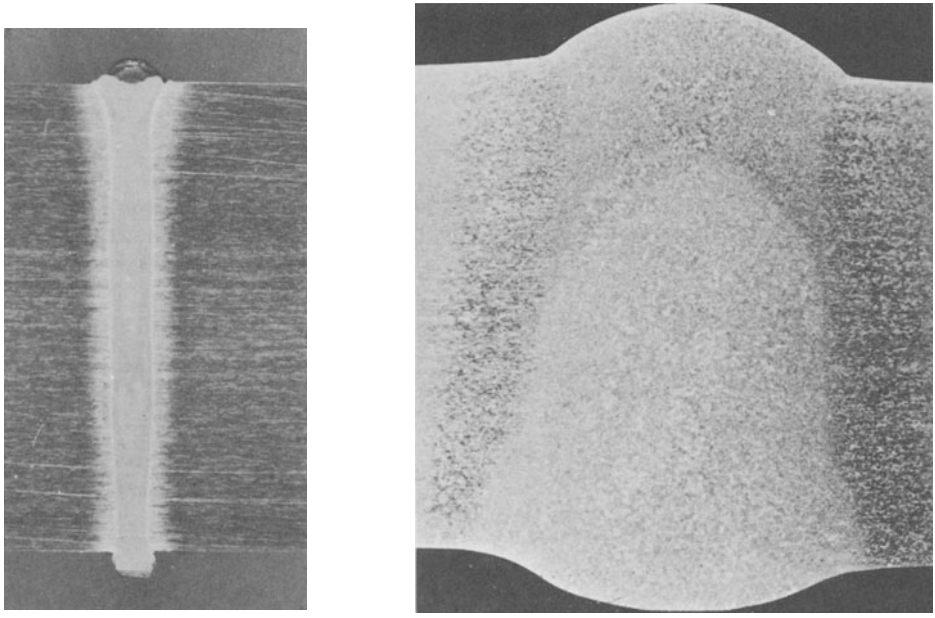


Fig. 47.23.—Some characteristics of typical electron beam weld cross-sections

Table 47.2—Unweldable materials made weldable by the introduction of a shim

Metal:	*Weldable:*	*Unweldable:*
Aluminum	Silver	Copper Stainless steel Steel Titanium
Copper	Stainless steel	Aluminum Steel Titanium
Molybdenum	Tungsten	Nickel Alloys Stainless Steel Titanium
Stainless Steel (300 Series)	Copper Inconel 700, 718, 606 Steel	Aluminum Molybdenum Titanium Monel
Steel	Stainless Steel Nickel Alloys	Aluminum
Titanium	Columbium	Aluminum Copper Molybdenum Nickel Alloys Stainless Steel



	Electron-Beam Weld	Gas Tungsten-Arc Weld		
		1st Pass*	2nd Pass†	Total
Voltage, volts	30 x 10^3	11.7	13.0	...
Current, amps	200 x 10^{-3}	270.	270.	...
Welding speed, ipm	95	6.5	7.5	...
Power, kw	6	3.2	3.5	6.7
Energy, kilojoules/in.	3.8	29.6	28.0	57.6

*without wire
†with 1/6 in. dia type 2319 wire

Fig. 47.24.—Comparison of electron-beam (left) and gas tungsten-arc (right) welds in 1/2 in. thick type 2219 aluminum

Table 47.3—Use of a third metal as a filler shim

Material #1	*Material #2*	*Filler Shim*
Tough Pitch Copper	Tough Pitch Copper	Nickel
Tough Pitch Copper	Mild Steel	Nickel
Hastelloy X	SAE 8620 Steel	1/32" 321 Stainless Steel
304 Stainless Steel	Monel	1/32" Hastelloy B
A-286 Stainless Steel	SAE 4140 Steel	1/32" Hastelloy B
Inconel 713C	Inconel 713C	Udimet 500
Rimmed Steel	Rimmed Steel	Aluminum

Some information has been published on the relative weldability of dissimilar metals. However, this information must be reviewed in the light of each particular application, with regard to joint restraint and service environment. The problem of incompatibility can sometimes be solved by the use of a third metal as a filler shim, Table 47.3, or by welding each of the incompatible materials to a transition piece, which is compatible with each. Table 47.4 presents a summary of the compatible and incompatible metal combinations derived from consideration of phase diagram information and accumulated practical experience.

Filler metal is often used for metallurgical purposes by sandwiching it into the joint. Wire feed is not employed exclusively; the dilution obtained from a dissimilar filler metal added at the surface does not dilute the weld metal uniformly to any great depth. In the case of heavy plate metal-shim fillers must almost always be employed. Due to the thickness of the filler shims a wide beam must be used in order to span the filler thickness and also melt base metal on both sides of the joint. This is not the case in regard to thin metal weldments where dilution will occur throughout the entire joint.

The addition of filler metal wire or shims to the weld melt frequently finds application in electron beam welding. Filler metal or shim materials may be added to the weld melt to produce certain physical and metallurgical weld bead characteristics. Among the weld bead characteristics that may be altered or improved by filler metal addition are ductility, tensile strength, hardness, and susceptibility to cracking. Addition of a small amount of aluminum (wire or shim) can also be used to produce a "killing" action (as in steel), by which porosity in the weld bead is reduced.

Filler metal may also be added after the weld pass has been made, for the purpose of filling in an underfilled weld bead top surface. The weld bead is crowned with the filler metal in this application, which again assures a specific weld bead characteristic.

Filler metal, when used for the above-mentioned purposes, requires no special joint preparations, since the use of filler metal is not merely to fill in a V-grooved joint, but rather is a means of obtaining specific characteristics at the top of the weld bead.

CHARACTERISTICS OF WELDS

The electron beam welding process produces weld fusion zone geometries that differ significantly from those made by the more conventional welding processes. A typical electron beam weld, as viewed in transverse cross section, is shown in Fig. 47.24 alongside with a tungsten inert gas weld.

Another factor to consider when comparing these two processes is that, generally speaking, the larger the mass that is made molten during the weld heat input cycle, the greater the loss of chemical constituents from the parent metal. Since allowable tolerance limits of the chemical constituents are important to fabricators of all products, it is imperative that the fusion welding processes do not alter the chemical makeup of the metal, except within allowable limits.

Table 47.4—Weldability of metals

1	VERY DESIRABLE (Solid Solubility in all Combinations)
2	PROBABLY ACCEPTABLE (Complex Structures May Exist)
3	USE WITH CAUTION (Insufficient Data for Proper Evaluation)
4	USE WITH EXTREME CAUTION (No Data Available)
5	UNDESIRABLE COMBINATIONS (Intermetallic Compounds Formed)

	Silver	Aluminum	Gold	Beryllium	Cadmium	Cobalt	Chromium	Copper	Iron	Magnesium	Manganese	Molybdenum	Columbium	Nickel	Lead	Platinum	Rhenium	Tin	Tantalum	Titanium	Vanadium	Tungsten
Aluminum	2																					
Gold	1	5																				
Beryllium	5	2	5																			
Cadmium	2	5	5	4																		
Cobalt	3	5	2	5	3																	
Chromium	2	5	3	5	3	2																
Copper	2	2	1	5	5	2	2															
Iron	3	5	2	5	3	2	2	2														
Magnesium	5	2	5	5	1	5	5	5	3													
Manganese	2	5	5	5	3	2	2	1	2	5												
Molybdenum	3	5	2	5	4	5	1	3	2	3	3											
Columbium	4	5	4	5	4	5	5	2	5	4	5	1										
Nickel	2	5	1	5	3	1	2	1	2	5	2	5	5									
Lead	2	2	5	4	2	2	2	2	2	5	2	3	4	2								
Platinum	1	5	1	5	5	1	2	1	1	5	5	2	5	1	5							
Rhenium	3	4	4	5	4	1	1	3	5	4	4	5	5	3	4	2						
Tin	2	2	5	3	2	5	2	2	5	5	5	3	5	5	2	5	3					
Tantalum	5	5	4	5	4	5	5	3	5	4	5	1	1	5	4	5	5	5				
Titanium	2	5	5	5	5	5	1	5	5	3	5	1	1	5	5	5	5	5	1			
Vanadium	3	5	3	5	4	5	3	3	1	4	5	1	1	5	4	5	3	5	5	1		
Tungsten	3	5	4	5	4	5	1	3	5	3	3	1	1	5	3	1	5	3	1	2	1	
Zirconium	5	5	5	5	3	5	5	5	5	3	5	5	1	5	5	5	5	5	2	1	5	5

Since the electron beam welding process is capable of producing a fused weld nugget whose width may be as little as 1/10 or 1/20 of the thickness of the part, the process is ideally suited to weld components of a critical nature, or components that must utilize the maximums in materials and design allowances.

Study of the nugget formations produced by the electron beam welding process shows another interesting feature which can be used to control distortion in weldments. In this type of weld (Fig. 47.23 left), except for where the electron beam first impinges on the top surface of the abutted members, the fusion zone through the joint is essentially parallel-sided and the fusion zone boundaries are relatively straight. The schematic illustration in Fig. 47.25 shows a comparable tungsten inert-gas arc weld in a prechamfered butt joint. As a direct result of the shape of the fusion zone, thermal contraction caused the plates to warp upward. This effect is substantially minimized in electron beam welding.

Since the electron beam welding process can penetrate through extremely thick cross sections, preweld manufacturing costs required for beveling or chamfering one or both sides of abutting members are eliminated.

In the medium vacuum mode, similar nugget cross section configurations exist, but the depth-to-width ratios are reduced.

In the non-vacuum electron beam welding mode, the weld bead may be as wide as a typical inert gas arc weld and the weld nugget possesses all the characteristics of the more conventional welding processes.

MATERIALS WELDED

The narrow range of specialty applications which introduced electron beam welding has long since been superseded. Today this technique can be used on virtually all weldable metals.

Representative mechanical property data and associated welding conditions for a number of thick structural alloys are given in Tables 47.5 and 47.6. In most materials, electron beam weld properties are as good or better than those of welds made by arc welding processes. General comments on electron beam welding as applied to specific metals and alloys are presented in the sections that follow.

ALUMINUM ALLOYS

A large range of aluminum alloys has been processed by the three electron beam welding modes. Even aluminum alloys types 6066-T6 and 6061-T6, both of which are considered difficult alloys to join, have been successfully welded by the electron beam process. Best results with this alloy have been obtained by using small amounts of type 4043 filler metal.

Table 47.5—Mechanical properties of electron beam welds in Ti-6A1-4V, René 41 and 7075 Aluminum

Materials & Thickness		Heat Treatment		Weld Parameters			Strength		Elong.	R. A.	KIC
		Pre	Post	Kv	MA	ipm	Tensile	Yield	%/in.	%	ksi √ in.
							ksi	ksi			
Ti-6A1-4V	1 in.	A	—	—	—	—	142	136	13.5	34.7	—
Ti-6A1-4V	1 in.	BC	—	—	—	—	159	148	18.0	43.3	70.7
Ti-6A1-4V	1 in.	BC	W	23	300	15	155	142	7.5	22.9	68.0
Ti-6A1-4V	1 in.	BC	C	23	300	15	156	143	6.5	19.9	63.0
Ti-6A1-4V	1 in.	A	BC	23	300	15	156	145	6.0	16.1	83.0
Ti-6A1-4V	1 in.	A	W	23	300	15	141	134	10.4	37.9	81.9
Ti-6A1-4V	1.75 in.	B	BC	55	360	40	154	142	8.9	20.3	75.0
René 41	1 in.	D	—	—	—	—	177	125	34.5	34.4	—
René 41	1 in.	DE	—	—	—	—	190	148	15.5	15.4	96.0
René 41	1 in.	D	E	22	290	13	174	141	8.1	9.7	99.0
René 41	1 in.	D	DE	22	290	13	183	146	10.0	9.4	63.0
René 41	1 in.	DE	W	22	290	13	148	118	6.8	30.0	83.0
7075 Aluminum	1.5 in.	T651	—	—	—	—	83	72	13.0	18.4	23.0
7075 Aluminum	1.5 in.	T651	W	22	280	8	52	35	6.8	20.0	21.1

A — 2 hrs 1300°F (704°C) air cool; B — 1 hr 1750°F (954°C) water quench; C — 4 hrs 1000°F (538°C) air cool; D — 1 hr 1950°F (1066°C) air cool; E — 16 hrs 1400°F (760°C) air cool; W — as welded
T651 — 850°F (454°C) 1 hr + 2% deformation + 250°F (121°C) 24 hrs.

Table 47.6—Mechanical properties of electron beam welds in maraging steel, HP9-4-25 Steel and 15-7 Mo Ph Steel

Materials and Thickness		Heat Treatment		Weld Parameters			Strength		Elong.	R. A.	KIC
		Pre	Post	Kv	MA	ipm	Tensile	Yield	%/in.	%	ksi √ in.
							ksi	ksi			
Maraging Steel	1 in.	F	—	—	—	—	150	111	19.0	69.1	—
Maraging Steel	1 in.	FG	—	—	—	—	259	252	12.0	50.5	88.6
Maraging Steel	1 in.	F	FG	50	320	40	257	254	6.2	35.2	79.1
Maraging Steel	1 in.	FG	G	50	320	40	263	259	4.0	24.8	65.2
Maraging Steel	1 in.	F	G	50	320	60	260	254	7.2	36.9	63.0
HP-4-25 Steel	1 in.	HK	—	—	—	—	198	184	18.0	59.3	14.7
HP-4-25 Steel	1 in.	H	K	23.5	300	7.5	193	181	10.7	52.2	121
HP-4-25 Steel	1 in.	HK	K	23.5	300	7.5	196	185	11.4	48.0	134
15-7 Mo Ph Steel	1 in.	LMN	—	—	—	—	170	145	17.7	40.6	90
15-7 Mo Ph Steel	1 in.	L	MN	50	320	50	154	138	3.5	18.9	33

F — 1 hr 1500°F (816°C) air cool; G — 3 hrs 900°F (482°C) air cool; H — 1 hr 1550°F (843°C) oil quench; K — 2 hrs 1000°F (538°C) air cool + 2 hrs 1000°F (538°C) air cool; L — 1 hr 1950°F (1066°C) air cool; M — 1.5 hrs 1400°F (760°C), running water quench 1 hr; N — 1 hr 1050°F (566°C) air cool.

In the as-welded condition, aluminum alloy 7075-T651 in 1.5-in. thickness exhibits lower mechanical properties than the corresponding unwelded plate (see Table 47.5). This loss in properties is caused by annealing of cold work and overaging in the heat-affected zone. Post-weld solution treating and aging can restore some of this loss. This aluminum alloy can be penetrated fully without difficulty, but at higher speeds excessive porosity occurs because vaporized elements in the alloy do not escape from the joint. The high zinc level is responsible for the vapor formation. At lower speeds, the vapor has time to escape before the puddle solidifies. Aluminum alloys not containing zinc can be welded at higher speeds without encountering a severe porosity problem. It is advantageous to weld hardenable aluminum alloys at high speed to minimize overaging and annealing.

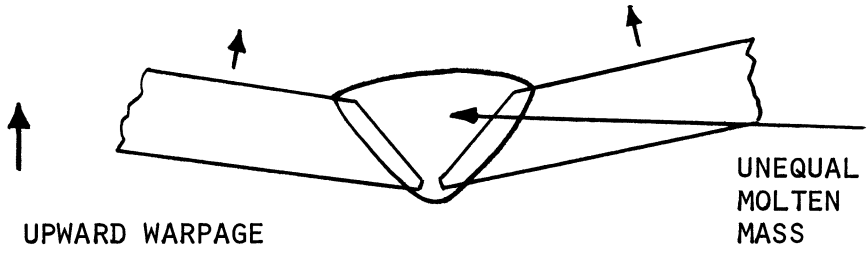


Fig. 47.25.—Schematic of one-half (½) inch thick chambered butt joint welded by gas tungsten arc process. Note: Plate warpage pattern

BERYLLIUM

Beryllium is satisfactorily processed only by the high vacuum mode. Satisfactory joints can be made without cracking and without excessive vaporization. Fusion zone strength is dependent on grain size. Up to 50% joint efficiencies are obtainable in 1/16 in. sheet of both pressed and sintered and hot rolled variety. Impact properties of material prepared by either process, however, are not entirely satisfactory.

It should be noted that processing of beryllium can be very hazardous unless recommended procedures for handling this metal are followed. Refer to *Recommended Safe Practices for Electron Beam Welding,* AWS A6.4, and *Safety in Welding and Cutting,* USAS Z49.1 (latest editions).

NICKEL BASE ALLOYS

An extremely large variety of nickel-base alloys exists. For example, René 41, Haynes 25, Waspaloy, the Hastelloys, Inconel 718, and Udimet. Many of these alloys are welded without difficulty.

Inconel

Inconel-600* displays two problems when electron beam welded: gross porosity and microfissures. The susceptibility of the material to this type of defect varies widely from heat to heat. Control of the problem may be achieved in a number of ways, all of which take cognizance of the basic causes of defect formation.

The principal approach is to control the material used for welding. This can be done either by controlling the raw material manufacturing process, or by selecting material with weldability characteristics that are known to be acceptable. Since the acceptable level of gas content varies with the weld size and shape, no universal requirements have been established. Each weld or series of welds is now qualified with a particular heat of material as one indication of weldability.

At present, the mechanism for the formation of microfissures is not completely understood. Consequently, the most effective known means of avoiding this defect is the selection of material that is not susceptible to this type of defect, as evidenced by passing a weldability test. While other techniques have shown progress in the elimination of microfissures, none has been so successful as the proper screening of starting material. Since most microfissures appear in the weld heat-affected zones, the starting material appears to exert more influence on the product than does the welding technique.

René 41

René 41** exhibits its best electron beam welded properties when welded in the solution treated condition, and then re-solution treated and aged after welding (see Table 47.5). However, fracture toughness is greatest for welds made in solution treated plate that is then only aged after welding. A sequence of: (1) solution treat, (2) weld, (3) solution treat and (4) age or direct age, yields 1600°F (871°C) stress rupture properties, only 1 to 2 kpsi lower than unwelded heat-treated plate. Welding solution treated and aged plate is not recommended because this gives the poorest as-welded mechanical properties.

The normal practice for joining René 41 is to weld after the components have been solution treated. If this alloy is welded in the aged condition, strain age cracking can be expected, especially if the weld is restrained and exposed to a subsequent aging heat treatment or service in the aging range.

Strain age cracking has been observed occasionally in two-pass and repair-pass electron beam welds in René 41 (Fig. 47.26) even though the material was in the solution-treated condition before welding. The cause of this cracking is not clear. It may be strain age cracking that occurs because some aging and some re-solution heat treatment takes place during the first weld pass. Also, the residual stress level is believed to be higher after a two-pass weld than after a single-pass weld.

* Trademark of the International Nickel Company.
** Trademark of Allvac Metals Company.

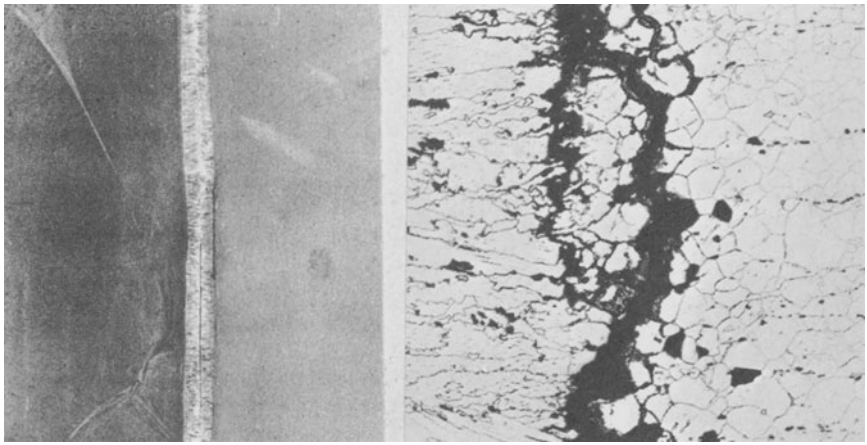


Fig. 47.26.—Strain age cracking in two-pass and three-pass electron beam welds in René 41

Strain age cracking occurs frequently in René 41 weldments made using conventional arc welding processes. Additional work is in progress on the strain-age cracking problem of René 41 and related alloys, and the literature should be consulted.

Inconel 718

Microcracking has been observed in the heat-affected zone of electron beam welds in René 41 and Inconel 718*. These cracks appear to be intergranular and related to grain boundary melting near the fusion zinc. This type of cracking also was encountered in a production application involving welding vanes to a 2-in. thick Inconel 718 shroud ring. In other applications, microcracks were observed in the heat-affected zone of resistance spot welds in Inconel 718, but not in gas tungsten-arc welds of the same material. The cause of this microcracking is not known, but it appears to be associated with the rapid cooling rates that occur in resistance and electron beam welding.

Refractory Metals

Electron beam welding is an excellent process for joining many of the refractory metals, because the beam's high power density allows the joint to be fused with a minimum of heat input to the weldment. This is important with many of the refractory metal alloys because fusion and recrystallization tend to raise the ductile to brittle transition temperature. The short time at temperatures associated with electron beam welding minimizes grain growth and other reactions that could raise the transition temperature. The refractory metals can be divided basically into two groups represented by rhenium, tantalum and columbium and their alloys, which are readily processed; and molybdenum and tungsten, which are more difficult to weld.

Table 47.7 gives comparable strength and bend ductility transition temperature data for electron beam welds in a number of columbium base alloys.

* Trademark of the International Nickel Company.

Table 47.7—Comparison of tensile properties and bend ductility transition temperature for electron beam welds in Columbium alloys

Alloy & Thickness		Weld Parameters			Room Temp. Properties			2200°F (1204°C) Prop.			Transition Temp.	
					Tensile	Yield	Elong.	Tensile	Yield	Elong.		
	(inches)	kv	Ma	imp	ksi	ksi	%/in.	ksi	ksi	%/in.	°F	°C
FS 85	sheet .060	—	—	—	103	190	15	40	35	22	—320	—196
FS 85	sheet .020	—	—	—	109	95	13	52	35	15	—320	—196
FS 85	EB .060	21.7	94	30	96	82	7	43	35	4	—200	—129
FS 85	EB .020	16.5	59	60	89	76	3	43	33	2	—300	—184
FS 85	GTAW .060	14.5	220	30	94	78	10	41	32	5	—250	—157
B 66	sheet .060	—	—	—	107	93	24	45	32	45	—320	—196
B 66	sheet .020	—	—	—	108	87	25	41	32	55	—320	—196
B 66	EB .060	18	77	30	109	88	19	46	32	33	—150	—101
B 66	EB .020	20.5	33	60	106	81	18	41	31	43	—200	—129
B 66	GTAW .060	14.5	165	15	107	85	19	45	32	32	—50	—46
Ch 752	sheet .060	—	—	—	76	59	24	35	32	33	—300	—184
Ch 752	sheet .030	—	—	—	85	69	24	28	24	38	—300	—184
Ch 752	EB .060	31	82	60	80	61	19	34	25	19	—200	—129
Ch 752	EB .030	22	35	30	84	64	19	26	22	32	—200	—129
Ch 752	GTAW .060	14	200	30	73	56	16	35	25	22	—140	—96
D 43	sheet .040	—	—	—	79	71	9	30	25	14	—320	—196
D 43	EB .040	24	41	30	81	—	—	31	—	—	—200	—129
D 43	GTAW .040	12	140	21	81	—	—	30	—	—	—150	—101

Molybdenum, tungsten and many of their alloys suffer considerably from general brittleness and low impact strength. As a rule, joining operations further aggravate these problems. They are susceptible to contamination, especially in the joints. For this reason, electron beam welding — and in particular the high vacuum mode using both high and low voltage guns — has led to satisfactory results. In general, better results are obtained by avoiding high depth-to-width ratios.

STEELS

Rimmed and Killed Steels

The most common metal used in industry is low carbon steel produced in the rimmed condition. Killed and semi-killed steels are also produced in considerable tonnages. Rimmed steel by its nature can present some welding problems due to the lack of deoxidizers and pronounced segregation in the core, regardless of the welding process.

Rimmed steel derives its name from the manner in which the steel freezes in the ingot. A typical macro cross section shows a rim or skin of nearly pure iron around the outer periphery of the cross section; in the central core area, practically all the carbon, phosphorus, and sulfur have segregated. A comparison of rimmed, capped, semi-killed and killed steels is shown in Table 47.8.

In the making of rimmed steel, the chemical reaction that occurs between carbon and oxygen to form CO gas will continue in the puddle of a weld. Therefore, violent weld puddle action and spatter, as well as porosity in the rapidly solidifying weld puddle due to the CO gas evolution, is expected in electron beam welding.

Election beam welding of rimmed steel can be accomplished if deoxidizers such as manganese, silicon or aluminum are incorporated through filler metal wire. Deoxidizers can also be added locally to the joint area by painting, spraying, shim inserts, etc.

Welding of rimmed steel can also be somewhat enhanced by the proper selection of electron beam welding conditions. For example, slow travel speed with a wider and shallower weld cross section — as compared to the classical high depth-to-width ratio electron beam weld cross section. These conditions generally provide the gases more time to escape from the molten weld puddle, and therefore a weld of reasonable quality can be obtained.

It should not be forgotten that the exterior surface of the rimmed steel is nearly pure iron. Thus, the problems caused by the central core impurities can be reduced substantially by judicious positioning of the parts, so that the weld is made wholly or principally into the rim material. (The same approach, in reverse, can be used where the surface of a killed steel has been modified by nitriding or carburizing; then the weld should be made so as to obtain a generous admixture of the purer center material.)

Alloy Steels

Welds in 250 ksi grade maraging steel exhibit strengths equivalent to the fully heat-treated plate materials after a post weld aging treatment. Ductility and fracture toughness are lower, however, and a full postweld heat treatment yields the best fracture toughness.

Table 47.8—Comparison of rimmed, capped, semi-killed and killed steels

	Rimmed	Capped	Semi-killed	Killed
Carbon Content	Up to 0.3%	Up to 0.2%	Up to 1.0%	Up to 1.5%
Silicon Content	Less than 0.005%	Less than 0.01%	0.01/0.10%	Over 0.10%*
Primary Piping (Shrinkage)	None	None	None	Severe
Porosity in Ingot	Considerable	Considerable	Some	None
Segregation	Pronounced	Little	Little	Very little

* Killed steel may have a very low silicon content if another deoxidizer, like aluminum, is employed.

Strength properties of electron beam welds in HP 9-4-25 are equivalent to those of unwelded fully heat-treated plate for welds which are post-weld tempered (see Table 47.6). This is to be expected, since this alloy after gas tungsten-arc welding and no post-treatment exhibits mechanical properties almost equal to the heat treated plate material.

Strength, ductility and fracture toughness of welds in 15-7Mo PH steel are significantly lower than the properties of fully heat-treated plate, even when the welds are conditioned and aged. This is believed to be caused by the formation of interdendritic chromium carbides in the fusion zone during the 1400°F (760°C) conditioning treatment.

Thick sections of hardenable steels can crack when electron beam welded with no preheat. Under these conditions, the very rapid cooling in the fusion and heat-affected zones will cause martensite formation. The combination of a hard, brittle structure and residual stresses causes crack formation. This kind of cracking can be prevented by preheating. If the hardenability is low, martensite formation can be prevented by holding above the Ms for a sufficient length of time to form bainite. If the hardenability is high, the hold time to form bainite may be too long, so that a better method is to preheat to the Mf temperature to form martensite, then temper the part without letting it cool to room temperature. This procedure avoids stressing the martensite before tempering. Preheating with a defocused electron beam is possible in many applications; however, careful programming is necessary to achieve the proper preheat temperature.

TITANIUM AND ITS ALLOYS

Titanium and its alloys show to best benefit the electron beam welding process. Best results in processing titanium and its alloys are obtained by using the high vacuum mode, but medium vacuum also permits processing of these materials with reasonable success. High vacuum welding data on Ti-6A1-4V is given in Table 47.5.

Strength properties of welds in titanium alloy Ti-6A1-4V are relatively insensitive to the weld and heat treatment sequence if a solution and age heat treatment are included. Weld strength for either the fully heat treated or annealed plate is greater than 95% of the unwelded material. Test specimen

fracture generally occurs in the weld fusion zone, except for welds made in annealed material and tested in the as-welded condition. In the latter case the weld thermal cycle causes local strengthening in the heat-affected zone and fusion zone. Optimum fracture resistance is attained in welds made in annealed material and tested in the as-welded condition. Stress rupture strength is best for welds that are solution treated and aged after welding, and is almost equal to unwelded plate rupture strength. Poorest stress rupture strength is attained on annealed plate in the as-welded condition.

ZIRCONIUM ALLOYS

Electron beam welding provides a number of substantial advantages in the joining of zirconium alloys. Since the material is highly reactive, the vacuum welding environment provides greater assurance of contamination-free welds than does the highest-purity inert-gas environment. The deep, narrow welds possible with the electron beam process produce minimal weld shrinkage and distortion. The dimensional control achieved during electron beam welding sometimes permits the welding of final-machined components within normal machining tolerances.

The normally high welding speeds used with electron beam welding do not materially influence alloy composition. However, a weld that remains in a liquid state in a vacuum for too long a period will exhibit a tendency toward alloy depletion. In anticipating correction of such a faulty set of welding parameters, caution must be exercised to prevent over correction. Excessively high cooling rates in a Zircaloy weld may reduce corrosion resistance. The material may also become susceptible to exaggerated grain growth during subsequent vacuum annealing.

The tensile strength of welded Zircaloy-2 has been investigated in both the longitudinal and the transverse directions. All specimens were annealed at 1100°F (600°C) before testing. The testing temperatures were selected to correspond to the range of operation temperatures in pressurized water reactors. As shown in Fig. 47.27 the specimens of welded material in general showed slightly higher ultimate and yield strengths, and correspondingly lower ductility (reduction in area and elongation) than did the hot-rolled plate material. These differences are the result of the quenched fusion structure, which is higher in strength than the surrounding material or base plate.

Impact test specimens were made from solid Zircaloy-2 plate in which 100% penetration welds had been made. Specimens were all annealed at 1100°F (600°C) prior to fracture. The test values obtained (Fig. 47.28) show that the electron beam welded Zircaloy-2 has higher impact strength than the gas tungsten-arc welded material.

Electron beam welding can be applied to Zircaloy joints up to 3-in. thick without forming extensive porosity or fissuring. Properly developed weld joints formed by this process are characterized by mechanical and corrosion properties approximating those of the parent metal. Weld shrinkage and distortion of electron beam welded Zircaloy is lower than that resulting from arc welding.

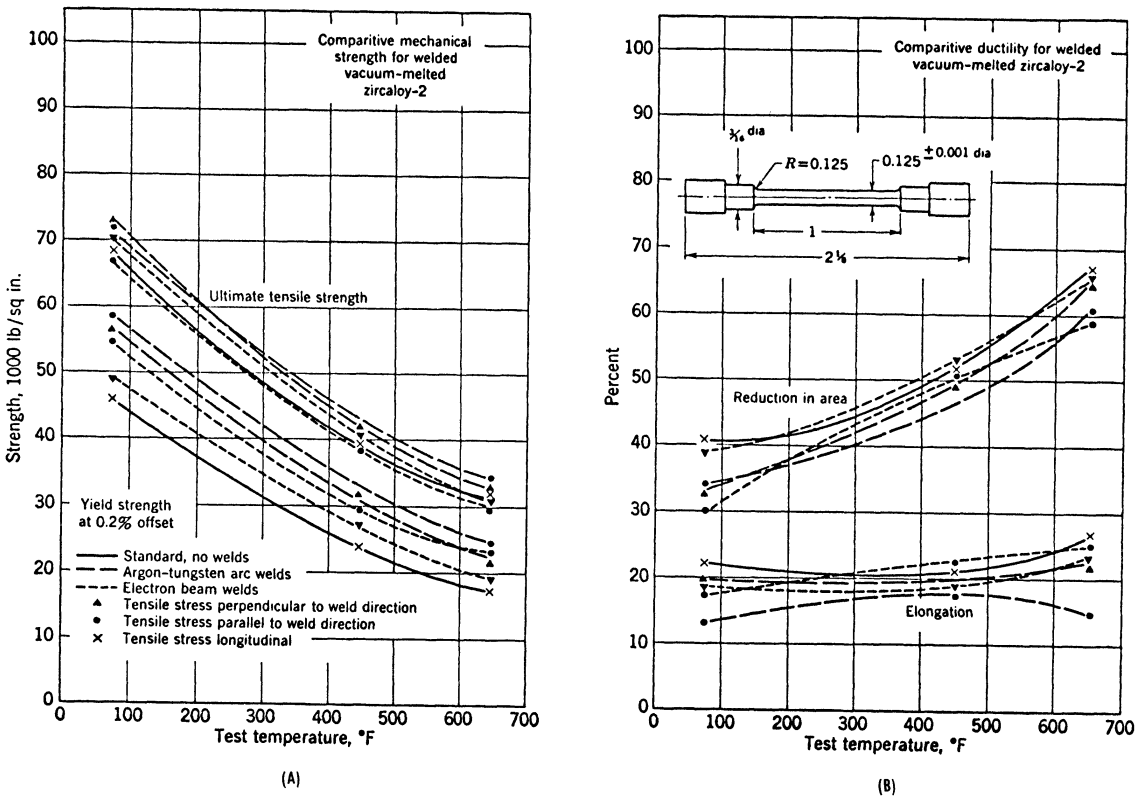


Fig. 47.27.—Mechanical properties of zirconium alloys welded by the electron beam welding process

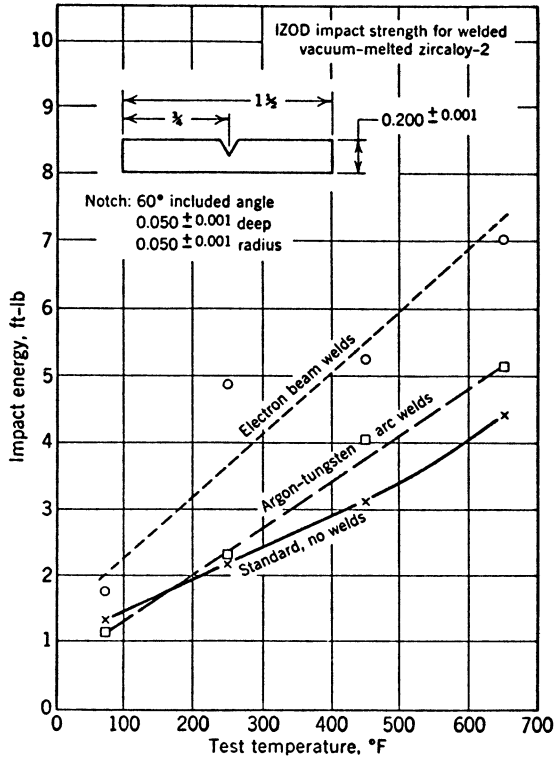


Fig. 47.28.—Zircaloy-2 impact data.

WELD QUALITY

INTRODUCTION

In order to produce welds that meet the requirements of specifications set forth by the welding industry, it is necessary to exercise good control over the three factors that are primarily responsible for electron beam weld quality: (1) joint preparation, (2) welding procedure (including keeping the beam on the seam), and (3) the characteristics of the material(s) being welded. The first two of these three items have been treated in the previous section.

The third factor is metallurgical and relates to the physical properties of the material being welded, as well as the metallurgical cleanliness of the material. The defects that result from these natural causes afflict every welding process and are not unique to electron beam welding. Under the heading of metallurgical origin of defects can be listed cracking, gas pockets, preferential vapor release from high vapor pressure constituents in the alloy, thermal cracking, heat-affected zone cracking, etc. These defects are discussed in detail in the following paragraphs.

A weld of any kind usually involves the transition of wrought material into cast material having a typical freezing pattern of columnar dendrites. Because a weld occurs locally in a limited area of previously wrought structure, it produces a cast weld path within a wrought matrix structure. Wrought structure is derived from a previous cast structure; therefore, the configuration of the metal grains is a result of the breakup, by mechanical deformation, of prior dendrites.

The equiaxed grain structure thus achieved by hot or cold working of the material is such that the individual grains are interlocked. This produces grain boundaries running randomly throughout the material, which produce a strong interwoven structure. However, when cast metal is inserted into the mold of the wrought material, the edges of the cast material do not blend into the surrounding base material. Therefore, the weldment of cast metal provides a discontinuity to the flow of stresses through the material.

Welding has been likened to a series of metallurgical operations involved in steelmaking, but performed in rapid succession and on a minimum scale. As with most processes, a volume of molten metal is formed within the confines of a mold formed by the solid parent metal. The parent metal may have been preheated to retard the cooling rate of the weld joint, just as molds are often preheated to delay the cooling of their contents. Generally speaking, the interest is in controlling the microstructural changes in the weld metal and the base metal heat-affected zones, and in avoiding dangerously high stresses in the final weld joint. Detrimental microstructural conditions are produced in some compositions of metal by fast cooling from the welding heat, while slow rates of cooling do harm to others.

Almost all defects unique to the electron beam welding process arise from a common cause. The first observed defect is seen in partially penetrating welds. The defect often appears as a large pore at the bottom of the weld melt. In all probability a large number of these pores when they occur are lined up single file so that linear porosity is observed, rather than scattered porosity such as that caused by surface impurities. When the tip of the weld just penetrates the back side of the material, the root porosity manifests itself in a lack of fill condition and spatter on the back side of the weld.

The remaining occurrence that is peculiar to the electron beam process and which sometimes creates a defect, is the release of trapped air through the molten metal. This, of course, only occurs by accident at such times that one attempts to weld a container filled with gas (air), which has not been properly vented for welding in vacuum.

As pointed out above, those defects that are to be considered are generally the same as those found in gas shielded-arc welds, resistance welds, submerged arc welds, etc. Electron beam weld defects include: (1) porosity and spatter, (2) shrinkage voids, (3) cracking, (4) undercutting, (5) missed joints, and (6) cold shuts.

The probability of encountering these types of defects is more pronounced in welding thick sections than in thin sections. Thus, a knowledge of the cause of these defects and means of avoiding them is essential to making high quality welds in thick sections. Equally important is a reliable nondestructive testing method to determine the presence of certain types of defects that are not detectable by radiography.



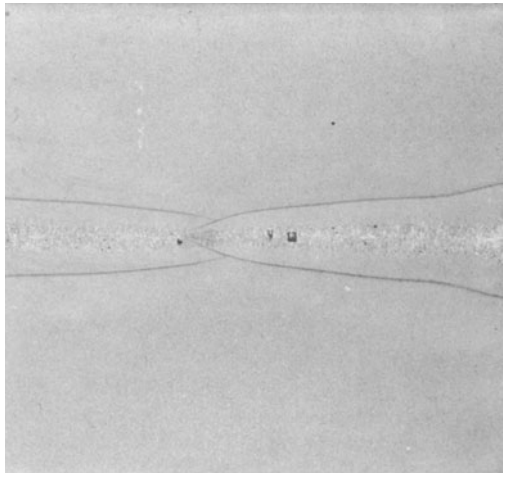


Fig. 47.29.—Spatter (above)

Fig. 47.30.—Porosity (left)

POROSITY AND SPATTER

Porosity in electron beam welds is caused by the evolution of abnormally large amounts of gas as the weldment is heated by the beam. The gas may form as a result of the volatilization of high vapor pressure elements in the alloy, the removal of dissolved gases, or the decomposition of compounds such as oxides or nitrides. Brasses, and aluminum alloys containing magnesium, are difficult to electron beam weld because of excessive metal vapor formation. Both zinc and magnesium have low boiling points, which tends to raise the

vapor pressure of the melt. Dissolved gases and compounds are more likely to be present in alloys melted in air or other protective gas atmosphere.

Spatter is caused by the same factors causing porosity. The rapid evolution of gas or metal vapor causes the ejection of drops of molten metal, which is scattered over the work surface and interior of the chamber. Spatter and porosity can occur in vacuum remelted alloys where a residual phase may volatize under the intense heat of the electron beam. Examples of spatter and porosity in HP 9-4-25 steel are shown in Figs. 47.29 and 47.30.

An effective means of preventing porosity and spatter is to specify vacuum melted material for electron beam welding applications. When gas-emitting or high vapor pressure alloys must be welded, special techniques are required to minimize porosity. The addition of filler metal wire containing a deoxidizer may be helpful in welding materials not completely deoxidized. Usually, slow welding speeds are sufficient to allow gas bubbles to escape to the surface. In extreme cases, it may not be possible to remove the porosity completely; re-welding the joint a second or third time will reduce the porosity. However, these techniques also reduce joint strength in age hardened materials in cases where postweld heat treatment cannot be used.

SHRINKAGE

Shrinkage voids may occur interdentritically near the center of the fusion zone of electron beam welds. These voids are characterized by irregular outlines, in contrast to the generally round outlines of pore-type defects. Shrinkage voids usually occur mainly in alloys having high volumetric shrinkage on solidification. In electron beam welds where the fused zone edges are essentially parallel, solidification proceeds uniformly from the plate edges toward the center. When the solidification shrinkage is great, there will be insufficient solid metal to fill the gap previously occupied by liquid metal, and voids will form if the outside surface freezes sooner than the center, and blocks liquid metal from completely filling the weld zone. An example of shrinkage voids in a weld of 15-7Mo PH is shown in Fig. 47.31. Low travel speed and/or beam oscillation will eliminate or minimize shrinkage voids by allowing more time for molten metal to fill the joint area. However, these techniques will generally form a wider fusion zone than would be attained otherwise.

CRACKING

Materials that are susceptible to cracking as a result of arc welding may crack during and after electron beam welding. Examples of these materials are nickel base alloys, such as Inconel 718 and René 41 and hardenable steels such as SAE 4340 and D6AC.

UNDERCUTTING

Undercutting (and also the similar, closely related defect called "underfill" — see Fig. 47.32) occurs in electron beam welds when metal melted in the joint area is displaced from the joint by spatter loss at the top or bottom, by metal forming a protrusion at the root, or by a joint gap. In some instances, undercutting can occur at the top by metal buildup in the center of the bead.

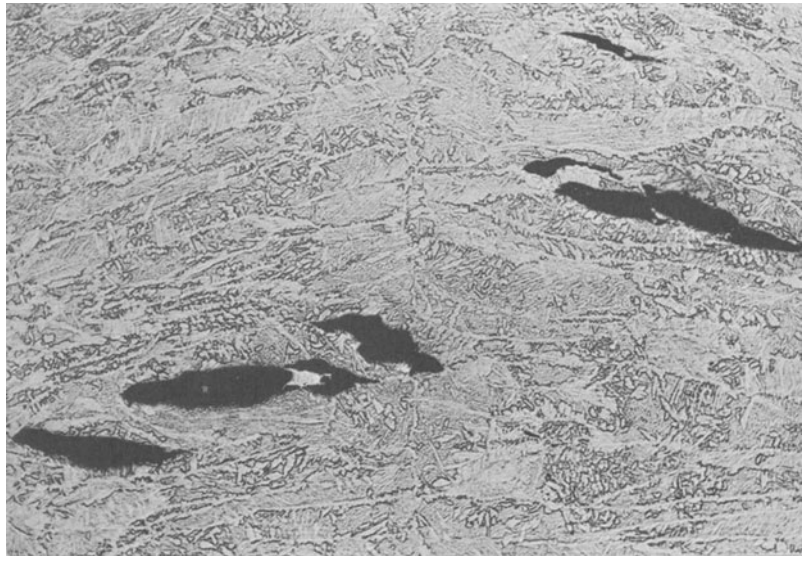


Fig. 47.31.—Shrinkage voids

Metal loss by spatter is difficult to avoid when welding a gas-emitting material. Bottom drop-through usually results from too high a beam energy or too wide a fused zone. This can be reduced by proper adjustment of the welding parameters. If top undercutting persists at the best beam parameters, metal must be added at the top to fill the groove. A number of techniques are effective in providing the required metal. One is to place a narrow strip over the top of the joint and weld through it. The thickness of the strip must be slightly greater than the depth of the undercut, so that the undercut, which still forms, will be entirely in the strip that can subsequently be removed. Filler metal wire may be added to the top of the weld as it is being made, or in a subsequent smoothing pass made with a defocused beam and low power. The gas tungsten-arc process is effective for the smoothing pass if no wire feeding equipment is available in the electron beam welding machine.

MISSED JOINTS

When a fine electron beam is used to make a long joint in thick material, the possibility of missing the joint at some location is great, unless extreme care is exercised to assure that the beam is parallel with the joint surfaces, and that the beam is aligned with the joint along the entire length of travel. Even when the beam is properly aligned with the joint, electrostatic or magnetic forces can cause beam deflection, resulting in portions of the joint being missed. An electrostatic field can be generated by the accumulation of scattered electrons on an insulating surface, such as the glass in the chamber windows. This charge can cause the electron beam to be deflected away from the window if the gun is located close to it.

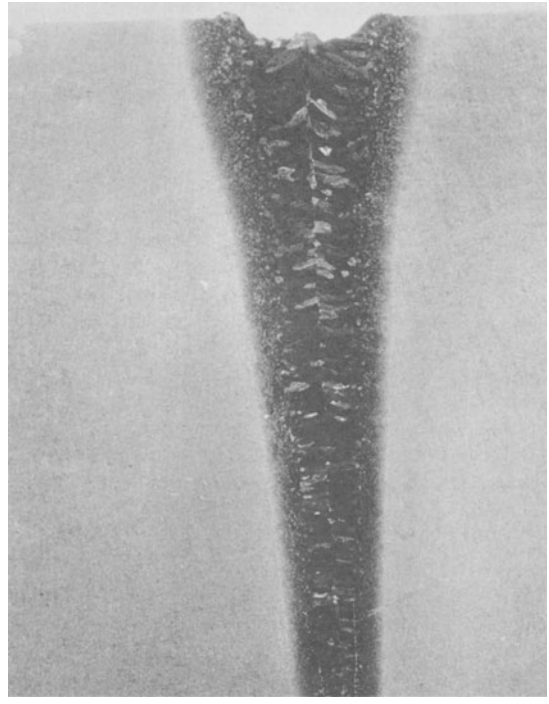


Fig. 47.32.—"Underfill"

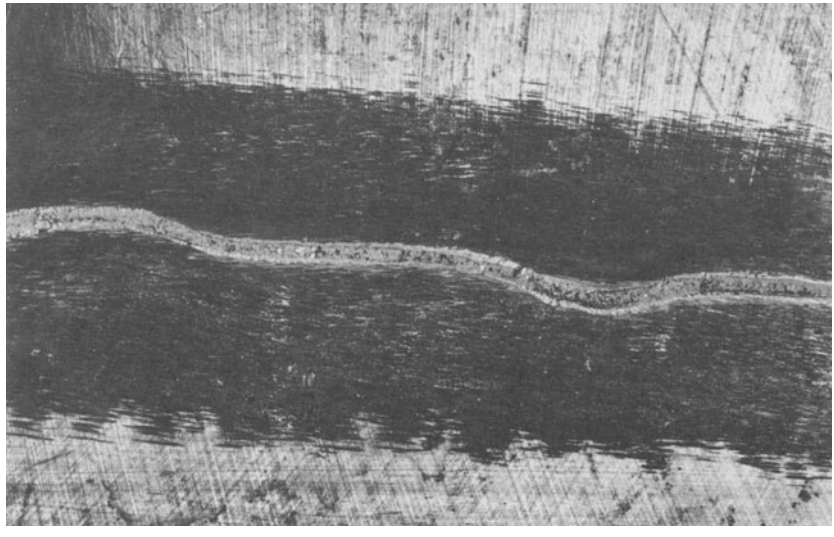


Fig. 47.33.—Unexpected beam deflection due to residual magnetism

Residual magnetism in a ferromagnetic material being welded, or in fixturing, can cause unexpected beam deflection. Fig. 47.33 shows the effect upon the electron beam's welding path in a steel that had been prepared for welding by surface grinding in a magnetic chuck, but was not subsequently demagnetized before welding. The beam was aligned with the top of the joint over the entire length, but deflected sideways in a periodic manner according to the residual magnetic field produced by the magnetic chuck. Magnetic deflection can be avoided by demagnetizing all ferromagnetic material before welding, and by using material for fixturing that is not ferromagnetic.

Unexpected beam deflection can occur when welding dissimilar materials, especially when one is ferromagnetic. An example of this is shown in Fig. 47.34 where René 41 was joined to maraging steel. When two dissimilar metals are heated and in contact, a voltage will be generated across the junction, as occurs in a thermocouple. If these two pieces of metal are in contact at another location that is at a lower temperature, conditions exist which cause an electric current to flow. This current can induce a magnetic field in the magnetic material, which will cause the beam to be deflected. If dissimilar materials are to be welded, it is important that test welds be made and examined to determine whether beam deflection will occur.

COLD SHUTS

Cold shuts have been observed in incomplete-penetration electron beam welds in Ti-6A1-4V, René 41, maraging steel, HP 9-4-25 steel, and Ti-7A1-2Cb-1Ta, from fractured surfaces of side-bend and metallurgical specimens. Longitudinal section in the horizontal and vertical planes of cold shuts in electron beam welds in Ti-6A1-4V are shown in Fig. 47.35.

In most cases, cold shuts occur in partial penetration welds; however, they can occur near the root of full penetration welds made with insufficient beam power. These types of cold shuts generally can be avoided by the use of adequate beam power and proper adjustment of the beam parameters. There are circumstances, however, where partial penetration welding is required. The most common instance is to be found in circular welds in which beam power and penetration must be decreased at the point where the end of the weld overlaps the start, to avoid crater formation. A partial penetration weld is formed in this zone of reduced power and cold shuts can occur. The need to employ two partial penetration weld passes, one from each surface, may arise when the material thickness is too great to be penetrated in a single pass. However, this situation is uncommon with the penetration capabilities of modern welding equipment.

The use of a slightly defocused beam operating at reduced travel speed to compensate for the lower energy density has been effective in eliminating cold shuts. Beam oscillation, either circular or transverse, is also effective. Preheating is helpful, because it reduces the thermal gradient at the root of the weld.

The presence of cold shuts is difficult to establish nondestructively by X-ray or dye penetrant techniques. Cold shuts are similar to fine cracks, and usually will not show up by X-ray. Penetrant tests are ineffective, because the cold shuts do not extend to an outer surface.

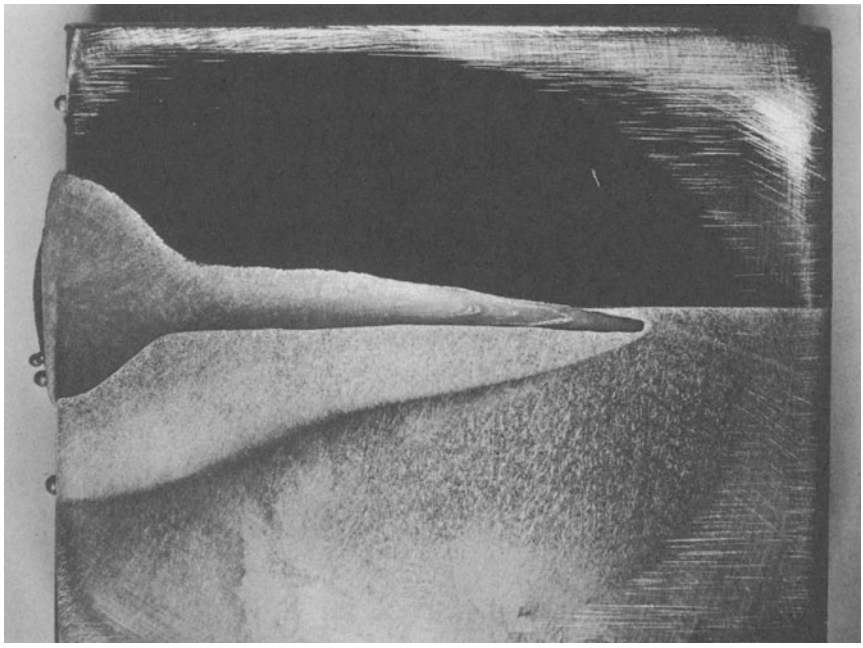


Fig. 47.34.—Unexpected beam deflection when welding dissimilar materials

Ultrasonic testing is the only nondestructive test method for detecting the presence of cold shuts in thick-section electron beam welds. However, experienced nondestructive test personnel are required to perform and interpret the tests if meaningful results are to be obtained.

APPLICATIONS

Electron beam welding is being used today in the fabrication of flight hardware, nuclear energy producing systems, deep submergence vehicles, and heavy earthmoving equipment. The automobile and truck industry, as well as others, make extensive use of the process.

NUCLEAR POWER

Electron beam welding was first used in the nuclear power industry. This industry has grown since electron beam welding was first introduced, and the growth of the electron beam process parallels the growth of the industry itself.

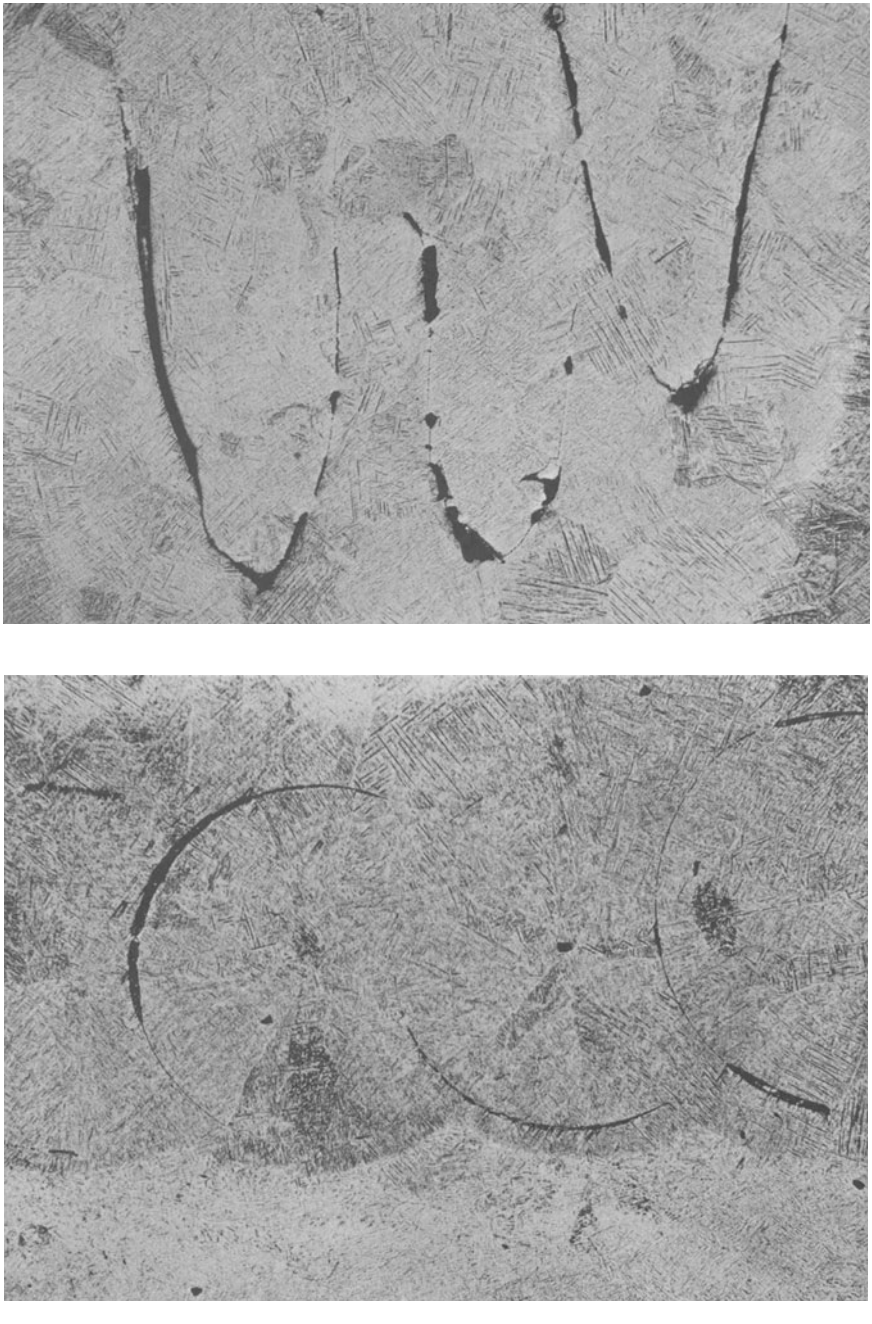


Fig. 47.35.—Longitudinal section in the horizontal and vertical planes of cold shuts

The needs of the nuclear power industry have fostered new developments in equipment, including miniature guns for producing welds within a variety of nuclear components as well as some very large chamber systems. Extreme quality control requirements have favored the high vacuum mode, and it is still the process most widely used in the industry.

The nuclear power industry was the first to specify electron beam welding for components used in high-reliability nuclear power plants. By virtue of the stringent requirements, and the type of materials which are habitually processed here, it is believed that high vacuum will remain the main mode.

AIRCRAFT AND AEROSPACE

Aerospace developers gave much needed financial support to electron beam welding equipment development. Although requirements are much different from those of the nuclear power industry, the materials used are often the same. Tungsten, ultra-high strength alloy steels, the high modulus light metals, and alloys including beryllium are being joined for aerospace use. The high vacuum mode was used for early applications, but cost considerations and the fact that it is impossible on a practical basis to build vacuum chambers large enough to contain large rockets, have opened up opportunities for the other two modes. Meanwhile, chambers have been adapted to join very large rocket components with special high vacuum equipment. Moveable chambers have also been used.

The aircraft industry also makes extensive use of the electron beam welding process.

ELECTRONICS AND MICROELECTRONICS

Although a tremendous potential for electron beam welding in electronics was envisaged, only a small part of these expectations has materialized. This is because heat input of electron beams is much beyond the tolerance limit of integrated circuits. The microelectronic industry has had to rely on alternate techniques to resolve interconnection problems. In the area of hermetic packaging of electronic components, however, electron beams and the high mode in particular are playing a much more important role, and the future here continues to look bright.

AUTOMOTIVE

Medium vacuum and non-vacuum welding are finding increased application in the automotive industry, where production requirements are high. Here, advantage is taken of the relatively simple tooling required, the high speeds obtainable, and the reliability and reproducibility of the process.

MISCELLANEOUS

Electron beam welding has continued to be used more and more for repair welding; the economic advantages already observed continue to accrue. Use of the technique will continue to expand as more industries realize the economic advantages it offers. The multiplication of electron beam welders in job shops that serve industry, and the establishment of new electron beam welding job shops, indicate the growth that is taking place in this field.

SAFE PRACTICES

Work with electron beam welding equipment may be dangerous. The personnel working with electron beams must be aware of potential hazards at all times. Three danger areas exist. The first danger area is a consequence of the high voltages needed to generate the electron beam (real); the second is the danger of potential exposure to the electron beam itself (not real, because of the nature of the beam), and the third real danger is the danger of radiation burns from the X-rays that the electron beam can generate.

Industries often produce experimental machines and modify existing systems, creating potential high voltage and X-ray hazards. In such cases, it cannot be overemphasized that precautionary measures must be taken at all times to assure proper protective procedures. Consult *Recommended Safe Practices for Electron Beam Welding,* AWS A6.4, and *Safety in Welding and Cutting,* USAS Z49.1 (latest edition).

HIGH VOLTAGE

Every operational electron beam welding machine is a high voltage machine, regardless of whether it is referred to as a "low" voltage machine (30 KV) or a "high" voltage machine (60 KV and above). The manufacturer of equipment, in meeting various underwriter requirements, usually has produced equipment well insulated against the danger of high voltages; however, all precautions that should be exercised with systems in which high voltages are present must be taken.

X-RAYS

The X-rays generated by an electron beam welding machine are an undesirable by-product occurring simultaneously with the impact of the beam of accelerated electrons upon the workpiece. There are fundamental requirements for the generation of X-rays, as there are laws for their propagation. A brief discussion of these dangers is important for the true appreciation of the problem and the potential danger they present.

X-rays are electromagnetic radiations having wave lengths greatly shorter than those of visible light. They have the ability to penetrate a wide range of materials.

The X-rays generated when an electron impacts a target (i.e., the workpiece) can be divided into two categories: (1) the so-called continuous spectrum or *Bremsstrahlung,* extending over a wide wave length range, and (2) the characteristic radiation, which is a specific wavelength. The *Bremsstrahlung* radiation, usually of relatively low intensity, begins at a wave length expressed in A and equal to 124/KV. Characteristic radiation, which has a higher intensity and penetration power, begins to become dangerous when at 22 KV, when MoKx is emitted.

As was stated with reference to the high voltage, so in the case of X-rays. Underwriters and the U. S. Department of Health have established firm rules as to permissible exposure levels, and producers and users of equipment must observe these rules.

As a rule, the steel walls of the chamber in systems up to 60 KV, assuming proper design, are adequate protection. All high voltage systems utilize lead lining to block X-ray emission beyond the chamber walls. Leaded glass windows are also used. X-ray protection problems are similar for the high and medium vacuum modes; generally the chamber walls provide adequate protection for the operator. In the case of non-vacuum systems, special provisions are made to assure the safety of the operators.

OZONE

In the non-vacuum mode there is danger from ozone, which is generated by the process. Proper ventilation should be provided.

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3) Transactions in Vacuum Soc. Vacuum Metallurgy Conferences

CHAPTER 48

ELECTROSLAG WELDING

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CHAPTER 48

ELECTROSLAG WELDING

FUNDAMENTALS OF PROCESS

DEFINITION AND GENERAL DESCRIPTION

Electroslag welding is a welding process wherein coalescence is produced by molten slag which melts the filler metal and the surfaces of the work to be welded. The weld pool is shielded by this slag which moves along the full cross-section of the joint as welding progresses. The conductive slag is maintained in a molten condition by its resistance to the electric current passing between the electrode and the work. The joint is generally accomplished in a single pass regardless of the thickness.

Single-pass welding of heavy plates has long been desired as a means of avoiding multipass welding techniques. Before 1900, graphite molds were placed on each side of a space between vertical plates to contain molten metal created by graphite electrodes, fusing the edges to form the weld. Graphite molds were replaced by copper molds or ceramic molds, and conventional welding arcs, gas torches or thermit mixtures were devised for generating the molten metal with a degree of superheat sufficient to cause uniform coalescence.

Meanwhile, metallurgists discovered that the electrical conductivity of certain slags could be used to control the amount of heat on the surface of molten metals in the refining process.

In the early 1950's, Russian scientists from the Paton Institute of Electric Welding in Kiev announced the development of machines that employed the principles of an electrically conductive slag to make single-pass vertical welds. Subsequent work at the Bratislava Institute of Welding in Czechoslovakia was made available to engineers in Belgium and, through them, to the rest of the Western world. An electroslag unit was introduced in the United States in 1959.

PRINCIPLES OF OPERATION

The process is initiated much like the conventional submerged arc process by starting an electric arc beneath a layer of granular welding flux. As soon as a sufficiently thick layer of hot molten slag is formed, all arc action stops and current passes from the electrode to the workpiece through the conductive slag. At this point, the process is truly electroslag welding. Heat generated by the resistance to the current through the molten slag is sufficient to fuse the edges of the workpiece and the welding electrode. Since no arc exists, the welding action is quiet and spatter-free. The interior temperature of the bath is in the vicinity of 3500°F (1925°C). The liquid metal coming from the filler metal and the fused base metal collects in a pool beneath the slag bath and slowly solidifies to form the weld.

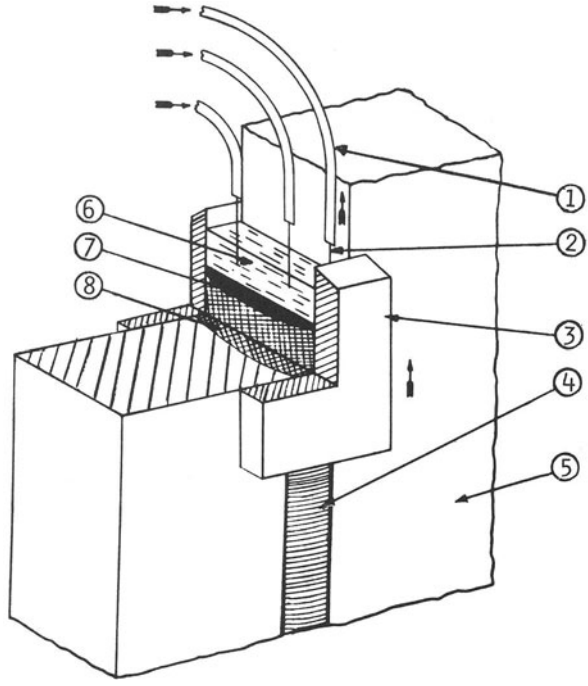
Because of the large volume of molten slag and weld metal produced in electroslag welding and the necessity to contain it, the process is generally used for welding in the vertical position. The parts to be welded are assembled with a gap of approximately 1 to 1½ in. between them.

A sump or starting tab is necessary in order to build up the proper depth of conductive slag before welding reaches the work. Likewise, at the end of the joint, a dam for the conductive slag is required to run off the weld. Both starting and run-off tabs may later be removed flush with the ends of the joint.

CONVENTIONAL WIRE PROCESS

One or more electrodes can be fed into the same joint depending on the thickness of the material to be welded. The electrodes are slowly oscillated horizontally to ensure an even distribution of heat across the joint and to maintain uniform penetration into the base metal (Fig. 48.1).

Water-cooled copper shoes are generally used on each side of the joint to retain the molten metal and slag pool and to act as a mold to cool and shape the weld surfaces. The copper shoes automatically slide upward on the plate surfaces as welding progresses. Movement may be automatic and controlled intermittently through a sensing element in the copper shoe in contact with either the solidifying weld metal or the surface of the molten flux. The vertical rise may also be accomplished by a variable-speed motor controlled by the operator.



48.1.—Schematic view of conventional wire method of electroslag welding: (1)—Curved wire-guides, (2) Electrode wires, (3)—Cooled shoes, (4)—Weld surface, (5)—Plates being welded, (6)—Molten slag pool, (7)—Liquid metal pool, (8)—Solidified weld metal

As the weld solidifies and becomes exposed, its surfaces are covered with a thin layer of vitreous slag, which is easily removed. This slag consumption must be compensated for by feeding flux to the slag pool during welding. The fresh flux can be added manually or by an automatic flux dispenser. It is replenished continuously when using flux-cored wires of the proper flux-to-filler metal ratio.

The wire electroslag process has been used for welding plates ranging in thickness from approximately ½ to 20 inches. The welding of greater thicknesses is technically feasible but requires custom installations. With each electrode the process will deposit from 25 to 45 pounds of filler metal per hour. The diameter of the electrode wire generally used is ⅛ inch. Electrode metal transfer efficiency is almost 100 percent. The flux consumption is small — approximately 5% of the wire consumed.

Because of the uniform heat distribution throughout the plate thickness during welding, electroslag welds are virtually free of distortion. The weld penetration contour is a function of the welding voltage, current and slag pool depth; it usually consists of approximately 30 to 50% of fused base metal.

CONSUMABLE GUIDE METHOD

The consumable guide electroslag welding method is a modified version of the wire process. In both techniques, the pieces to be welded are placed in a vertical position with a gap between the abutting edges of the plates. In the wire method, the shoes, wire-feeding mechanism and associated equipment ride upward on the side of the plate as the weld progresses. The consumable guide method uses instead a metal tube extending the full length of the weld joint to guide the welding wire to the welding zone. The molds and all wire-feeding equipment remain stationary, with the wire being the only moving part. The guide tube melts in the weld pool as the pool rises, supplying additional filler metal.

Fig. 48.2 illustrates consumable guide welding. A flux coating is generally provided on the outside of the consumable guide to insulate it electrically from the base plate and to replenish flux that solidifies on the surface of the copper mold forming the weld contour. The flux coating thus helps to maintain a level of molten slag adequate to provide resistance heating and to protect the weld pool from atmospheric contamination. If bare tubes are used without suitable insulators, shorting to the side walls can occur. It may also be necessary to add flux periodically to the slag bath. As welding proceeds and the weld pool rises, the consumable guide melts (because of its close proximity to the rising molten slag bath) and becomes part of the weld metal. The electrode wire transfers welding current from the end of the consumable guide to the molten slag, producing resistance heating of the slag bath as in the conventional wire process.

The welding wire extends for a short distance into the slag and is melted into droplets which transfer to the weld pool.

PLATE ELECTRODE METHOD

Another form of electroslag welding utilizes plate electrodes instead of wires. For relatively light sections (4 to 6 in. thick) a single plate electrode (as wide as the work being welded is thick) is fed into the pool. For heavier sections, multiple-plate electrodes, side by side in the joint, are used. The dimensions of the plate electrodes are calculated from the volume of metal required to fill the joint.

It is possible to use greater currents and lower voltages than with conventional wire electrodes. Currents as high as 1500 to 2000 amperes are used with the electrodes of larger cross section. Typical electrode current densities are in the range of 400 to 800 amperes per square inch. With plate electrodes, a shallower depth of molten slag is possible. It is difficult to make joints longer than 3 feet because the plate electrode is too long to manipulate in the joint.

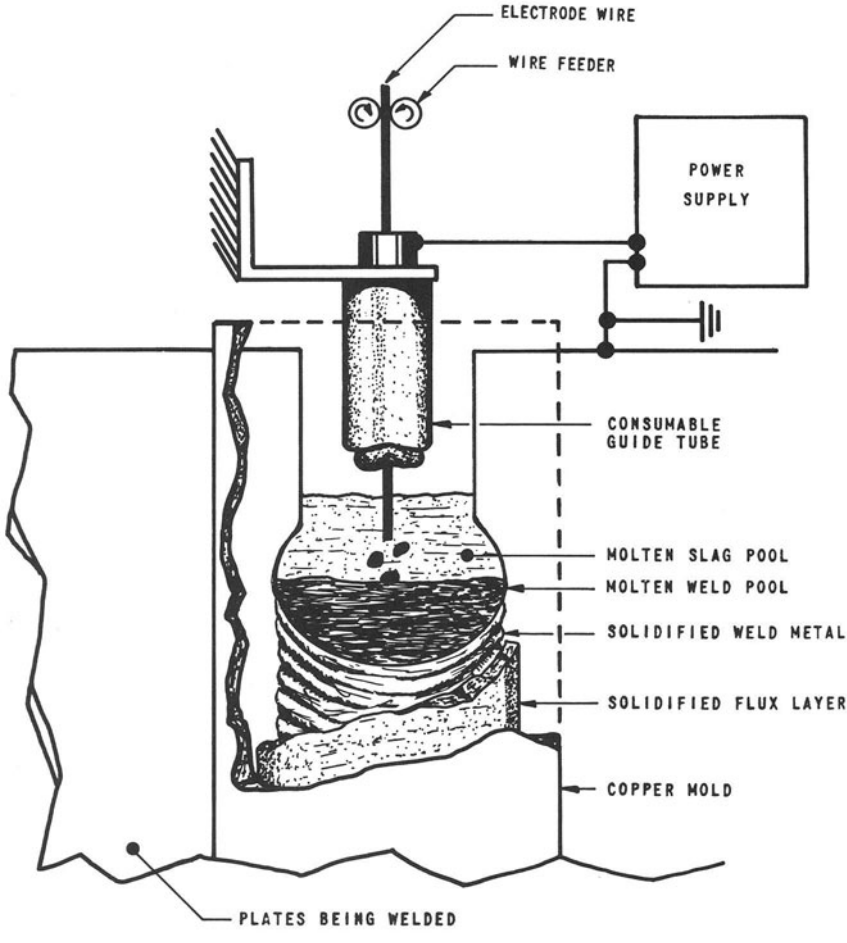


Fig. 48.2.—Consumable guide welding

PROCESS VARIABLES

PREPARATION AND ASSEMBLY

One of the major advantages of the electroslag process is the relatively simple joint preparation. The weld is basically a square groove weld in a butt joint, so the only preparation required is a straight edge on the groove faces, which can be produced by thermal cutting, machining, etc. However, if sliding copper shoes are used, the surfaces of the material on either side of the groove must be reasonably smooth to prevent slag leakage and jamming of the shoes.

The parts to be welded are assembled with a gap opening that may be as much as 1½ in. at the start for 7 to 8 in. plate. Plate that is 2 to 3 in. thick usually requires a 1 in. gap at the start. The assembled gap opening at the finish of the weld is generally wider than at the start because of shrinkage and contraction produced in the welding operation. Generally, the gap opening at the finish should be greater than that at the start by ¼ inch. The assembly of the parts may be done in a number of ways, such as horseshoe-shaped clamps, that do not interfere with the sliding shoes or other equipment during welding or simple bars which are removed as welding progresses. In welding massive parts, their weight alone will provide adequate restraint. The parts are positioned in such a manner that the joint, at the point where welding is occurring at any given time, is in essentially the vertical position.

Although the most common weld joint is a butt joint, the process can also be used to weld a variety of joints as shown in Fig. 48.3. Of course, the actual weld in these cases is still basically a butt joint at the region of welding using somewhat specialized shoes or dams. Overlays or built-up sections can also be deposited by utilizing special shoes or dams.

WELDING VARIABLES

The welding variables have a significant effect on the operation of the process, the quality of the weld and the economics of the process. They influence the operation of the process with respect to adequate penetration, complete fusion of the entire joint area and freedom from cracks. The effect of economics is with respect to maximum deposition rate, consistent with the other factors.

Form Factor

The resistance of the weld to cracking on solidification is greatly influenced by the manner in which it solidifies. If the dendritic grains growing from each side of the joint meet at the center with, in general, an obtuse included angle, the cracking resistance will be low. On the other hand if the included angle is acute, the cracking resistance will be high. The solidification pattern, in turn

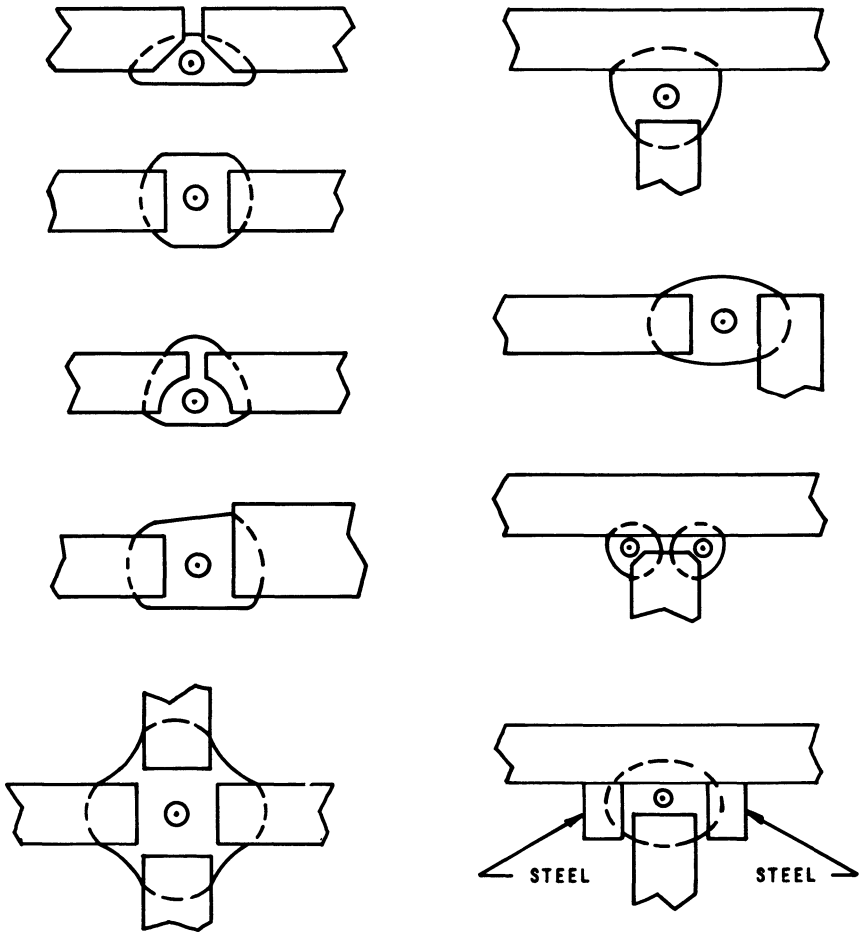


Fig. 48.3.—Various joint configurations

is controlled by the shape of the molten weld pool. The weld pool shape can be expressed most effectively by the term *form factor*. The form factor is the ratio of the total width of the weld pool (gap opening plus depth of fusion into the sides) to its maximum depth. Welds having a high form factor; i.e., shallow depth with respect to width, tend to solidify with the grains meeting at an acute angle as shown in Fig. 48.4, and hence have a high resistance to cracking. Welds made in such a manner as to produce a low form factor (i.e., a deep weld pool with respect to width) tend to solidify with the grains meeting at an obtuse angle. Such welds have low cracking resistance and may produce a crack as shown in Fig. 48.5.

The shape of the weld pool and the resultant form factor is controlled, to a large extent by the welding variables as will be described in succeeding paragraphs. It should be noted, however, that form factor alone does not control cracking resistance since obviously the specific alloy being welded also has a significant effect on cracking propensity.

Welding Current

Welding current and electrode feed rate are directly related and hence can be treated as one variable. Increasing welding current is accompanied by increased electrode feed rate and hence increased deposition rate.

Increasing welding current increases the depth of the weld pool. At low current levels an increase in current also increases weld width. However, at currents above about 400 amperes for a ⅛ in. diameter electrode, a further increase in current reduces weld width. The net effect of current increases on form factor is to decrease it — moderately at low currents and more pronounced at high currents as shown schematically in Fig. 48.6.

Welding currents in the order of 550 to 650 amperes are most commonly used for ⅛ in. diam. electrodes. Highly crack-sensitive materials may require a high form factor associated with currents in the order of 400 amperes, whereas crack-resistant materials have been welded at 900 amperes.

Welding Voltage

Welding voltage is an extremely important variable in that it has a major effect on depth of fusion into the base metal and on the stable operation of the process. Welding voltage is the primary means for controlling depth of fusion. Increasing voltage increases depth of fusion and the width of the weld. Depth of fusion must be somewhat more than necessary in the center of the weld to assure complete fusion at the edges where the chilling effect of the water-cooled dams must be overcome.

Since an increase in welding voltage increases the weld width, it also increases the form factor and thereby increases cracking resistance, as shown in Fig. 48.7.

The voltage must also be maintained within limits to assure stable operation of the process. If the voltage is too low, short circuiting, or arcing to the weld pool will occur. Too high a voltage may produce unstable operation due to slag spatter and arcing on the top of the slag pool. For ⅛ in. diam. electrode, 40 to 55 volts are generally used, although the actual voltage depends on the slag, as well as on the other factors associated with a specific weld joint.

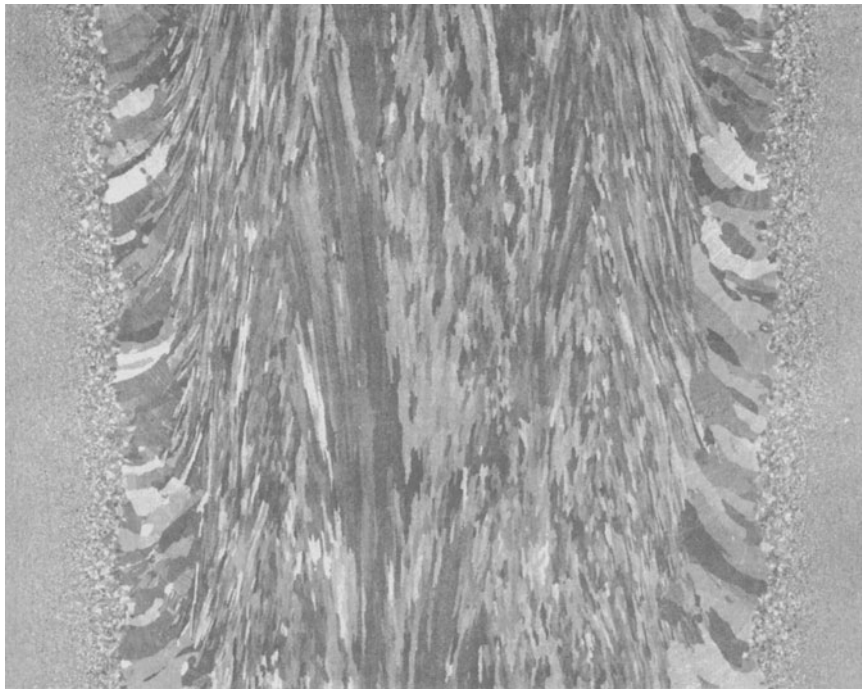


Fig. 48.4.—Solidification pattern of high form factor weld with grains meeting at an acute angle

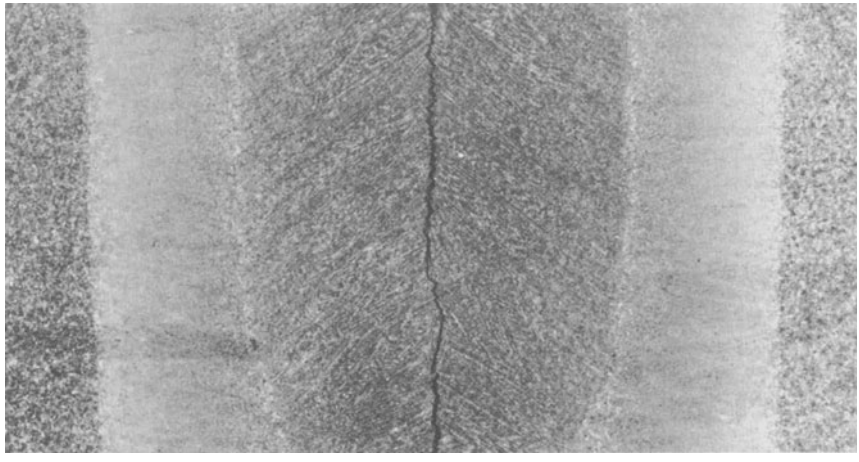


Fig. 48.5.—Solidification pattern in low form factor weld with grains meeting at obtuse angle and a crack present

Electrode Extension

Electrode extension generally refers to dry electrode extensions in the wire method, i.e., the distance between the slag surface and the end of the contact tip. Increasing electrode extension, maintaining other variables constant, increases electrode melting rate and deposition rate and reduces weld width and hence form factor. This effect is due to the electrical resistance heating (I^2R) of the electrode by the welding current. An increase in electrode extension first stabilizes the process. However, a further increase ultimately leads to gross instability due to melting of the electrode at the slag surface. Long electrode extensions also lead to problems in accurately locating the electrode in the weld groove. For a ⅛ in. diam. mild steel electrode an extension of about 3 in. is generally best when used with the oscillating wire method. It should also be noted that the electrode wire can extend into the slag pool as much as 1 inch. In the consumable guide method, electrode extension is not a controlled variable.

Electrode Oscillation

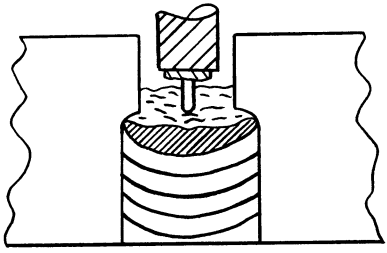
For weld joint thicknesses greater than about 1½ in. (one electrode) it is preferable to oscillate the electrode across the joint to distribute the heat and obtain complete fusion. However, increased oscillation or traverse speed reduces weld width and hence form factor. Therefore the oscillation speed must be properly balanced with the other variables. In addition, it is necessary to use a dwell period at each end of the oscillation to obtain complete fusion at the weld corners because of the chilling effect of the water-cooled dams. The dwell period may vary from 2 to 7 seconds.

Slag Depth

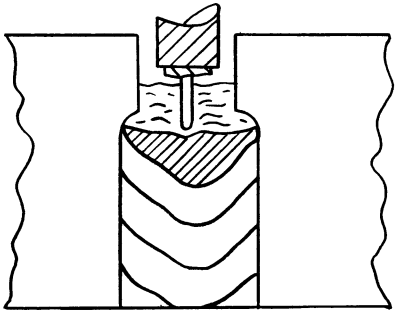
The slag pool must be sufficiently deep to allow the electrode to extend into it and permit current to exist by the conductivity of the slag pool rather than by arcing to the molten weld pool. Excessive slag depths reduce the depth of fusion and hence the form factor. The reason for the reduced width is that for a given amount of input energy, as the slag depth increases, it is distributed over a greater area of base metal, and consequently slag bath temperature is reduced. Some of this preheat is useful in raising the metal toward the melting temperature. However some is lost so the net effect is reduced base metal fusion. Increased currents will generally permit deeper slag pools. In general, slag pool depths in the order of 1½ to 2 in. are optimum.

Number of Electrodes

For a given thickness of material being welded the weld width, or degree of penetration, increases as the number of electrodes increase. For a given number of electrodes, as the thickness of the material being welded increases, the weld width decreases. The point is finally reached where the weld width becomes less than the groove opening; i.e., there is no fusion in the material. At this point the number of electrodes used must be increased to weld that particular thickness. In general one electrode can be utilized for material thicknesses to 5 in., two electrodes up to 9 in., and three electrodes up to 20 in. for the oscillating wire method and oscillating consumable guide method. With the non-oscillating consumable guide method, each electrode will handle approximately 2½ in. of plate thickness.

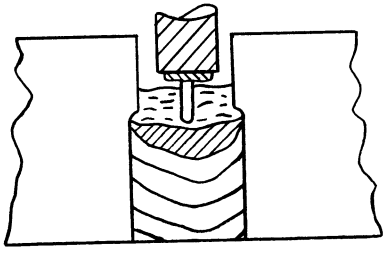


LOW CURRENT

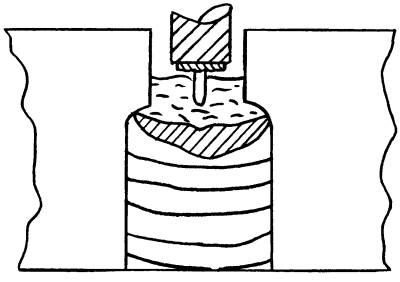


HIGH CURRENT

Fig. 48.6.—Effects of current on weld pool depth.



LOW VOLTAGE



HIGH VOLTAGE

Fig. 48.7.—Effect of voltage on weld pool with end base metal dilution.

EQUIPMENT

WIRE WELDING

A typical electroslag wire machine designed for one, two or three wires is shown in Fig. 48.8. One wire is used for welding up to 5 in. in thickness, two wires up to 9 in., and three wires up to 20 in. in thickness.

The welding heads, wire reels, as well as the operators ride up on the operator's platform as the weld progresses. Typical machines can weld joints up to 16 feet long. However, extensions of the vertical frames can be made for longer runs. The vertical travel during welding is controlled by use of a photoelectric cell which keeps the pool level at a constant distance from the top of the shoe. The free-floating welding head section is self-tracking in the joint and oscillates across the joint to keep the pool molten throughout the cross section. Wire feed speed, voltage, oscillation and vertical travel are under the control of the operator. The welding power source is either dc or ac. Most of the equipment in the United States has been supplied with dc power sources. Small portable units using one or two wires are also available (Fig. 48.9). Such machines can be used for electrogas or consumable guide welding in addition to electroslag welding.

CONSUMABLE GUIDE

The equipment used in consumable guide electroslag welding is simpler compared to the wire method as is illustrated in Fig. 48.10. A constant voltage power source coupled with a constant-speed wire feeder is used. For most applications, a 750 ampere capacity power source rated at 100% duty cycle is required. Direct current is used, with the positive terminal connected to the guide tube. By varying the electrode feed rate, the welding current is controlled as well as the rate of welding. Voltage adjustments are made at the power source.

The wire feeder and consumable guide holding device can be mounted on top of the work as shown in Fig. 48.10. The wire feeder can also be located remotely as shown in Fig. 48.11. An oscillating mechanism can also be provided on the welding head. This allows the guide tube to be moved laterally across the plate thickness. Thus, thicker plates (up to 5 in.) can be welded with one electrode.

Equipment is also available to feed two electrodes. Using two electrodes and oscillation, plates from 5 to 12 in. thick can be welded. When using two electrodes, it is normal to use two power sources.

MATERIALS

BASE MATERIALS

Among the many base materials that have been electroslag welded in production, the largest tonnages have been in the following steels:

ASTM A515 and A516
ASTM A302 and A533
ASTM A387 and A542
ASTM A543 and HY80
ASTM A36 and A441

In addition to the above materials, regular mild steels, such as 1020 and 1045, and stainless steel in both wrought and cast conditions, have been successfully electroslag welded.

Maraging materials have been welded experimentally, as have been alloys of nickel-chromium-iron.

ELECTRODES

There are generally three forms of electrodes used with the electroslag welding process, namely: (1) solid, (2) flux-cored or composite and (3) braided or twisted wires. All three types have been successfully used, but the solid wire has found more extensive application. All are available in various chemical compositions designed to introduce the necessary alloying elements to achieve strength, impact properties, or appropriate combinations of these in the deposited weld metal, depending on the particular requirement. These properties are obtained normally by heat treatment after welding, which tends to result in considerable grain refinement.

In the welding of carbon and low-alloy structural steels with the electroslag process, the electrodes generally contain less carbon than the base metal, much the same as in submerged arc welding. To obtain desired strength and impact properties in the weld metal comparable to those of the base metal, additional alloying elements, such as manganese, silicon, nickel, etc., are employed in the electrodes. This approach is preferred in electroslag welding of structural steels containing up to 0.35% carbon.

With the higher carbon and higher alloy steels, or when special heating for hot forming and subsequent heat treatments are required to achieve desired properties, the best approach is to have the weld metal of such composition that it will have a response to the particular heat treatment similar to that of the base material, a desirable condition in welded fabrication.

In selecting electrodes for the electroslag welding process it must be recognized that the base metal composition strongly influences the final weld metal analysis because of the deep penetration on both sides of the joint. Possibly as much as 30 to 50% of the weld cross section consists of base metal as the result of dilution.

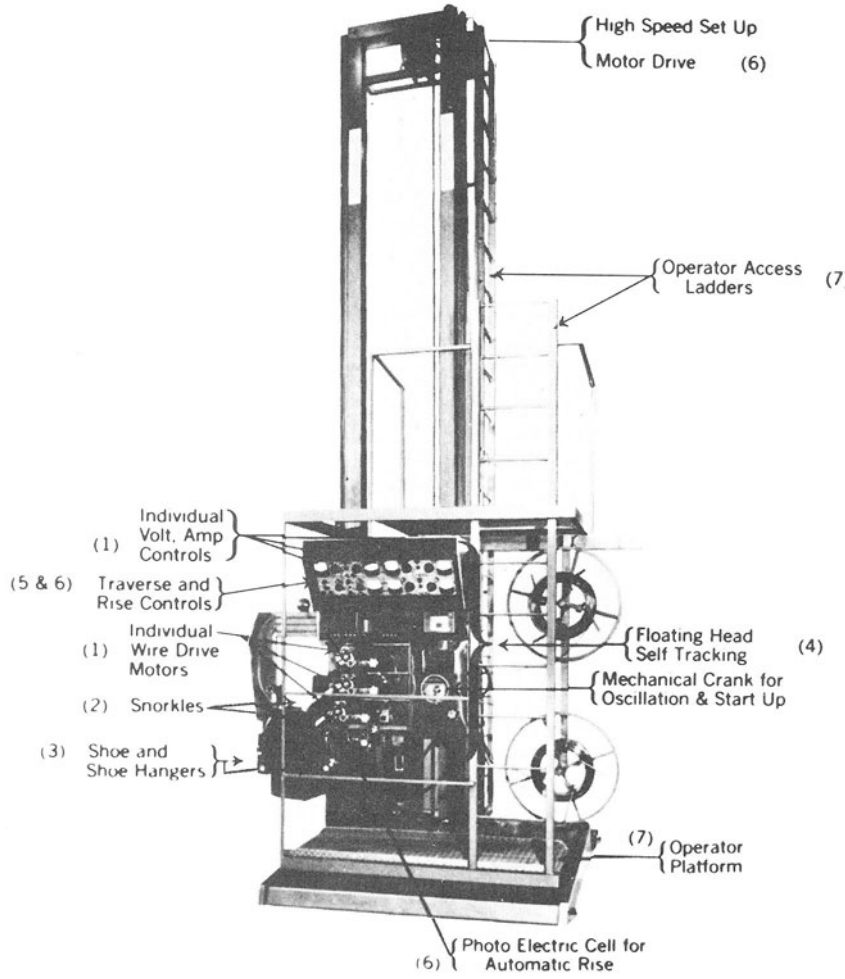


Fig. 48.8.—Three wire electroslag machine

FLUX

The molten flux, or slag, is an important element of the electroslag process, since it is in the slag that the heat for melting is generated. Although a relatively small amount of flux is used (about 5 pounds of slag to 100 pounds of metal deposited) it is vital to the successful application of the process.

The flux used must have several important characteristics. Its electrical resistivity must be high enough to generate a sufficient amount of heat for melting purposes, yet it must not be so high that arcing will occur from the

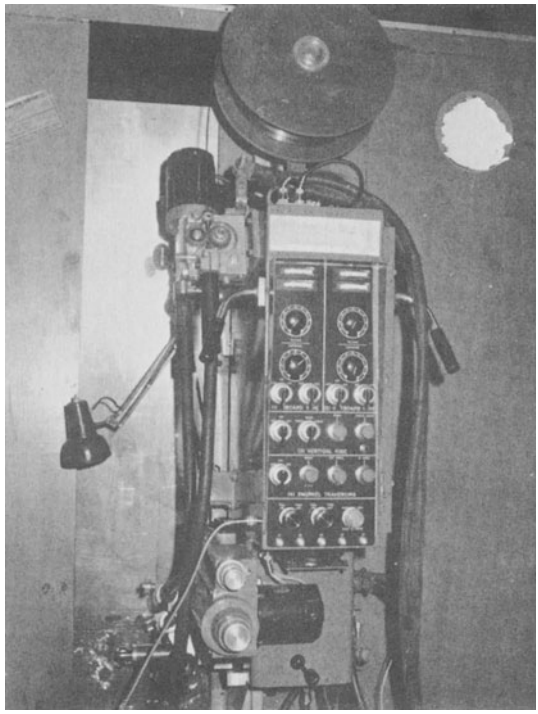
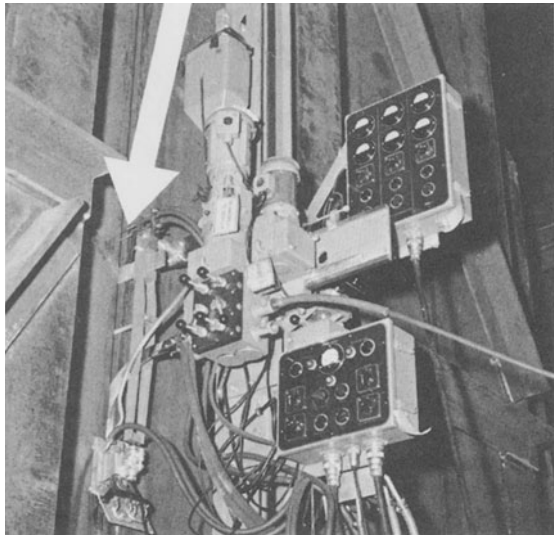


Fig. 48.9.—
Small portable electroslag/electrogas machine



Two-piece heads in marine application shown electroslag welding low-alloy high-yield strength plate. Note twin consumable electrodes (arrow) entering the seam.

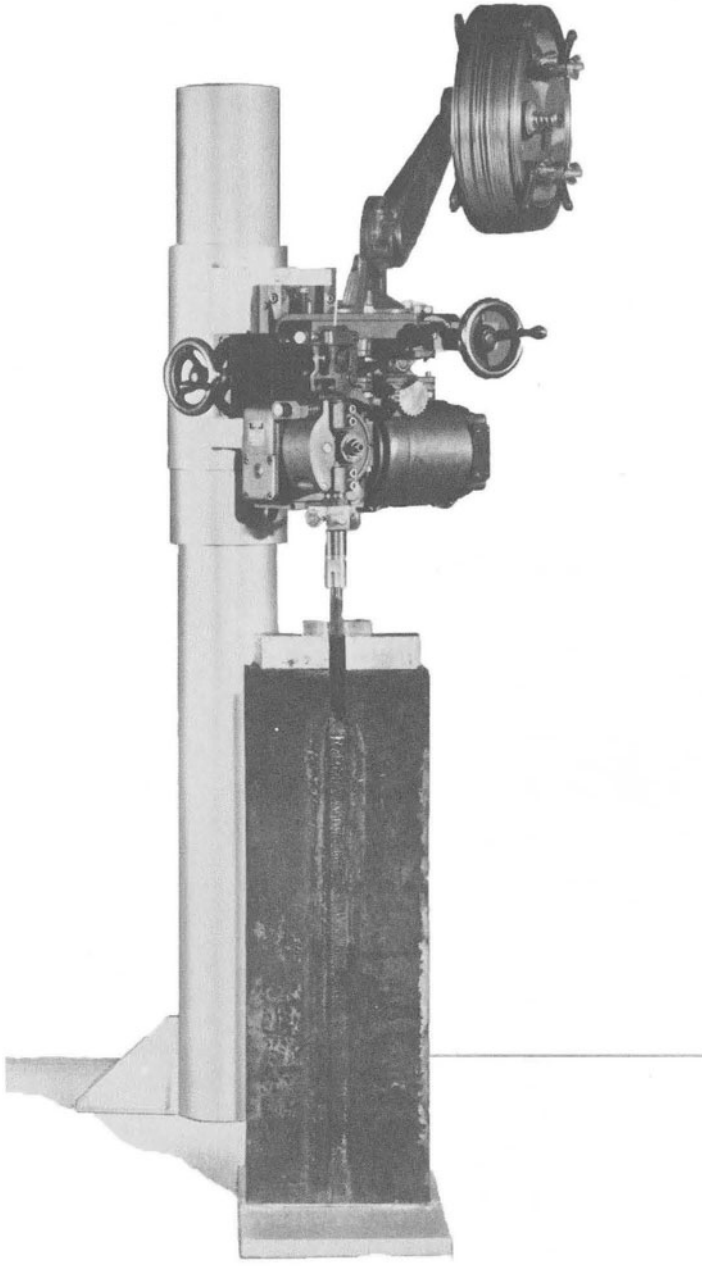


Fig. 48.10.—Consumable guide electroslag machine

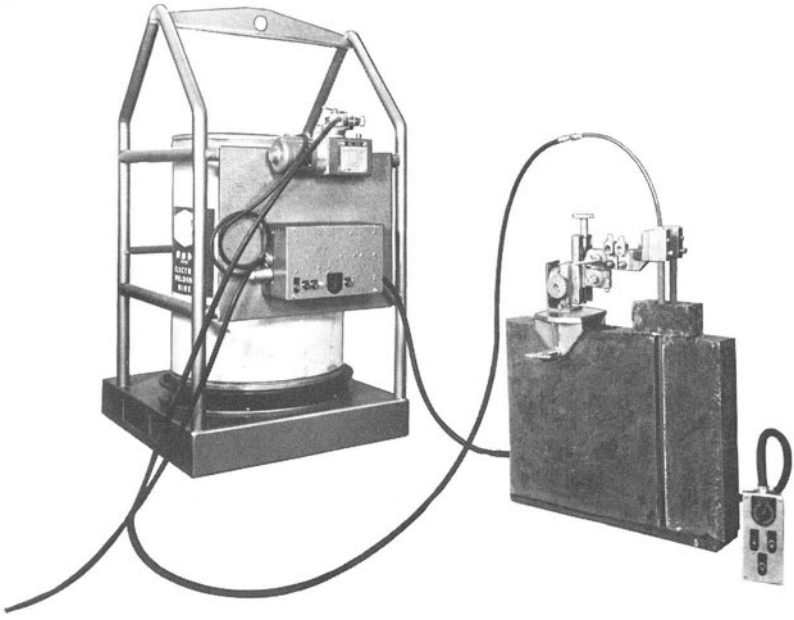


Fig. 48.11.—Consumable guide electroslag machine with remotely located wire reel and wire drive

electrode. The slag viscosity must be fluid enough for good circulation to occur, for even distribution of heat and to permit the flux to rise easily above the molten metal to prevent slag inclusions. On the other hand, flux must not be so fluid as to leak out of small openings between the work and cooling shoes. The slag melting point must obviously be well below that of the material being welded, yet its boiling point must be high enough so that no losses occur during welding to adversely change operating characteristics. Finally the slag should be reasonably inert to reactions with the alloy being welded; the solidified slag at the edges of the weld should be readily removable, and the flux should be inert to moisture pickup during storage.

The fluxes are usually combinations of complex oxides of silicon, manganese, titanium, calcium, magnesium and aluminum, with some calcium fluoride (CaF_2) always present. The calcium fluoride is generally added to a basic oxide or silicate system to achieve the proper resistivity and fluidity. Increasing CaF_2 decreases viscosity, melting point and resistivity. Additions of TiO_2 also decrease resistivity, whereas $A1_2O_3$ increases it. Lower resistivity generally produces lower slag temperatures for a given power input. In general those fluxes containing high CaF_2 ($>10\%$) are more fluid, have lower resistivity, operate at lower temperatures, produce less base metal penetration, operate at lower welding voltage and are easier to start than those containing CaF_2 in the order of 5 to 10 percent.

It is also important that the flux be formulated so that its conductivity is not changed greatly with temperature. With increasing welding current, the slag temperature increases, and if the conductivity increases rapidly, the slag will become unstable, causing arcing on the surface of the pool with violent explosions of the slag. The composition of a typical flux which has performed satisfactorily is: 35% SiO_2, 40% MnO, 5% $A1_2O_3$, 7% CaO, 6% CaF^2, 3% FeO, 3% TiO_2 and 1% Na_2O.

METALLURGICAL CONSIDERATIONS

THERMAL CYCLE

During electroslag welding, heat is generated by the resistance offered to the current during its passage from the electrode wire through the molten slag into the weld pool. The slag tends to be set in motion, due to metal transfer from the electrode to the weld pool. Thus, the heat generated diffuses very rapidly throughout the entire cross section being welded.

The large, slowly moving weld pool produces a protracted thermal cycle. A study of the thermal cycle of the heat-affected zone indicates a low heating rate and a long holding time at elevated temperatures. Because of this, the width of the heat-affected zone is considerably greater than in conventional arc welding. Temperatures attained in the electroslag welding process are unexpectedly low. The slag pool surface temperature is about 3000°F (1925°C) and the maximum temperature attained is around 3600°F (2040°C) at the point of electrode melting. The slag pool temperature must exceed the melting point of the plates being welded.

The protracted thermal cycle of electroslag welds results in a weld structure of large grains with a marked tendency to columnar growth. Since the joints are completed in a single pass, there is no opportunity to produce a refined structure with subsequent passes. However, the slow heating and cooling of the weld metal, as compared with arc welding, considerably reduces the risk of cracks developing in the weld. Also, the heat-affected zone has a high resistance to cracks resulting from the thermal cycle.

PREHEAT

The circulating slag bath washes the joint edges and melts them in the lower portion of the bath. The continuing circulation serves to preheat the unmelted edges in the upper portion of the bath.

The majority of the heat generated in electroslag welding is carried away into the workpieces. The heat carried away is not wasted in most cases since it serves to preheat the base metal to some extent. This action is owing to the relatively slow moving weld pool. Preheating of the base metal is usually unnecessary.

STRUCTURE

The macrostructure of electroslag welds is determined mainly by chemical composition and welding conditions which, in turn, affect the primary crystallization of the weld pool.

Since there is no theory of crystallization to date (even for ingots and castings), the exact type of structure cannot be predicted. It is, therefore, necessary to examine cross sections (longitudinal and transverse) of various electroslag welded joints made under various conditions. A typical cross section is shown in Fig. 48.12.

The structures found can be divided into four categories:

1. Entirely coarse columnar dendrites oriented in the axial direction. This is the result of low current and voltages when the weld width per electrode is high, i.e., 5 in. or more.
2. Entirely fine columnar dendrites oriented from the fusion boundary to the weld axis. Such fine columnar dendrites, meeting at the center line, may be caused by too little penetration of the base metal, by low carbon and manganese in the weld metal or by the use of small section components.
3. One zone of coarse columnar dendrites and one zone of refined or fine columnar dendrites. The width of the two zones varies considerably depending on the composition of the weld metal, temperature of the weld pool, intensity and direction of heat removal and shape of weld pool. Increased carbon and manganese in the weld metal increases the width of the coarse zone. High currents contract the coarse zone. If the cooling rate is lowered (as by low thermal conductivity of the materials, preheating, etc.), the width of the coarse zone decreases.
4. One zone of coarse, one zone of fine columnar dendrites and one central zone of fine columnar dendrites viewed at right angles. The equiaxed grains result from very slow cooling in the center and have been observed in carbon structural steels with over 0.35% carbon that have been welded with high current. The different structures have different properties. The coarse zone has better overall impact values, higher tensile strength, but lower ductility than the fine zone. Intergranular cracks have been observed in the fine zone in welds of this type, but they do not penetrate to the equiaxed zone.

SOUNDNESS

Welds made by the electroslag welding process under normal operating conditions result in high-quality welds free from defects.

In any welding process, however, abnormal conditions that may exist or occur during welding will result in defective welds. Some of these defects and their causes are indicated in Table 48.1. They are very general and data listed refer chiefly to carbon and low-alloy steels.

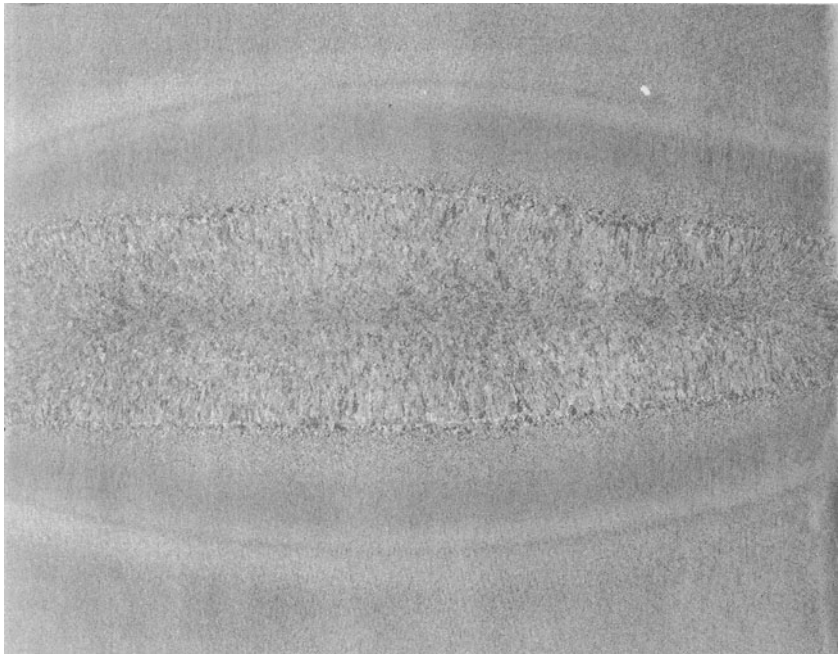


Fig. 48.12.—Typical electroslag cross section in 7½ in. thick plate welded with 2 electrodes

HEAT TREATMENT

Most applications of electroslag welding, particularly the welding of structural steel, require no postweld heat treatment. In weldments requiring optimum notch toughness, a postweld heat treatment, such as normalizing, may be required. Quenched-and-tempered steels require a postweld heat treatment to restore the original properties of the base material.

MECHANICAL PROPERTIES

Some typical all-weld-metal mechanical properties are listed in Table 48.2 (for welds in various alloy steels) and in Table 48.3 (for welds made in structural steels).

With the exception of Vee-notch impact properties, the mechanical properties of electroslag welds can be made equal to, or better than, those of the base metal by using suitable alloyed electrodes and controlled welding procedures. If optimum notch-impact properties are required, it is recommended that weldments be postweld heat treated by normalizing (air cool) to obtain grain refinement of the coarse dendritic structure of the weld and base metal heat-affected zone. This postweld heat treatment is recommended in ASME Boiler and Pressure Vessel Code (Case 1355) for construction of pressure vessels.

Table 48.1—Electroslag welding defects and their causes

Location	Defect (see Fig.13)	Causes
Weld	Porosity	Gas, inadequate deoxidizers in wire. Insufficient slag depth. Rusty or oily plate.
	Cracking Lack of fusion	Weld rate excessive. Poor form factor. Center-to-center distance between consumable guide excessive or insufficient number of guide or electrodes.
	Non-metallic inclusions	Excessive slag depth. Rough plate surface. Unfused non-metallics from plate laminations.
Fusion line	Lack of fusion	Low voltage. Excessive wire feed rate. Excessive slag depth. Misaligned electrodes or consumable guide. Inadequate dwell time or excessive oscillation speed. Excessive electrode-to-shoe distance.
	Undercutting	Excessive slag depth. Welding speed excessively slow. Voltage too high. Excessive dwell time. Inadequate cooling shoes.
	Metal washout	Poor shoe fitup.
Heat-affected zone	Cracking	Rapid cooling of weld. Incomplete penetration. High restraint. Crack sensitive material. Excessive slag depth.

Table 48.2—Typical mechanical properties of electroslag welds in carbon and alloy steels
(All-Weld-Metal Properties)

Material ASTM	Thickness, in.	Wire Electrode		Heat Treatment	Yield Strength, ksi	Tensile Strength, ksi	Elong. in 2 In., %	Charpy Impact Tests +10°F (—12.2°C) Vee Notch Location		
		Type	No.					WMFG	WMCG	BM HAZ
A204-A	3½	Mn-Mo	1	NT	55.5	81.5	27	34	29	13
A515 GR70	1½	Mn-Mo	1	SR	52.0	84.1	26	45	26	7
A515 GR70	2	Mn-Mo	1	SR	68.1	85.2	23	46	21	5
A515 GR70	3⅜	Mn-Mo	2	NT	57.5	78.0	29	34	33	22
A515 GR70	6¾	Mn-Mo	2	NT	45.5	74.3	31	24	21	12
A302-B	3	Mn-Mo-Ni	1	NT	57.0	82.0	28	53	52	63
A387-C	3	1¼ Cr-½ Mo	2	NT	46.5	73.0	29	70	76	57
A387-D	3¼	2¼ Cr-1 Mo	1	SR	57.5	82.0	25	46	50	48
A387-D	7½	2¼ Cr-1 Mo	2	SR	80.0	95.5	20	*62	*75	*83

*Impacts at +50°F (10°C)
NT — Normalized and Tempered
SR — Stress Relieved

WMFG — Weld Metal Fine Grain
WMCG — Weld Metal Coarse Grain
BM HAZ — Base Metal Heat Affected Zone

Table 48.3—Typical mechanical properties of electroslag welds in structural steels (Consumable Guide Method—All-Weld-Metal)

Material ASTM	Thickness, In.	Wire Electrode Type (AWS)	No.	Heat Treatment	Yield Strength, ksi	Tensile Strength, ksi	Elong. in 2 In., %	Reduction of Area, %	Impact Str. Ft. Lbs.*
A441	1	E70S-3	1	AW	49.9	75.8	28.0	59.0	17
A441	2½	E70S-3	1	AW	45.8	73.3	26.5	66.0	27
A36	6	E70S-3	2	AW	46.0	79.5	28.5	52.8	—
A36	12	E70S-3	2	AW	37.0	67.3	33.5	71.0	—
A572 Gr. 42	8	E70S-3	2	AW	58.2	84.8	25.0	67.6	28
A572 Gr. 60	2¼	E70S-G	1	AW	61.5	98.5	18.0	35.6	—

*Impacts at 0°F (—17.8°C)
AW = As Welded

Table 48.4—Typical mechanical properties of electroslag welds in stainless steels and special alloys (Wire Electrode Method)

Material	Thick-ness, In.	Heat Treat-ment	Test Loca-tion	Yield Strength, ksi	Tensile Strength, ksi	Elong. in 2 in., %	Reduction of Area %	Impacts CVN†	Temperature
Cr-Ni Stainless Steels									
304 (308 wire)	2	AW	Weld	36.6	77.9	49	70	33	—425°F (—254°C)
304L (308L wire)	11	None	Weld	—	77.5	—	—	19.2	—423°F (—253°C)
316 (316 wire)	2	None	Weld	36.6	77.9	49	70	36	—320°F (—196°C)
Special Alloys									
Inconel (Inconel wire)	2	None	Weld joint	27.6	69.9	57	74	—	—
D6 (D6 wire)	1¾	(1)	Weld	155.3	204	12	38	7	+10°F (—12°C)
Maraging* (Maraging wire)	2	(2)	Weld	160.7	171.6	10.5	45.2	34	R.T. (5)
HY-80 (HY-80 wire)	3⅜	(3)	Weld	88.6	112.9	—	—	NDT (4)	—

(1) 4 cycles 2050°F, AC to 1500°F; Temper 1350°F, AC.
(2) 900°/24 hours.
* 12 Ni-5 Cr-3 Mo.
(3) 1700°F Water Quench; 1650°F Water Quench; Temper 1180°F.
(4) NDT — No Break @ — 30°F.
(5) R.T. — Room Temperature.
† Charpy Vee Notch — foot pounds.

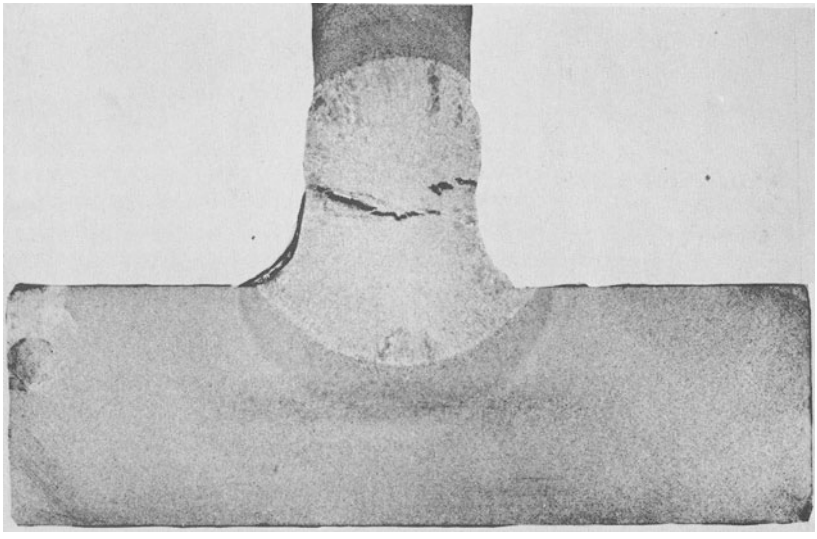


Fig. 48.13(a).—Cracking caused by excessive welding rate

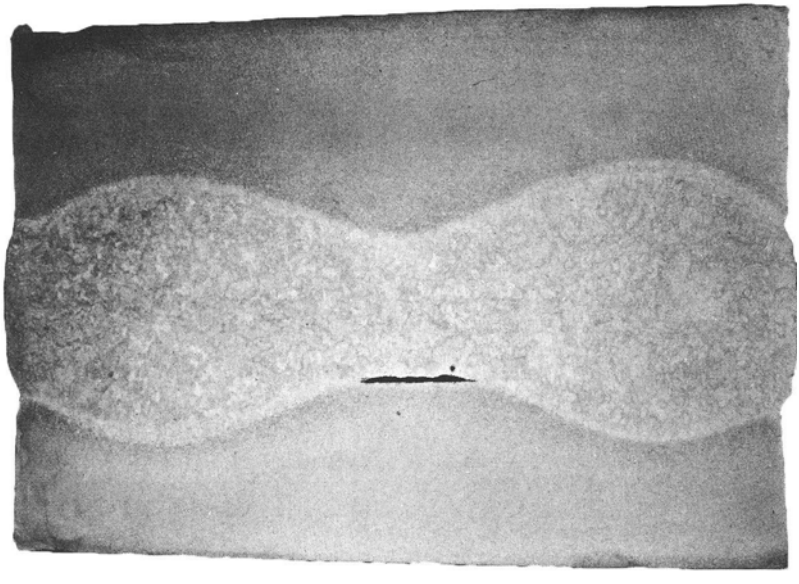


Fig. 48.13(b).—Lack of fusion defect

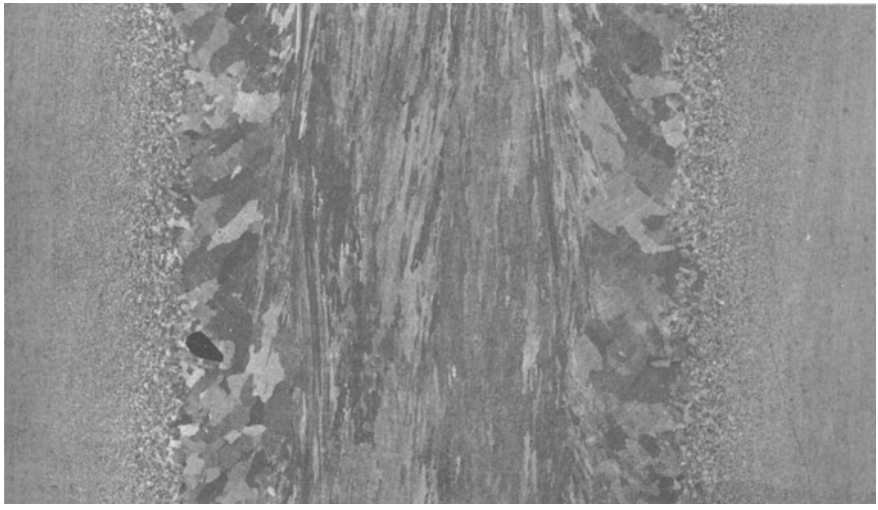


Fig. 48.13(c).—Slag inclusion defect

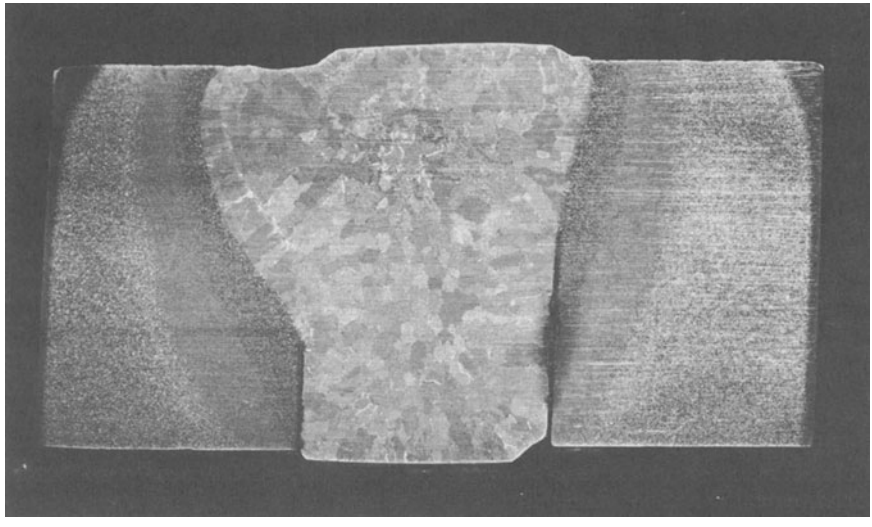


Fig. 48.13(d).—No fusion defect due to misaligned electrode or consumable nozzle



Fig. 48.13(e).—Undercutting type defect

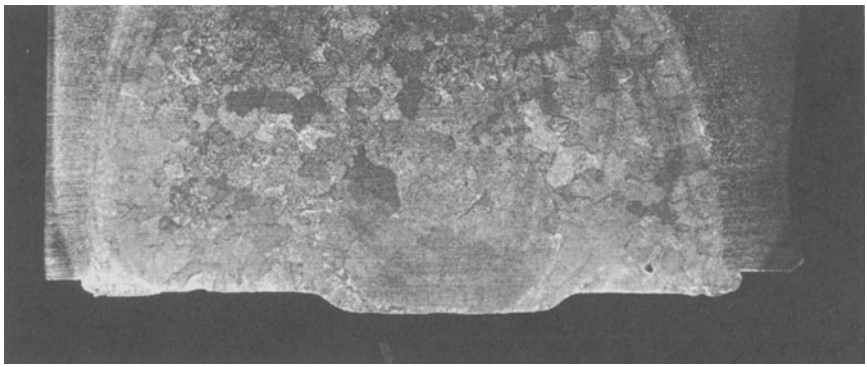


Fig. 48.13(f).—Metal washout type defect

It has been found, however, that with materials such as A387-D (2¼ Cr-1Mo) and thinner sections (below 2 in.) of A515 grade 70 steel, a postweld normalizing heat treatment for grain refinement may not be required; acceptable impact properties of the weldment may normally be achieved with a stress-relieving heat treatment only. One factor that allows this practice with A387-D steel is the inherently finer grain structure of electroslag welds in this material.

Annealing followed by furnace cooling, if used as a postweld heat treatment for grain refinement to improve impact properties, tends to lower the tensile strength of the base metal below the minimum acceptable by the ASME Boiler and Pressure Vessel Code; therefore, this specific postweld heat treatment is not recommended for electroslag welds.

Typical mechanical properties obtained for electroslag welds in stainless steels as well as other special alloys are listed in Table 48.4.

APPLICATIONS

The application of electroslag welding in American industry has increased greatly in the last five years. This is owing, in large part, to increased experience with the process and recognition of its capabilities and economic advantages, as well as increased equipment availability and the acceptance of this process by various codes and regulatory commissions.

In the structural steel field, the process is used for both shop and field fabrication. Fig. 48.14 shows a shop fabrication where the copper molds are being set on the sides of a joint formed by a diaphragm plate and the column side in the construction of a massive building column varying in length from 26 to 42 feet and 18 to 26 in. square. Diaphragm plates spaced at intervals inside the column were welded by the consumable guide process to all four sides of the column.

Fig. 48.15 shows beam flanges being aligned and prepared for consumable welding in the erection of a 100-story building.

In the machinery area manufacturers work with large and heavy plates. Quite often they are unable to buy the thick plate required in the width or length necessary. Fig. 48.16 shows 8 in. thick plate 13 feet long being electroslag welded by the oscillating consumable guide method to fabricate a side member of a press frame. The length of the weld was 12 feet.

Electroslag welding has also been used to manufacture motor housings, turbine rings and shrink rings. Fig. 48.17 shows a motor housing that has been welded. Both sides of the housing were welded simultaneously to control distortion.

A three-wire method weld made in 15 in. plate, 200 in. long is shown in Fig. 48.18.

Since acceptance of the electroslag welding process by the ASME Boiler and Pressure Vessel Code (Code Case 1355) in March 1965, the process has been used extensively for fabrication of heavy wall pressure vessels for the chemical, petroleum, marine and power generating industries.

Some of the applications include welding of longitudinal seams in boiler drums, downcomer piping, header and feedwater heater shells, nuclear reactor vessels and, to a lesser extent, welding of circumferential seams in liquid hydrogen spherical storage tanks and heavy nuclear pump cases. The process has also been used by at least one manufacturer for making massive weld buildups around large diameter vessels for the petroleum industry.

Some of these electroslag welded vessels sections have been fabricated having lengths up to 38 feet, with inside diameters from 15 in., and in thicknesses ranging from 2 to 18 inches. One pressure vessel manufacturer alone reported making upward of 6000 feet of longitudinal seam welds per year since early 1966 in the fabrication of ASME Code vessels in thicknesses from 2 to 7½ inches.



Fig. 48.14.—Setup of consumable guide method for welding stiffener plate in building column



Fig. 48.15.—Assembly for consumable guide method weld in building fabrication

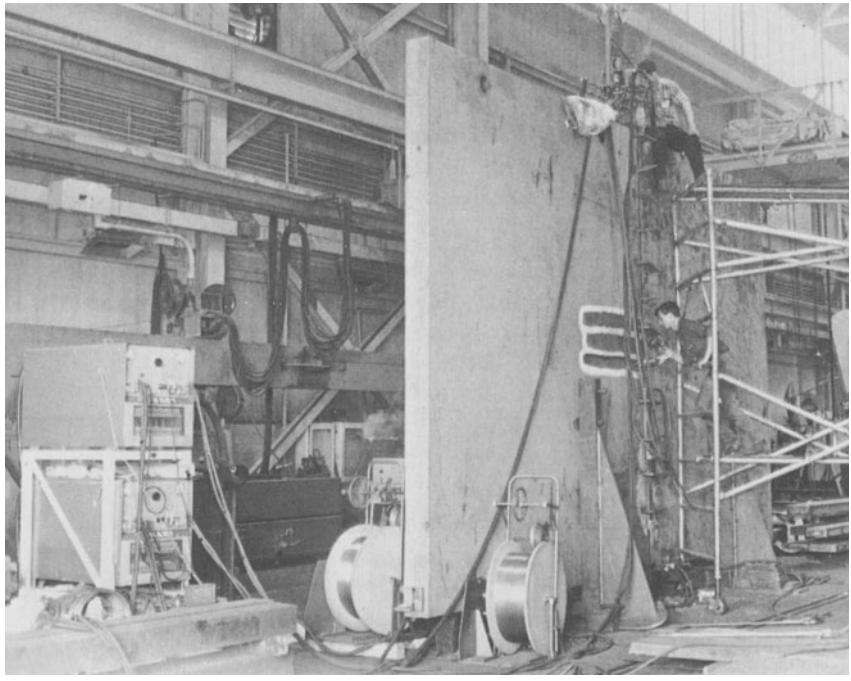


Fig. 48.16.—Consumable guide method welding of plates to fabricate side members of press frame

All electroslag welds in pressure vessels fabricated to the requirements of the ASME Code must meet both radiographic and ultrasonic inspection standards specified in Code Case 1355 after, in most cases, the recommended postweld heat treatment to achieve grain refinement in the weld zone and in the base metal heat-affected zone.

A new dimension in heavy section welding is made possible by the electroslag method, it has opened a new field for cast weld assemblies. Sections up to 15 in. thick of types 316 and 304 stainless steel are being joined in production on a large scale basis saving thousands of dollars not only in welding, but in foundry capacity as well. Medium-size foundries can, by the cast weld process, produce and ship complete units with a weight up to 100,000 pounds or more. Before electroslag welding, these large components could be produced only by foundries with large furnace capacity.

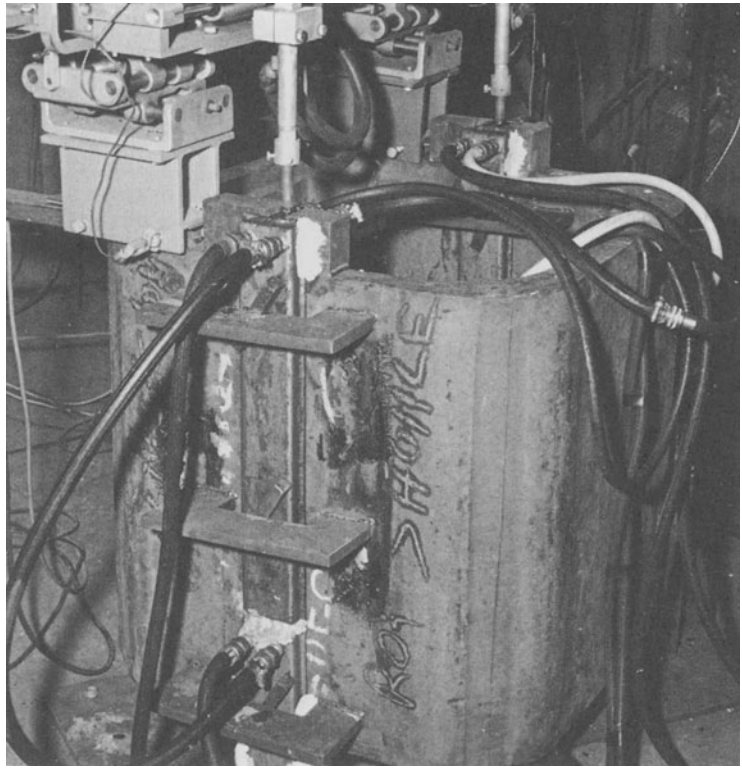


Fig. 48.17.—Consumable guide method welding of a motor housing

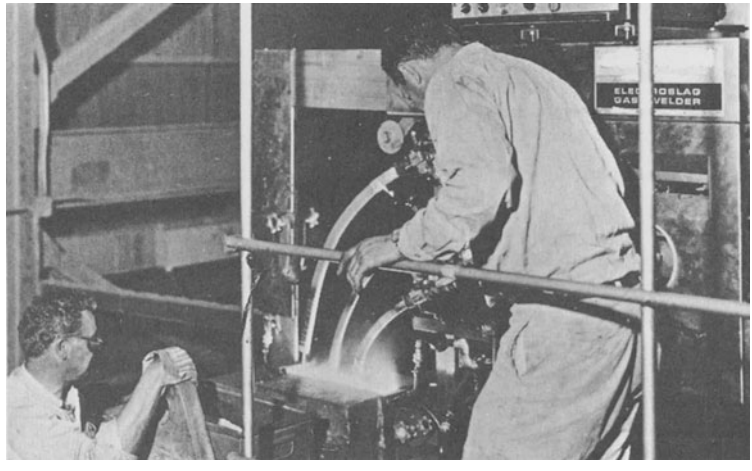


Fig. 48.18.—Wire method weld using 3 wires

For circumferential joints, the parts are placed on powered turning rolls and the mechanism that "senses" the rate of progress of the weld provides the signal to operate the turning roll. The welding head is thus kept stationary in the "three o'clock" position from the start until near the finishing point. While the weld is progressing, the starting tab is removed by one of the thermal cutting processes, leaving a straight surface approximately tangent to the inside circumference of the vessel. As the weld approaches the tie-in point, the turning rolls are stopped and the machine is allowed to progress vertically upward against suitable dams to retain the molten slag until the tie-in is completed. A typical application of this type welding, by the wire method, is shown in Fig. 48.19 for an 11-in. thick vessel made of stainless steel.

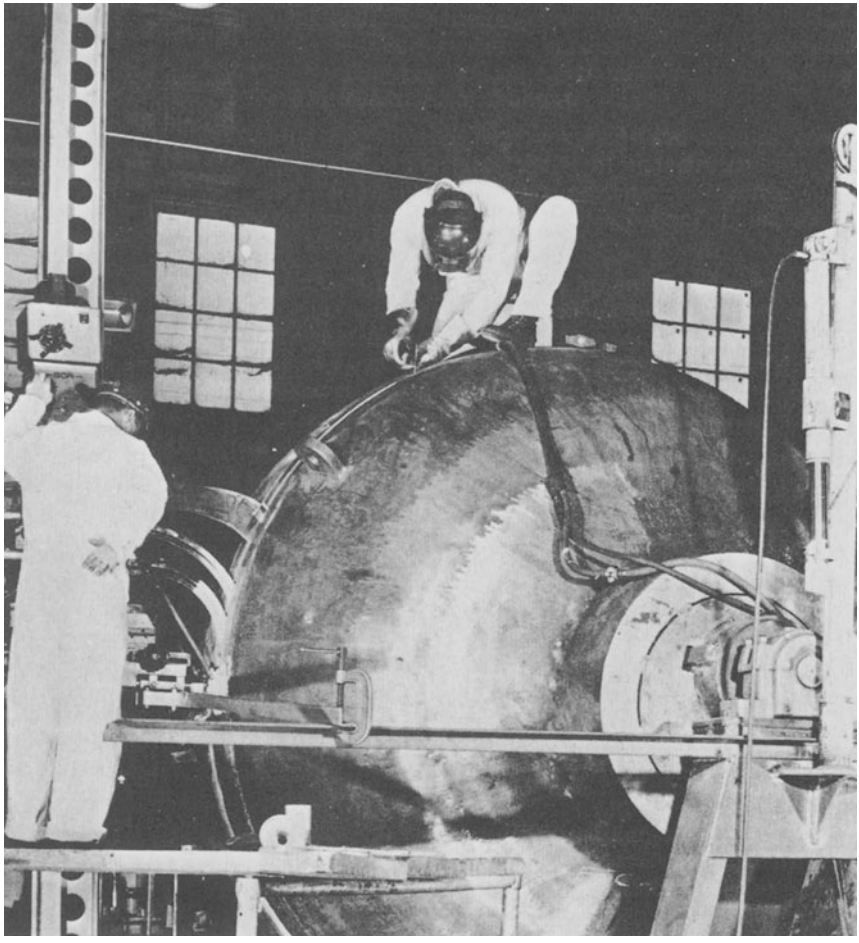


Fig. 48.19.—Circumferential weld made by the 2 wire method

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CHAPTER 49

ADHESIVE BONDING OF METALS

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CHAPTER 49

ADHESIVE BONDING OF METALS

FUNDAMENTALS OF PROCESS

ADHESIVE BONDING is a joining method that has achieved substantial industrial recognition. It is continuing to gain acceptance, particularly in the metalworking field, as a standard assembly method for manufacturers who seek to utilize the various advantages offered by modern industrial adhesives.*

Although many simpler types of adhesives have been used for hundreds of years, it was not until the early 1940's that the development of synthetic resin formulations began to focus more attention upon adhesive bonding in metal-to-metal and metal-to-nonmetal joining applications. These early synthetic adhesives, the phenolic blends, were the first to provide the strength and permanence necessary to produce good bonds between metals.

The success of these adhesives in the aircraft and automotive industries led to the acceptance of adhesive bonding for many metal-joining applications that had formerly been confined to conventional joining techniques.

Since that time many significant advances have been made in adhesive formulating, not only in the field of metal-to-metal bonding but also to satisfy the demands created by the introduction of new materials and composites into the

*Today the word "adhesive" is, in a broad sense, a representative term; it includes such substances as glues, cements and other bonding agents. In many quarters the term "glue" and "adhesive" are synonymous. Prior to the synthetic resins, the term "glue" referred to materials of animal and vegetable origin. These early commercial glues were all of a sticky nature and found uses in furniture assembly, bonding of wood veneers, bookbinding, gummed labels, corrugated boxboard, wallpaper, paper bags, envelope glues, household glues and various other wood, paper and textile applications. Their uses are necessarily limited because of poor resistance to water and weather. Their continued use is primarily due to low cost and good serviceability and their adaptibility to use with automatic equipment in the paper and textile fields.

field of production joining. Particularly important here is the rapidly growing use of plastics and the need for joining them to metals.

In answering such new demands, "chemical fastening" has found a definite place in joining technology. Adhesives should be regarded in much the same light as are filler metals in welding operations. Design engineers and others concerned with joining techniques should consider adhesive bonding as an additional tool, to be specified when and where it can be used to advantage.

ADVANTAGES OF ADHESIVE BONDING

BONDING DISSIMILAR MATERIALS

Since the adhesive layer can isolate the metals and minimize electrolytic corrosion, it is possible to bond dissimilar metals. Many types of adhesive formulations are also flexible enough to permit the bonding of dissimilar metals with widely varying coefficients of expansion; such possibilities depend, of course, upon the size of the pieces and the degree of bond strength required. In addition, a single adhesive formulation may be used for joining many different metals regardless of their metallurgical properties. Adhesive bonding also makes it possible to join metals to numerous other materials, such as various types of plastics. Fig. 49.1 shows the bonding of rigid urethane foam to sheet steel with a free-flowing room-temperature-curing epoxy adhesive in the fabrication of insulating panels.

BONDING THIN-GAGE METALS

Very thin metal parts, including those too thin to be joined by any other method, can be adhesive bonded to themselves or to other substrates. For example, multiple layers of thin metal sheets can be bonded together to form motor laminates; foils of various metals can be joined to themselves or to other materials; thin-gage metal sheets may be used as sandwich panel "skins."

HEAT REQUIREMENTS

The temperatures involved in the heat curing of most adhesives are between 150 and 250°F (66 and 177°C), temperatures that fall into the low soldering range. Also available are room-temperature-curing formulations that provide sturdy structural bonds at service temperatures up to 180°F (82°C). This means that many heat-sensitive components may be joined without damage. Because distortion, burn-through, embrittlement, disorientation, etc., can be minimized or eliminated completely, adhesive bonding should be considered when such conditions may result from high-temperature operations.

Some adhesives differ from metal solders in that they can sometimes operate at temperatures considerably in excess of their cure temperature.



Fig. 49.1.—Rigid urethane foam bonded to sheet metal

BONDING AND SEALING

The same adhesive that bonds the components may serve as a sealant or coating, thus improving resistance to oils, chemicals, moisture or a combination of these factors. In Fig. 49.2 a room-temperature-curing adhesive is used to seal the ends of an antenna circuit built into the handle of a marine radio. The same adhesive is also used to bond neoprene tubing and plastic-coated lead-in wires to aluminum at three points within the housing of the set.

VIBRATION AND SOUND DAMPING PROPERTIES

Adhesives can also serve to damp shock and vibration.

THERMAL AND ELECTRICAL INSULATION

Adhesives can provide thermal and electrical insulating layers between the two surfaces being joined. For example, almost all printed circuits made in mass production involve adhesive bonding. In this application, the adhesive used to bond the copper is expected to have electrical characteristics similar to those of the insulating base material (Fig 49.3). The copper may be precoated with adhesive or a synthetic resin liquid adhesive may be used to bond uncoated copper to the insulating base material. The adhesive also serves as an insulating surface between adjacent conductors.

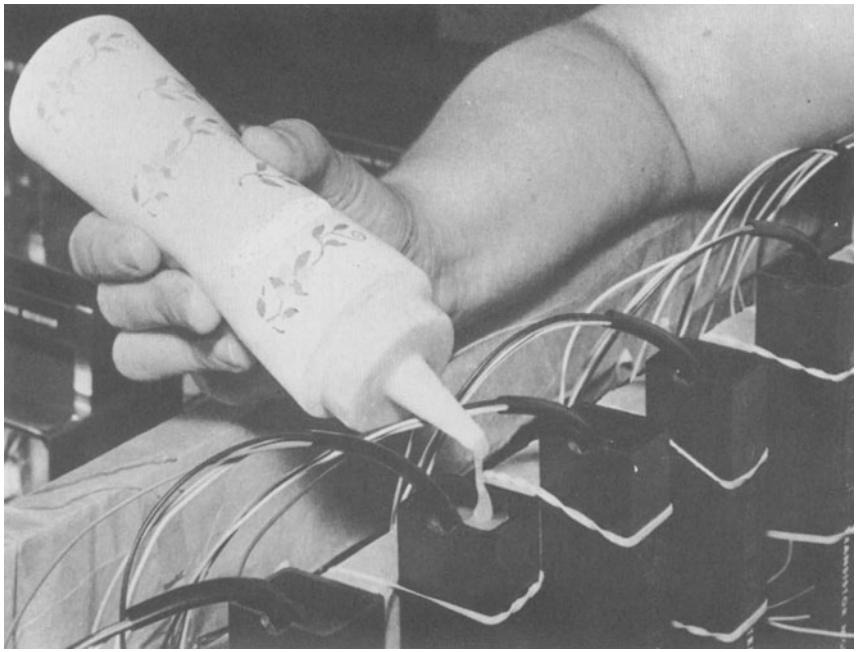


Fig. 49.2.—Room-temperature curving epoxy adhesive used to seal the ends of a marine radio antenna

UNIFORM STRESS DISTRIBUTION

Loads can be distributed over the entire bonding area, thus minimizing localized stress. This is demonstrated in curtain wall panel construction, for example, where metal skin sheets are bonded to metal or paper honeycombs, to formed polystyrene or to other core materials.

SURFACES

Adhesives can ensure smooth, unbroken surface contours without protrusions, gaps or holes. Typical is the postformed vinyl-to-metal laminate widely used in the production of television cabinets, housings for electronic equipment and automotive trim. Fig. 49.3 shows adhesive bonded truck door panels, which typify the advantages of adhesive bonding where broad, unbroken areas are involved.



Fig. 49.3.—Truck door panels of aluminum adhesive bonded to chipboard

FATIGUE RESISTANCE

Adhesives have high resistance to fatigue and thus help to provide long service life under dynamic loading conditions. The use of adhesives in place of rivets has increased fatigue resistance by a factor of ten or more, as in helicopter rotor blades. The use of adhesives with rivets in very large aircraft structures has increased the fatigue life of a joint from 200,000 cycles for rivets alone to more than 1,500,000 cycles for the bonded/riveted joint.

LIGHTWEIGHT STRUCTURES

Designing for adhesive bonding may also bring about a significant reduction in the weight of the finished product. Honeycomb panel assemblies used extensively in the aircraft industry and, more recently, paper honeycomb in the construction field for both exterior and interior installations, provide an excellent and important example of weight reduction (Fig. 49.4). (Not only is the honeycomb core material bonded to the metal face sheets but, in addition, most honeycomb is itself and adhesive-bonded assembly.) Weight reduction is important in the function of the end product; it may also represent considerable cost savings in packing, shipping and installation labor.

DESIGN SIMPLIFICATION

Adhesives often permit design (and production) simplification. In Fig. 49.5 a structural adhesive is used to bond aluminum die cast pump sections to steel cores. Previously the part was cast in one piece, but blow holes in the casting resulted in too many rejects. Adhesive assembly made a practical design possible, reducing rejects to nearly zero.

MATERIAL COST

On a straight cost-per-pound basis, adhesives are usually far less expensive than many other conventional joining materials.

PRODUCTION COSTS

Application

Application procedures can be expedited or simplified in order to lower costs. Formulations designed for a wide variety of equipment permit the use of methods ranging from fully automated flow coating and mass production spraying to hand application with simple, easy-to-use tools such as paint brushes.

Assembly

Assembly time can often be cut considerably, even when large or intricately designed components are involved. The identification plate in Fig. 49.6, which has been precoated with adhesive, is applied quickly and easily by moistening the adhesive surface lightly with solvent and pressing the plate against the metal surface.

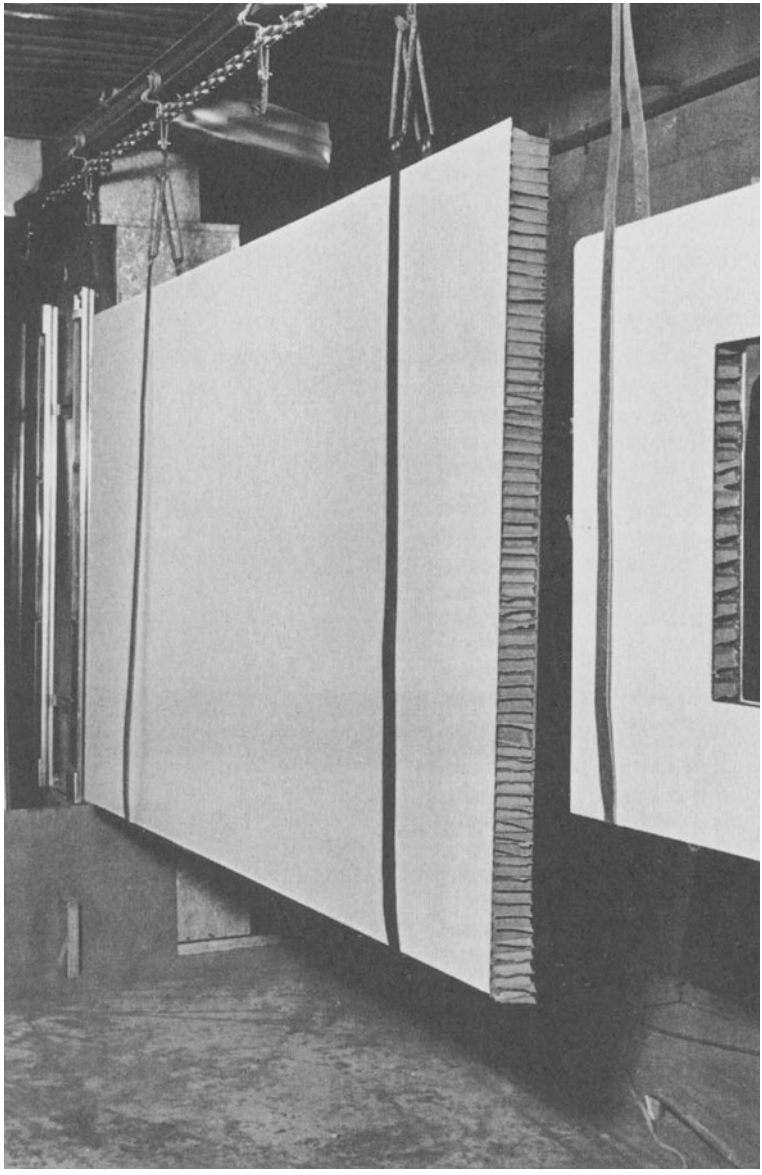
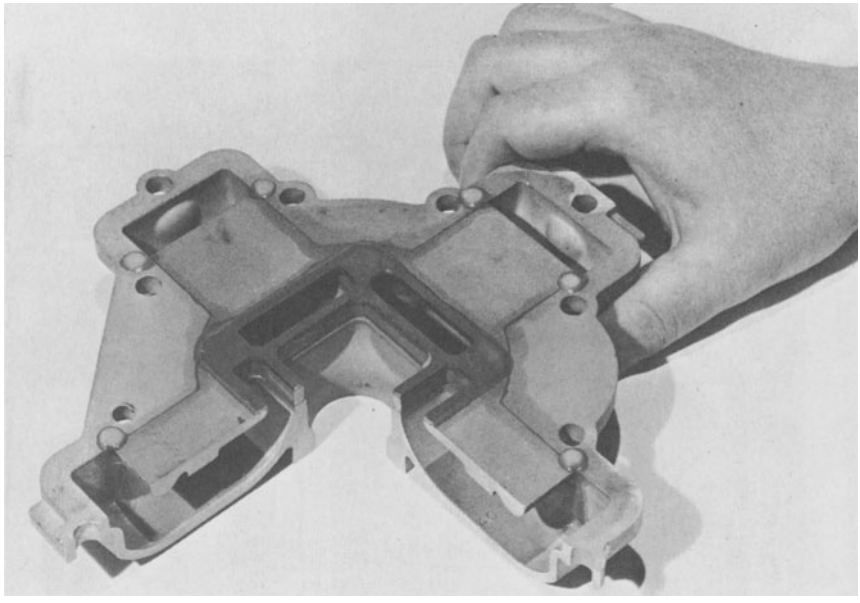


Fig. 49.4.—Adhesive bonded honeycomb panels combine light weight with high strength



49.5.—Aluminum die cast pump sections adhesive bonded to steel core

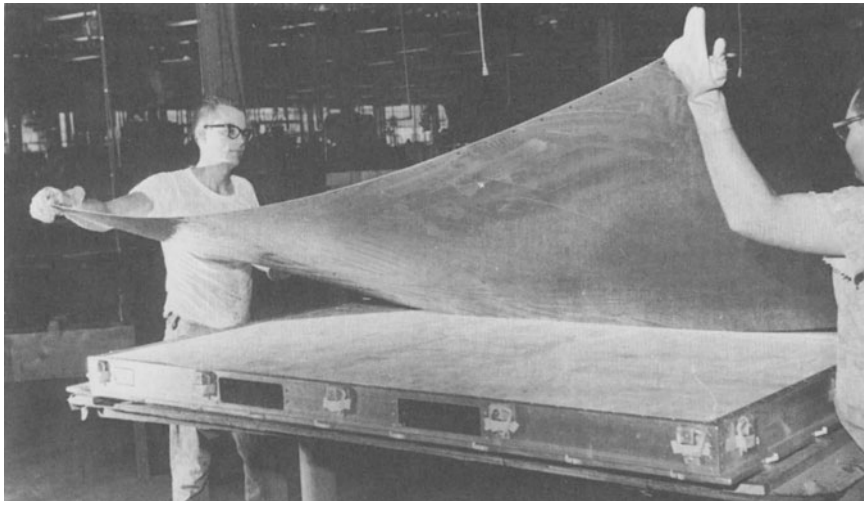


Fig. 49.6.—Identification and name plates are easily and quickly installed by adhesive bonding

Accessibility

Adhesives can be applied to areas inaccessible to the equipment normally required for other joining techniques. Thus, simplification of initial design can often be realized.

Finishing

Finishing operations may be kept to a minimum. Some adhesive formulations incorporate thixotropic additives which restrict flow, thus minimizing running or dripping during the entire bonding operation.

Uniformity

The uniformity of bonds obtainable with adhesives can lead to fewer rejects and, in turn, lower costs. Since consistency of performance is less dependent upon the skill of the worker, greater uniformity can be anticipated.

Dimensional Tolerances

Riveting or bolting of light-gage metals causes bulging between fasteners. Welding of aluminum and other metals may result in distortions regardless of the care and the tooling used. Adhesive bonding, properly carried out on well-designed structures, can produce assemblies with much tighter dimensional tolerances.

LIMITATIONS OF ADHESIVE BONDING

Although adhesive bonding has many advantages, certain limitations should be considered:

1. Redesign of joints may be necessary to utilize adhesives properly.

2. Elastomeric adhesives, even those with high tensile shear strength at temperatures as high as 300°F (149°C), will not support high peel loads above 200°F (93°C).

3. For applications where high peel strength is essential, some mechanical reinforcement may be necessary.

4. Adhesives such as epoxy-phenolics that are designed for low creep at elevated temperatures have an operational temperature ceiling of about 500°F (260°C). New high-temperature adhesives from heat stable polyimides, polybenzimidazoles and related compounds show promise for use at temperatures up to 900°F (482°C), but are costly and difficult to process.

5. Initial capital investment may run high when large bonding areas or special end-use service requirements are involved. The benefits of a bonded joint must be balanced against the cost of autoclaves, presses, tooling and any other special equipment that might be needed to perform the bonding operation.

6. Process controls may be a limiting factor. Before bonding, surfaces must be properly cleaned and treated, and must be protected from contamination until they are bonded. Surface preparation can range from a simple solvent wipe to multistep cleaning, etching, rinsing and drying procedures, which must be very carefully followed in critical structural bonding applications. Control of ambient temperature and humidity may also be necessary.

7. Full joint strength requires time, either at cure temperature or at room temperature. Mechanical fasteners produce full strength immediately, hence do not require extensive fixturing.

8. Inspection methods used with other joining techniques are not generally applicable to evaluation of adhesive bonds. Testing, both destructive and nondestructive, must be used, together with process controls, to establish effectiveness and reliability of bonded joints. Ultrasonic test procedures are in use today. An ASTM D-14 (Adhesives) Standard Ultrasonic Test method is now being written. Other nondestructive test procedures are being developed and are in limited use.

ADHESIVE TYPES

THERMOPLASTIC AND THERMOSETTING TYPES

The thermoplastic type of adhesive is one that will soften at elevated temperature and, if the temperature is sufficiently high, flow and fill the bond area. Bond strength is achieved after the adhesive solidifies by cooling. The thermoplastic nature of the adhesive permits the joint to fail at relatively low stress if the temperature is raised sufficiently.

Thermosetting adhesives harden or cure by chemical reactions, such as polymerization, condensation, cross linking, vulcanization or oxidation caused by the addition of a coreactant or catalyst; heat, pressure, radiation or other energy can also effect hardening or curing. Once hardened or cured, these adhesives cannot be remelted and a broken joint cannot be rebonded by heating. Depending on composition, thermosetting adhesives may soften or weaken and ultimately decompose at high temperatures.

Most nonvulcanizing elastomeric-based adhesives may be considered as thermoplastics, whereas most vulcanizing elastomeric-based formulations may be considered as thermosetting.

ADHESIVE TYPES

Air-drying

The air-drying adhesives are predominantly thermoplastics, supplied as dispersions, emulsions and solutions. These achieve their bond strength upon removal of the solvent. They are applied to the adherend surfaces and, if necessary, time is allowed for the solvent to evaporate. The adhesive-coated surfaces are then joined under the prescribed amount of pressure. Sometimes heat is applied to fuse the coated surfaces after drying.

Fusible

The thermoplastics are fusible. After the adherends have been coated and mated, heat and pressure are applied to the assembly, which is then cooled to solidify the adhesive.

Pressure-Sensitive

Pressure-sensitive adhesives are formulations that provide a relatively low-strength bond instantly upon the application of slight pressure. They may be applied to any clean, dry surface. Because they retain their flow characteristics throughout their useful lives, they are capable of sustaining only very light loads.

Chemically Reactive

The chemically reactive type of adhesive consists primarily of thermosetting adhesives in liquid and solid forms (including films and tapes) that are activated by the addition of a hardener or by the application of heat. Bond strength is achieved through the chemical reaction of the resinous components and catalysts or hardeners. The latter may be incorporated by the adhesive manufacturer or may be added by the user just prior to application. Such formulations generally must be used within a prescribed length of time after mixing (pot life) to avoid premature gelling. Other chemically reactive adhesives contain a latent hardener that activates and cures the adhesive at elevated temperatures. The time required for bonding is approximately 24 hours for room-temperature-curing adhesives and from a few seconds to several hours for heat-curing formulations.

Anaerobic

Anaerobic adhesives are unique in that they are shelf-stable, solventless, ready-to-use formulations that cure at room temperature. Their cure is inhibited by the presence of air (oxygen) in the package and during application. Once the joint is assembled, thus effecting the exclusion of air, curing begins almost immediately.

Structural Adhesives

The ultimate objective of a "structural" adhesive is to create a bond that is stronger than the materials it joins. Since this goal is not always attainable, a structural adhesive can perhaps be defined more accurately as one whose properties are such that, when used in well-designed joints, it can produce bonds with strengths and durability approaching or exceeding those of the adherends. This definition implies that the adhesive will allow the adherends to be stressed beyond their elastic limits. In this sense, most adhesives used to bond paper, for example, would be classified as structural since the paper usually tears before the bond fails.

To approach this objective in metal-bonding—particularly in the aircraft industry—improved adhesive technology was called for. Early adhesives were too brittle, too rubbery or lacking in resistance to atmospheric conditions, solvents or strong chemicals.

Phenolic resin adhesives, modified with thermoplastics or elastomers, did much to overcome these weaknesses. These modified phenolics are available as solutions in organic solvents and as films, both supported and unsupported. Such adhesives feature high peel strength and tensile and shear values on the order of 3000 to 5000 psi.

The next important step was the development of epoxy resin-based adhesives. The epoxies combine the properties of excellent wetting action, low shrinkage, high tensile strength, toughness and chemical inertness to produce adhesives noted for their strength and versatility.

The epoxies were the first "100% reactive" liquid adhesives that could be applied without a solvent carrier. Because of this property, there is no danger of entrapped solvent, with the consequent bond-weakening effect. Little shrinkage occurs during cure, and there are no volatile by-products of the curing process. No pressure, other than that necessary to maintain intimate contact between the adherends, is required to make the bond. Equipment requirements are greatly simplified as a result.

Epoxy adhesives are available as free-flowing liquids, films, powders, sticks, pellets and mastics, allowing for considerable latitude in the selection of application technique and equipment.

Fillers or flexibilizers may be added which tend to minimize stress that can occur when the adherends have differing coefficients of expansion.

The wide choice of curing agents available for use with epoxy formulations offers curing cycles ranging from several hours at room temperature to a matter of minutes at elevated temperatures. It must be kept in mind, however, that higher temperature cures are required for the more heat-resistant formulations.

Such a range of curing agents also makes it possible to produce an adhesive system having the best possible balance of properties for a given application. However, in order to obtain this balance, certain properties may be enhanced at the expense of others. The adhesive may be flexibilized to increase its peel strength and adhesion to diverse materials, for example. But the addition of such flexibilizers generally lowers hot strength as well as the solvent and chemical resistance of the completed bond.

Thus it is apparent that curing agents recommended for "general purpose" epoxies usually produce systems having the best compromise of properties rather than the ultimate in any single property. Certain "specific use" adhesives, on the other hand, are designed for high temperature resistance or for adhesion to specific substrates.

Consultation with the adhesive supplier will reveal that, whereas one curing agent may be recommended for an adhesive to achieve the best balance of properties, other hardeners often may be substituted for use with the very same adhesive to provide improved performance characteristics in the specific area of interest in a given application.

Fig. 49.7 illustrates a study made of the effect of curing agent variation on the bonding properties of a 100% reactive, solvent-free, thixotropic, intermediate strength type of epoxy. Because of its specific adhesion to many types of surfaces and the ease with which it can be handled, this formulation has had wide commercial acceptance.

Combination "F," a high-strength epoxy, specially formulated for its properties at high temperatures, was included for purposes of comparison with the so-called general purpose epoxy adhesive used in this test series.

From the results of this evaluation, it can readily be seen that different strength properties are obtainable from a single adhesive simply by changing the curing agent. Other properties differ in a similar manner, depending upon the hardener selected.

The epoxy-based adhesives, as a general class, feature high shear and tensile strengths (up to 10,000 psi) and low creep tendencies. Generally speaking, however, their peel strength is low, although specially formulated epoxy adhesives have been developed which provide improved peel values, especially those modified wth nylon.

An epoxy-phenolic resin, cured with dicyandiamide, is an adhesive that performs well in the 400 to 500°F (204 to 260°C) temperature range. Cured in a representative cycle of 2 hours at 350°F (177°C) at 150 psi pressure, it will produce a bond having good shear and creep properties at 500°F (260°C) but relatively poor peel resistance. Accordingly, better "all-around" strength properties are often obtained by using this adhesive in conjunction with specially formulated primers having high peel strength.

The elastomer-modified phenolics, which require curing at temperatures from 300 to 350°F (149 to 177°C) and under pressure up to 100 psi, offer increased heat resistance. But temperature requirements for bonded structures keep rising.

Another class of high-temperature-resistant resin systems—polybenzimidazole (PBI) and polyimide (PI)—have been developed for application as structural adhesives for service use from −424 to nearly 1000°F (−253 to 538°C). These systems have been evaluated for bonding aluminum, stainless steel, titanium, beryllium and other exotic metals as well as reinforced plastics with excellent results. Shear strengths of over 2000 psi on 1/2 in. overlaps have been obtained on stainless steel alloys. Short-time exposures (15 min. at 1000°F/538°C) have given shear strength in excess of 1000 psi for stainless steel, titanium and beryllium metal adherends in test evaluations. These adhesive systems have also been successfully utilized for fabricating stainless steel honeycomb sandwich constructions. Research is continuing on these linear polyaromatic resin systems to improve the aging properties at elevated temperatures and to synthesize other inorganic and organic resin systems for reinforced plastic and adhesive composites used, for example, in high-speed aircraft and hypersonic missiles.

STRUCTURAL DESIGN

In order to incorporate as many of the advantages of the adhesive-bonding technique as possible, joint design should be a part of the early stages of product planning. If bonding is being considered as part of a redesign program, structural adhesives should not be substituted directly for other joining methods. The joint itself should be redesigned to avoid the weaknesses and to take advantage of the virtues of adhesive bonding.

Although the primary objective remains a strong assembly capable of meeting end-use service requirements, proper joint design can often lead to other cost-saving benefits. Through good design, it may be possible to achieve more than satisfactory results with a less costly adhesive formulation, to develop a simpler bonding process and to eliminate some of the quality control testing steps needed to ensure reliability.

Before discussing types of joints and stresses, it should be noted that joint design often influences the form and characteristics of the all-important glue line. Obviously, the design must provide room for sufficient adhesive, but in some instances it may also be necessary to incorporate means of getting the adhesive into the joint area.

Joint design may also play an important role in determining the thickness of the glue line. In this connection, thin glue lines, on the order of 3 to 5 mils, are better for high-strength adhesives because there is: (1) less likelihood that the adhesive will creep or flow; (2) less deformation under pressure; (3) more resistance to cracking (especially with hard adhesives); (4) less danger of locked-in stresses, and (5) less danger of gross porosity in the adhesive.

Another obvious advantage of thinner glue lines is their lower adhesive requirements. The savings can be sizable in long-production runs.

When considering a new design or a redesign, there are two rules to observe when designing joints for bonding:

1. Uniform distribution of working stresses should be maintained over the entire bonding area.

2. The main working stress should be put in shear or tension; cleavage or peel stresses should be minimized.

Both rules express ideal conditions that are rarely, if ever, realized in practice. Some stress concentrations are all but unavoidable, and it is rare indeed to find a joint that will be loaded exclusively in one mode of stress.

Nevertheless, careful design and judicious selection of adhesive can minimize the forces that are most destructive to bonded joints. The four main modes of loading are illustrated in Fig. 49.8. The adhesive-bonded joint performs best

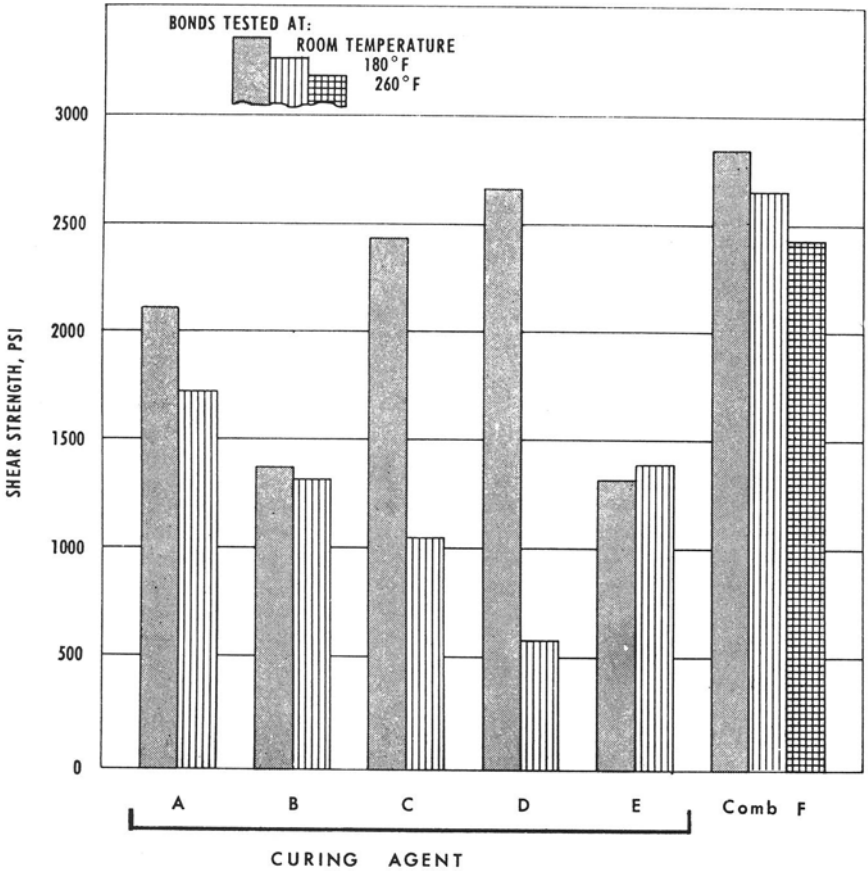


Fig. 49.7.—Effect of curing agent variation

when loaded in shear; that is, when the direction of stress is parallel to the plane of the faying surfaces. This puts all the adhesive to work at the same time and minimizes stress concentrations.

This is also true of a joint that is loaded in pure tension, with the stress perpendicular to the plane of the joined surfaces. All the adhesive works to resist the stress, which is distributed uniformly over the entire joint area.

Difficulties may arise when cleavage or peel stresses are present. As shown in Fig. 49.8 cleavage loading concentrates all the stress on one side of the joint, with the other side under little or no load at all. Obviously, such a joint is considerably weaker than the same bonded area stressed in shear or tension.

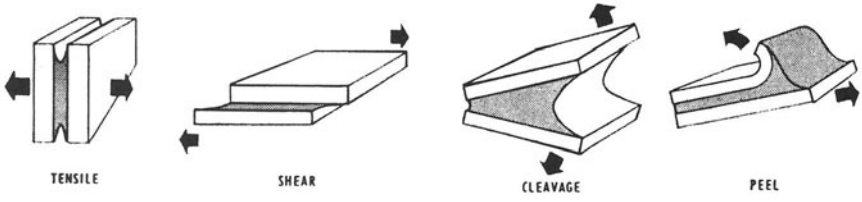


Fig. 49.8.—Four principal types of stress

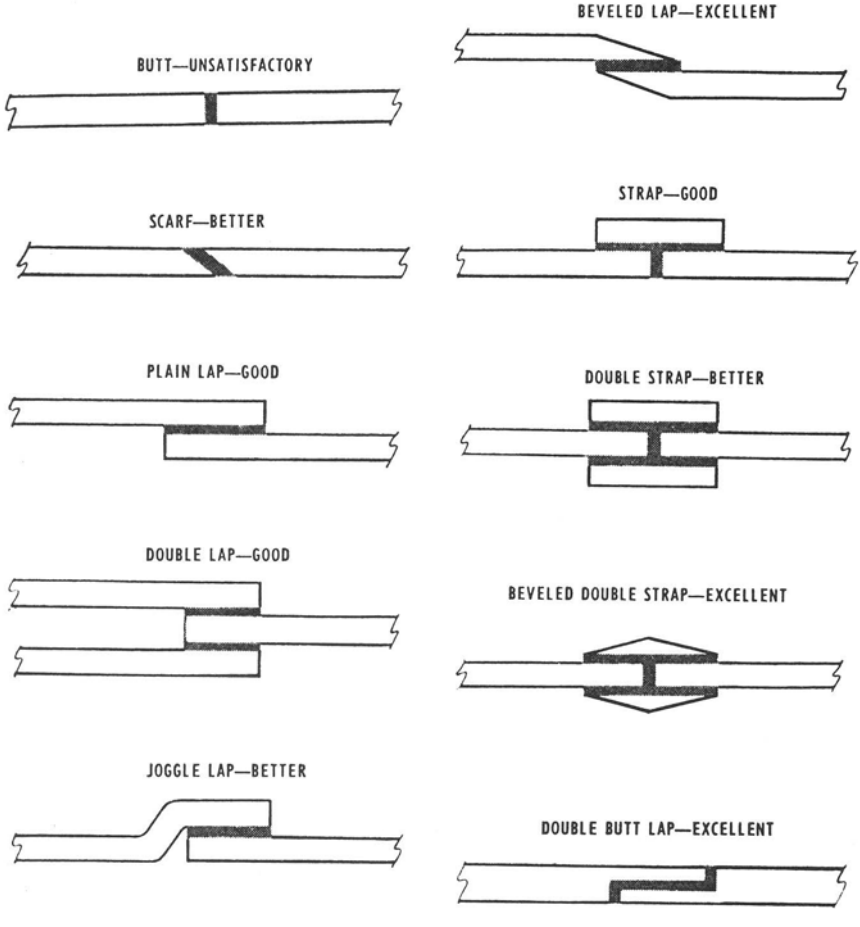


Fig. 49.9.—Types of joints

The situation is even more critical in the peel-loaded joint. An almost infinitely narrow line of adhesive at one edge of the joint must withstand the full load. Failure results from a peel load that is only a fraction as great as the tensile stress needed to rupture a bond.

As noted earlier, however, unidirectional stress is a rarity. Most joints are subjected to a combination of stresses, which may include cleavage or peel.

For example, a straight butt joint may be designed to be stressed strictly in tension, but any slight lateral movement will create cleavage forces. A simple lap joint may be designed to withstand expected shear loads easily, only to have cleavage or peel stresses appear when the joint tilts slightly because the plane of the faying surfaces is not precisely aligned with the direction of the stress.

Such difficulties can usually be avoided or surmounted by selecting the adhesive most able to carry the type of stresses expected and by employing the proper joint design.

Several of the more common types of joints are shown in Fig. 49.9. The butt joint shown at the top is branded "unsatisfactory"; cleavage stresses will be caused by any lateral movement.

Much better results will be obtained with the scarf joint, which offers a larger bonded area to withstand loads. Also, stress concentrations at the edges are minimized by the tapered edges of the adherends. Although widely used in wood bonding, this configuration is difficult to machine in metal.

The simple lap joint, probably the most commonly used type, is adequate for many applications. Its strength can be increased by simply increasing the area of bonded overlap. This overlap, however, should not be increased beyond the point where the joint strength exceeds the yield strength of the adherends being joined.

If joint strength is critical, and if the materials joined are thin enough to be bent by the loads anticipated, the joggle lap is better. It places the plane of the joined surfaces in line with the direction of stress, thus minimizing the possibility of the creation of cleavage forces.

Still better is the beveled lap, whose feathered edges will reduce stress concentrations at the edges of the bond. The thinned edges of the adherends "give" with the bend, absorbing cleavage or peel stress.

If the sections to be bonded are too thin to lend themselves readily to edge tapering, the strap joint or double strap joint will give good results. Even better is the beveled double strap, with its flexible tapered edges.

The types of joints discussed so far are mainly applicable to sheet metal assemblies (although a scarf joint would probably be difficult to execute in light-gage metal). However, adhesive bonding can be used to advantage on extruded, cast or machined components.

For example, the double butt lap shown at the bottom of Fig. 49.9 is a type of configuration that could easily be incorporated into extruded shapes that are to be assembled and bonded. The joint would not only align the load-bearing interfaces with the plane of shear stress, but also provide good resistance to bending stresses. A double scarf lap (not shown) would be even better and would be no more difficult to extrude.

Other basic joint designs that could be applied to extruded or cast shapes are the tongue-in-groove joints shown in Fig. 49.10. (They also serve as good examples of how to avoid the weaknesses of the straight butt joint.)

The landed scarf tongue and groove offers production advantages; its configuration automatically indexes the parts to be mated and the length of joint and thickness of glue line are controlled without costly jigs or fixtures. It is a good design for use in an assembly that will be subjected to high compressive forces. Finally, the tongue and groove produces a clean appearance.

Corner joints similar to those illustrated in Fig. 49.11 can be adhesive bonded if the production setup will permit the machining of assembly components. The end lap is the easier one to produce, but the mortise-and-tenon design will provide better resistance to cleavage stresses created by twisting of the assembly. The provision of adequate space for the adhesive should not be neglected in setting up the machining operation.

Adhesive bonding is especially good for tube joints, two examples of which are shown in Fig. 49.12. The large continuous-bonded areas result in very strong assemblies with a clean appearance.

The tube-and-sheet joint in Fig. 49.12 shows one way of bonding the tube fittings to sheet metal; the sheet has been flanged to boost the resistance to cleavage stresses. Adhesives that cure without pressure are usually needed in these types of joints.

Corner joints involving sheet metal can pose problems for any joining process, especially in products such as shipping containers and truck bodies that are too large for drawing or other press operations. Three design approaches for right-angle corners are shown in Fig. 49.13.

The right-angle butt joint can employ either extruded or formed sheet angles in conjunction with sheet sidewalls. It has good strength in shear, but may be prone to cleavage failure if lateral loads are imposed on the assembly in service. Feathered edges would help, but might be difficult to fabricate.

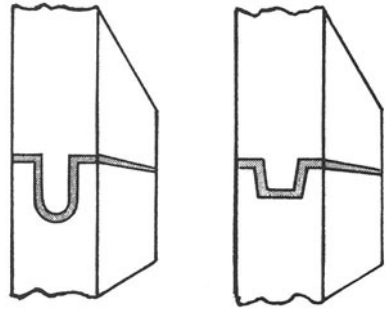


Fig. 49.10.—Butt joints

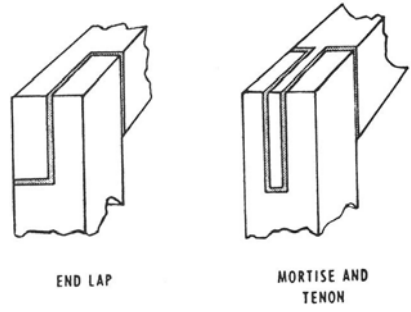


Fig. 49.11.—Corner joints

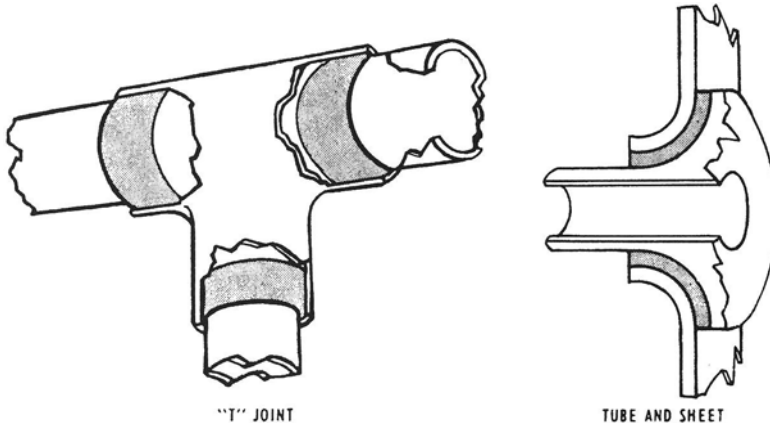


Fig. 49.12.—Tube and pipe joints

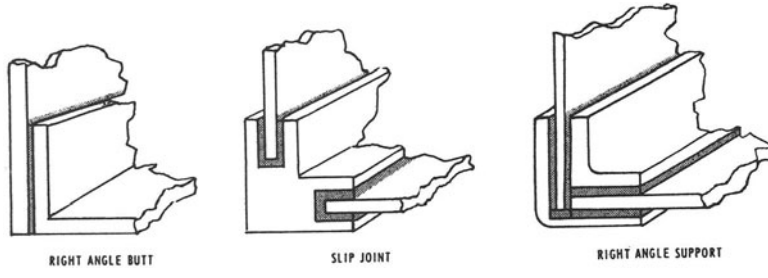


Fig. 49.13.—Corner joints, sheet metal

The slip joint shown in Fig. 49.13 is a better approach, particularly if the assembly will be exposed to a combination of stresses. An extrusion would make an ideal corner member in this joint, which is readily adaptable to a wide variety of applications.

The supported right-angle joint shown in Fig. 49.13 may be unnecessarily cumbersome, considering the design latitude offered by extrusions; it does provide a sturdy construction, however, and may prove more economical on short-run jobs that would not justify a special shape. Standard angles could be used.

With the possible exception of the right-angle butt joint, these corner joints generally require adhesives that cure without pressure. There are many standard epoxy adhesives that may be used. Some are one-part compositions that require a heat cure; others are two-part systems that cure at room temperature. Since they are virtually nonshrinking and do not give off fumes or water vapor during cure, epoxies are ideal for void-filling applications involving nonporous adherends.

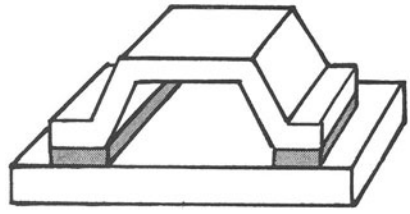


Fig. 49.14.—Sheet and stiffener

The sheet-and-stiffener design shown in Fig. 49.14 illustrates how bonding can simplify production and reduce weight. The usual function of this type of joint is to increase the rigidity of large sheet assemblies without suffering the weight penalty entailed in increasing the sheet thickness. The most familiar example is the riveted sheet-and-stringer construction used by the aircraft industry.

The use of adhesives can reduce the weight of such assemblies, not only by eliminating the rivets but also by permitting use of thinner sheet than would otherwise be practical. Fabrication is simplified since there is no need to punch or drill fastener holes. Problems can arise if the assembly is subjected to considerable flexing in service, which might tend to peel the facing sheet away from the stiffeners. To overcome this effect, the flange of the stiffener could be tapered so that it can "give" with the flexing.

In this connection, it is interesting to note that bonded assemblies comprise nearly 54% of the total area of at least one modern airplane. Bonding is used in about 400 major assemblies ranging from 3 × 13 in. section to 408 in. long tapered spar caps and panels measuring up to 52 × 192 inches. Bonded stiffeners are used on all single curvature panels forming the fuselage skin. Use of bonding resulted in an appreciable reduction of weight, since areas of high stress concentration can be reinforced locally by building up laminations of material.

Extensive testing has indicated that bonded joints have up to 20 times the fatigue life of conventional riveted joints.

SANDWICH CONSTRUCTION

The greatest advantages of structural adhesive bonding are probably realized in sandwich construction. First used in the aircraft industry to answer the demand for a high stiffness-to-weight ratio, the sandwich panel is now widely used throughout industry. Its special characteristics make it equally valuable in the fabrication of walls, truck bodies, refrigerators, cargo pallets and a great many other commercial applications.

Dense sandwich skins, or facings, behave approximately as membranes stabilized by a lightweight core material that transmits shear. Basically, a high stiffness-to-weight ratio is achieved by placing the bending material (the skin) as far from the neutral axis as possible to transmit shear between these two elements.

In a sense, the sandwich is to flat surfaces as the I-section is to a beam. The flanges of the I-section behave as the skins of the sandwich and the web behaves as the core.

Adhesive bonding has made this structurally desirable combination of materials and geometrics possible. And, although additional requirements may have to be met, the adhesive bond in a sandwich performs much the same function as the welds that join the web and flanges of a welded beam; that is, the bond must be strong enough to allow the core to stabilize the skins so that they can act together as a unit.

Vibration and fatigue characteristics are even superior to those of metal-to-metal continuous-surface bonded panels of equivalent weight. Fewer details are required, thus eliminating many of the local "stress risers" and producing a "cleaner" structure, which can be fabricated with simplified tooling at lower overall cost.

The selection of skin and core materials to be used in sandwich construction is dictated by end-use service requirements and, of course, economic considerations, including the cost of fabrication as well as the cost of materials.

Many different skin and core materials may be used as sandwich components. Sheets of metal, plastic and wood are all commonly used as skin materials, Core materials are of three basic types: (1) solid, such as hardwood, balsa, cement-asbestos board or metal; (2) "honeycomb" or corrugated types made of various kinds of metal foils, resin-impregnated paper, reinforced plastics, etc., and (3) open- or closed-cell framed materials such as polystyrene, polyurethane and glass.

Metal foil honeycomb cores are available both with and without perforations in the cell walls. The perforations serve to equalize pressure in the completed panel and act as vents for gases produced during bonding if adhesives that give off volatiles during the curing process are used. (Such cores are also available in truss and waffle configurations, which are formed by corrugating and folding or by pressing to shape between matched dies.)

Expanded plastic cores may be supplied in a formed state that calls for a separate bonding step, or the plastic may be formed in place, thus simultaneously forming its own bond to the skins of the sandwich.

Therefore, special consideration should be given to selecting from among these types of materials the combination that will produce the optimum composite structure for the specific end use. For example, a honeycomb core between thin-gage metal skins will allow for high strength with less weight; a foamed plastic core can be used to assure high insulation values with almost any skin material.

Actual selection, then, depends largely upon what characteristics are demanded of the completed sandwich.

The choice of an adhesive for bonding laminates and sandwich structures is generally based upon several considerations:

1. The type of material to be bonded.
2. Exposure conditions: humidity, salt spray, weathering, immersion in water, fuels, etc., and the loads to be sustained under these conditions.
3. Acoustic or harmonic vibration environment (in which case peel resistance is desirable).
4. Maximum temperature to which the finished sandwich will be exposed in service; how long it will be exposed to that temperature and whether such exposure will be constant or intermittent.
5. Reliability of the bonding process.
6. Production experience with the bonding process.
7. Cost of the bonding material and cost of the required method of processing.

There are several basic types of adhesives with very similar properties that are used in panel manufacture. These basic formulations, moreover, have been modified in various ways to meet specific enviornmental conditions. Consequently, a satisfactory choice can only be made after careful study of design and environmental factors and evaluation of the various properties of the component materials.

ADHESIVE SELECTION

The selection of the proper adhesive for production in any industry depends basically upon specific, detailed answers to three key questions:

1. What materials are being joined?
2. How is the completed assembly expected to perform in service?
3. What method of adhesive application is most suitable?

The fullest amount of detail is necessary in specifying the end-use properties required of the completed assembly. Type of loading (impact, shear, peel, etc.), operating temperature, chemical resistance, weather and climatic resistance, flexibility, different thermal expansion coefficients, taste, odor or toxicity problems, and color match are among the many factors to be considered in describing the bonding application. The ability of the adhesive supplier to solve a bonding problem is in direct ratio to his understanding of *all* aspects of it.

Once the service requirements are known, it is possible, within limits, to select the desired form of the adhesive (liquid, paste, film, etc.) and method of application (trowel, brush, spray, etc.). The adaptability of the chosen adhesive and method of application to production equipment and scheduling may then be determined.

Just as important in adhesive selection is the importance of avoiding "overdesigning." To demand higher strength or greater heat resistance than is actually required for the specific application, for example, may eliminate from consideration many formulations that are more than adequate for the job, and perhaps far less costly, or easier to handle in production.

APPLICATION METHODS

Most industrial adhesives are available in a number of forms: liquids, ranging in viscosity from free-flowing to thick syrups; pastes; mastics; solids; powders, and supported and unsupported films and tapes. Selection from among these is dependent upon: (1) the kind, size and configuration of the materials being joined; (2) the application and assembly equipment available or preferred, and (3) the required speed of assembly.

LIQUID ADHESIVES

Most widely used are liquid adhesives, either solvent dispersed or "100% reactive."

With solvent-dispersed liquids, time must be allotted to allow evaporation of the solvent carrier before the components are mated. This can be done at room temperature or, more rapidly, by force drying with infrared lamps, hot air, oven, etc.

With the solvent-free, 100%-reactive formulations, even nonporous surfaces such as metals and plastics may be mated immediately after application. Adhesives in this group are also particularly useful for joining plastics susceptible to solvent attack.

For small assembly work, liquid adhesives are commonly applied by brush, by short-napped paint roller or by dipping. The more viscous liquids are often applied by trowel, by caulking or pressure-flow guns. In this connection, and when polyethylene squeeze bottles are employed, special precautions should be taken against scraping the polyethylene nozzles across prepared surfaces (e.g., etched aluminum). This action can cause deposition of a waxlike coating which the adhesive cannot wet. Small applicators resembling a ballpoint pen or a hypodermic needle may be used to lay down very narrow glue lines for "spot" application. The silk screen process is also useful for applying an adhesive to selected areas.

Automatic machines which simplify the proportioning and the mixing (or whichever of these activities is required) of many two-component formulations are also available.

For large areas such as those encountered in curtain wall panel fabrication liquid adhesive may be applied by spraying, flow coating, roller coating or troweling. Depending upon the application method selected, consideration must be given to the viscosity and pot life characteristics of the adhesive formulation.

PASTE ADHESIVES

Pastes and other viscous adhesives may be applied with a smooth or serrated trowel, by knife or roller coater, or by various extrusion devices.

Some paste-consistency formulations contain a thixotropic additive that inhibits sag or flow during application and cure. This feature permits their use of vertical or overhead surfaces and may eliminate or significantly reduce the need for special clean-up operations.

SOLID ADHESIVES

Solid adhesives were formerly considered rather difficult to apply but several methods have been developed and are now being used for large-scale production bonding.

One method is to heat the component to a temperature slightly above the melting point of the solid adhesive, then apply the adhesive to the hot surface. Some rod and powder forms of epoxy adhesives are applied in this manner. Specially developed flame spray guns can also be used. However, this method may require powders with a particle size held within severe tolerances and care must be taken to avoid overheating the adhesive during application.

HOT MELTS

Most hot melts are "100% solids" modified synthetic polymer-based adhesives, which liquefy when heated and set when cooled. Such formulations combine the features of "100% solids" liquid adhesives with the advantages of rapid automated application and nearly instantaneous setting.

Currently, their use is largely confined to packaging, bookbinding, laminating and shoe manufacture, but development work is being done on formulations that should find use in other industries.

Hot melts may be heated to the liquid state and applied, or the liquid may be cast onto a substrate for later heat reactivation. Solid forms are processed into various shapes (ropes, pellets, billets, buttons, films, etc.) suited for use with a wide range of equipment specially designed for applying this type of adhesive.

FILM ADHESIVES

Adhesives in film or tape form are extremely simple to use and produce a bond line having relatively constant thickness and adhesive coating weight per unit area, important factors in most bonding applications. Films made from adhesives that are thermoplastic, thermosetting or pressure sensitive are supplied in rolls or sheets that can be blanked out or cut to the required shape and size with a pair of scissors.

Such films are particularly useful for bonding large areas such as honeycomb sandwich panels. Special films are also available for use as adhesive backing for items such as nameplates and escutcheons.

Generally, the film is simply laid in position and reactivated with heat or solvent or, in the case of pressure-sensitive films, by applications of pressure. Films used in applications demanding higher strength at elevated temperatures usually require both heat and pressure to create the bond.

Solvent-reactive and pressure sensitive fiims are intended primarily for bonding performed or large sheets that require only nominal pressure for bonding. These types eliminate the need for special heating equipment and are particularly useful for short-run production or for bonding parts too large to be heated.

Duplex bonding films that combine the poperties of elastomeric adhesives and epoxies have been developed for honeycomb sandwich constructions. The elastomeric component (usually a nitrile phenolic) provides peel resistance and is bonded to the facing. The epoxy fillets around the cell ends, thus increasing both the effective bonding area and the joint strength.

Low-temperature curing, modified epoxy films are also available. They are packaged and stored in dry ice until ready for use, at which time they are allowed to warm to room temperature, then they are applied to surfaces that have been primed or otherwise prepared; the completed assembly is allowed to cure at room temperature or above.

ADHESIVE-COATED FOILS

An allied development by the adhesives industry involves the precoating of copper, aluminum and other metallic sheets, rolls and foils with specially formulated adhesives. Such materials are pre-inspected and cut to size where required, thereby offering the ultimate user great potential economies in handling and labor.

For example, adhesive-coated copper in sheet and roll form has been used extensively in the manufacture of etched and stamped printed circuits. The die stamping method of mass producing printed circuits permits the bonding of adhesive-coated copper foil to a wide range of plastic base materials in addition to the conventional phenolics and epoxies used in etched circuitry.

PRIMERS

Certain end-use service requirements may call for the use of an adhesive primer to provide flexibility, shock resistance and peel resistance for improved strength characteristics. Primers may also be used to wet or penetrate the adherend better than the adhesive itself or to protect a treated surface of a substrate prior to the application of adhesive. Most primers are low-viscosity solutions commonly applied by spraying, although brush application may be a satisfactory substitute when relatively small areas are to be coated. In some cases, roll coating or dipping may be employed. Several primer coats may be required to build up the desired thickness, particularly if the adherends are porous. Air drying and full or partial curing are generally necessary prior to further processing.

SURFACE PREPARATION

Frequently, the weakest link in the chain constituting a high-strength bond is the "interfacial bond" between the adhesive and the adherends. Exactly the right adhesive may have been selected for the job, the joints may have been designed property, and correct application and cure procedures and equipment used; however, if the adherends are not properly cleaned and prepared to receive the adhesive, the bond may fail.

Proper pretreatment is essential whether metal is to be bonded to metal or to another material. Many plastics, for example, may bear a light film of mold release that will prevent the adhesive from wetting the bonding surface.

The extent of surface preparation depends chiefly upon that nature of the material and also, to some extent, on whether maximum strength and durability are required of the resulting bonded joint. For some less critical applications, a solvent-wipe or washing in a detergent solution may prove to be adequate. Care should be taken, however, to remove all cleaning agents from the surface by rinsing thoroughly and drying completely prior to the application of the adhesive.

It is also important to avoid recontamination of the surfaces during processing. Components should be handled with clean tongs or hooks, and all contact with the bonding area should be avoided. Priming, bonding or a combination of these should be accomplished as soon after surface treatment as possible. In the interim, parts should be stored in a clean, dry place.

METAL PREPARATION

Metal surfaces may be cleaned by chemical means, by mechanical abrasion and by degreasing. These are the three basic methods but some variation in procedures is advised by various adhesives suppliers, and it is wise to follow their recommendations carefully.

Metal faying surfaces should be free from scale, deep scratches, burrs and other irregularities. Cleaning should be done after machining, heat aging, welding, sandblasting, abrading, deburring, polishing or any similar treatment that might affect the condition of the metal surface.

The cleaning method selected should be reproducible and controllable, practical from a production standpoint and economical. In addition, it should satisfy the following requirements:

1. It should remove all contaminants from the surface.
2. It should leave the surface chemically receptive to the adhesive (or primer) to give maximum wetting characteristics.
3. It should not form weakly adhering surface compounds or compounds that are cohesively weak.
4. It should not remove excessive amounts of metal, cause embrittlement or corrosion, or form a surface prone to environmental attack.

To obtain optimum strength characteristics, surface cleaning is usually done in a series of steps, including: (1) vapor degreasing with trichlorethylene or perchlorethylene; (2) drying; (3) chemical cleaning (e.g., an alkaline precleaning and rinse followed by an acid etch); (4) careful rinsing in clean (preferably de-ionized) water; (5) air drying, force drying, or a combination of these.

The vapor degreasing solution should be checked periodically for oily contaminants and decomposition products. Solvent degreasing is rarely recommended, but if it is used, care should be taken to use plenty of clean cloths or disposable tissues.

The recommended composition of the chemical bath varies from one supplier to another and also depends upon the kind of metal being treated. Stress-corrosion cracking of titanium attributable to degreasing solutions containing chlorinated solvents has been reported.

The use of an overflow tank serves to avoid the buildup of an oil slick on the surface of the rinse water. The presence of such contamination can negate all the previous cleaning steps.

Force drying in an oven is preferred since this reduces the possibility of recontamination, which could easily result from impurities in the atmosphere if the slower air-drying procedure is followed.

Mechanical abrading is sometimes used to clean metal and increase the effective bonding area by roughening the surface. Cleaning by this means is not usually as effective as chemical treatment but may be adequate in certain cases. If abrasive belts or disks are used, there may be danger of contaminating the surface with grease-base lubricants. Therefore, it is wise to follow abrading with degreasing.

If magnesium is involved, it is preferable to use one of the corrosion-inhibiting pretreatments developed specifically for this metal. It is possible to clean magnesium mechanically, but care must be taken to prevent the grindings, or magnesium powder, from coming into contact with an open flame. Such pretreatments should not be used for structural magnesium joints or for those that will be subjected to severe environments. Some treatments for magnesium have been found to be effective with certain adhesives but not with others.

Sandblasting may be used on metal thick enough to resist distortion. However, oil can get into compressed air lines, so a check for contamination should be made and the parts degreased if necessary.

PREPARATION OF OTHER MATERIALS

Rigid plastics can be lightly sanded to reduce gloss and to remove all traces of mold release compound, then wiped with an oil-free solvent. Certain rigid types (e.g., nylon, polyacetal) are difficult to bond and may require chemical treatment.

Wood may be sanded smooth or planed, but extreme care should be taken to remove all sawdust or other foreign matter from its surface.

Glass is easily cleaned by wiping with isopropyl alcohol, although joint durability can be greatly enhanced, particularly in moist environments, by cleaning with laboratory glassware cleaning solutions or with 30% hydrogen peroxide.

Concrete should be wire brushed or etched with hydrochloric acid. Such surfaces usually require special priming. The adhesive supplier's recommendations should be followed carefully in this respect.

INSPECTION OF PREPARED SURFACES

The affinity of a clean metal surface for water is the basis for the most common test for a chemically clean surface: the "water-break" test. If pure water from the rinse bath spreads smoothly over the metal surface as it runs off, it serves as proof that the surface is clean. If it collects in droplets, there is probably a thin film of oil on the surface. The oil should be removed completely and the water-break test tried again.

WATER DROP TEST (CONTACT ANGLE CHECK)

If water drops placed on a flat, dry, treated surface spread rapidly and uniformly, this indicates that the surface is free of grease. If the contact angle of the water drops is low (measuring 10° or less), the surface has been cleaned adequately to remove greases, oils and other nonpolar contaminants. When contact angle measurement is used as a quality-control device, inspection should be made immediately after the metal has been dried.

If the water remains in droplet form, the surface has not been suitably prepared and the piece should be reprocessed.

INSPECTION OF TREATING SOLUTIONS

A thorough check of treating-solution concentration should be made periodically. Special consideration should be given to the rate of metal processing over a given period of time. Failure to control the concentration of strong acid or alkali solutions may result in excessive loss of metal. Aluminum and magnesium alloys are more reactive than stainless steel and titanium alloys, and exposure of these metals to high concentrations of acid or alkali may affect adhesion characteristics with certain kinds of adhesives. The time between concentration checks depends upon the rate of exhaustion of the treating solution.

ASSEMBLY AND CURE

The procedures and equipment used for assembly and cure of bonded components depend upon: (1) the type of adhesive used; (2) the type, size and configuration of the assembly, and (3) the end-use service requirements of the completed assembly (strength, heat resistance, outdoor weathering, etc.).

ASSEMBLY

"Open time" (the time that must be allowed for the evaporation of volatile solvent or other carrier after the adhesive has been applied and before the parts can be mated) is an important governing factor when solvent-dispersed adhesives are used. Since this span varies with different formulations and even within the same chemical family, it is essential that the adhesive manufacturer's recommended open time for a given adhesive be provided for in the production sequence. Evaporation of the solvent may be done at room temperature or be speeded by moderate heating with infrared lamps, a hot air oven, or whatever means is recommended by the adhesive manufacturer.

If there is porosity sufficient to allow the solvent to escape through one or both of the components, the parts may be mated during the open-time period. Such assemblies must not be heated to the setting or curing temperature, however, until the open-time span has elapsed and the solvent has had time to evaporate. At the other end of the bonding range, it is also essential that coated parts be mated before the "tack life" of the adhesive has expired.

Parts that have been coated with 100%-reactive adhesives may be mated immediately after application. Mating may also be delayed, but it must be done before the reactive adhesive starts to "body" or thicken excessively.

POSITIONING

Provision should be made for positioning the components for mating and for holding them in place while the assembly cures or sets.

Positioning is particularly important when the "contact bond" type of adhesive is used. Since a strong bond is created instantly upon contact between two coated, properly dried surfaces when they are mated, care should be taken to align the parts accurately. The use of release sheets (silicone-treated paper, for example) often proves helpful in avoided accidental premature contact. With formulations of less aggressive tack, positioning may not be as critical, since it may be possible to readjust the parts.

Assembly fixtures are frequently used for positioning. These range from simple jigs or locating rivets, pins or bolts, to self-contained equipment which also includes provision for applying pressure, heat or both. The design of such equipment is often dependent upon the amount of heat and/or pressure needed to cure the adhesive being used and, of course, upon the size and configuration of the assembly.

Pressure-sensitive tape may be used to hold parts in position, provided it can withstand the curing temperature. Tapes are particularly useful with epoxy-based formulations that cure at room or at relatively low elevated temperatures. Moreover, since the epoxies require only contact pressure during cure, tape may be used for many applications, not only to position the parts but also to provide adequate pressure.

When adhesives that produce a strong bond without reliance on heat or pressure are used, or in applications where strength requirements are not severe, positioning and mating represent the final steps in bonding. With other types of formulations, or where bonds must meet higher requirements of strength, heat resistance or both, the adhesive may be cured or set by: (1) heat alone, (2) pressure alone, (3) both heat and pressure or (4) by heating the adhesive coating before mating and combining the components under pressure (as is done in "hot" contact bonding).

In some applications, it may be desirable to advance the cure by heating the adhesive before mating the components. If cure is advanced too far, however, adhesive flow and wetting of the adherends will be impaired.

PRESSURE

With certain adhesive formulations, it is necessary to maintain adequate pressure during cure in order to:

1. Produce a uniformly thin glue line in order to achieve optimum strength characteristics over the entire bonded area.
2. Facilitate flow or spreading of viscous adhesives.
3. Counteract any internal pressure buildup resulting from release of volatiles so that proper adhesive/adherend contact is maintained.
4. Counteract minor imperfections in the faying surfaces.
5. Counteract variations in flatness or thickness of the adherends.
6. Compensate for pressure loss owing to adhesive squeeze-out, solvent loss and thermal dimensional changes.

Phenolic-based adhesives generally require curing pressures in the 300 psi range, although adequate bonds may be attained with pressures as low as 50 psi.

Flat panels coated with neoprene contact bond adhesive are generally mated by passing through rollers under as much pressure as the components will withstand without crushing. For assemblies of such size or shape that they cannot be processed in this manner, a weighted hand roller or other pressure device can be used.

During the cure of skin-to-core bonds in the fabrication of sandwich panels, the upper pressure limit is governed by the compressive strength of the core material. The lower limit is set by the requirement of the adhesive formulation employed. For sandwich panels containing solid inserts or edgings, special fixtures may be used so that higher pressure can be applied over specific areas of these continuous-surface bonds.

Throughout the curing cycle, pressure should be kept as uniform and constant as possible over the entire bond area. If necessary, pressure pads of compressible material should be used to build up irregular surfaces so that pressure is kept uniform. In some cases compressible pads made of rubber, wood or hardboard are used to compensate for variations in the dimensions of sheet material and fixtures. The mass of such materials should be kept as low as possible to reduce its heat capacity and insulating effect. Matched tooling, which would require the use of a large amount of packing material, is not often used for curved panels. Rather, a male or female tool, used in conjunction with the vacuum bag or autoclave technique, is generally preferred.

In vacuum-bag curing, pressure is applied by drawing a vacuum under a rubber sheet or other impermeable, flexible material that has been sealed and clamped along the edges of the assembly.

CURING TEMPERATURE

Since variations in the heat conductivity of the components influence the degree of heat reaching the adhesive layer, it is important that curing temperature be measured at the glue line.

Most phenolic-based structural adhesives require elevated curing temperatures, generally from about 300°F (149°C) to as high as 400°F (204°C), for periods ranging from 30 minutes to 2 hours. Many one-part epoxy-based adhesives can be cured at temperatures as low as 250°F (121°C). A great number of two-component epoxy systems cure at room temperature, although properties are generally improved by curing at elevated temperatures.

When neoprene contact-bond adhesives are used, the adhesive-coated surfaces are frequently heated during the drying (solvent-evaporation) cycle and mated under pressure while still hot. Where lower physical properties can be tolerated, the coating may be dried and the components mated "cold" under pressure. Results using this method tend to be more variable, however, than those obtained when the "hot" contact bonding procedure is followed.

As a general rule, the higher the curing temperature, the shorter the cure time; conversely, the lower the temperature, the longer the cycle. Even the room-temperature-curing epoxies may be heated to moderately elevated temperatures to speed the cure to a matter of minutes instead of hours.

In some instances, increasing the time of cure at elevated temperatures has been found to improve bond strength of the assembly at high operating temperatures. Post-curing (additional heating or the bonded assembly without applying pressure) can also improve the heat resistance of the bond. For best results, however, the temperature-time recommendation of the adhesive manufacturer should be followed.

OVENS

For heat curing when only moderate pressure or simple positioning of the parts is required, ovens represent a widely used and inexpensive method. They can be heated by gas, electricity or steam. Neither exposed flame nor electrical elements should be used with adhesives that give off flammable vapor or solvent during cure. Ovens should be vented, temperature-controlled for uniformity of heat throughtout the entire area and fitted with an air-circulating fan.

Infrared lamps or ovens are commonly used for force drying and heating of neoprene contact-bond formulations.

PRESSES

For flat assemblies, hydraulic platen presses are frequently used for applying heat and pressure. These are usually heated by electricity or are cored to heat by high-pressure steam, hot water or other heat-exchange fluid.

When the work is placed into the press at temperatures below about 150°F (66°C), it is called "cold entry." Entry at the full curing temperature is known as "hot entry." In general, adhesives containing volatiles, or releasing volatiles by chemical reaction perform better when cold entry is employed. Certain adhesives are also affected by the rate of temperature rise or heat input. These factors influence the chemical reactions, the flow and the density of the cured adhesives of volatile-containing types. For example, cold entry and a rate of heat input of less than 10°F (12.2°C) per minute for certain nitrite-phenolic film adhesives result in better shear strength at high operating temperatures. Other adhesives, such as epoxy-phenolics, require either stepped heat input or pressure release—"breathing"—at certain temperature levels to allow the escape of volatiles. Nonvolatile adhesives, such as epoxies, are not affected to any great extent by entry temperature or by the rate of heat input.

If the length of the assembly is greater than that of the platen, the assembly may be moved along and pressed in steps. If this is done, care must be taken to keep the unbonded section outside the press cool enough to prevent excessive advancement or pre-curing of the adhesive.

Large autoclaves are used for bonding aircraft assemblies and other extremely large parts. The typical operating range of such autoclaves is 200 psi maximum pressure and 350°F (177°C) maximum temperature. Pressure is generally provided by compressed air. Heating may be done with live steam or dry heat through steam tubes or electrical elements.

Vacuum pressure, frequently applied in conjunction with the autoclave, serves to assure positive mating of component parts before closing the autoclave.

TESTING PROCEDURES

Many different testing procedures are used to determine whether an adhesive bond meets all the fabricator's requirements; the end use of the bonded assembly governs the kinds of tests that are performed.

Tests may range from simple empirical procedures to the carefully controlled and frequently performed multistep inspection and testing of individual components, fabrication processes and bonded assemblies used during the production of aircraft and missiles.

For example, flexible plastic foam sound-deadening material bonded to a metal housing for interior use at room temperature can be adequately checked by pulling the foam by hand. If the foam tears and the bond remains intact, the bond strength, although of a low order as compared to that required for metal-to-metal bonds in aircraft structures, is completely satisfactory for the specific application.

As end-use service requirements become more rigorous, so do testing procedures. Military and commercial test specifications exist for a number of bonding applications. Many more procedures have been developed by manufacturers to supplement these, or to meet their individual needs.

To illustrate, the curtain wall industry has no "official test" accepted and used by all fabricators, although most use the Forest Products Laboratory (FPL) test cycles that are also described in ASTM D1037. Others perform still further testing, with emphasis on specific physical properties in the areas they feel will be most important when their products are put into use (freeze/thaw cycles, extended water immersion, applied load tests, peel strength evaluation, etc.).

Thus, testing in many kinds of production consists of accelerated, simulated or actual use tests of the end product devised by the individual manufacturer or an industry group. For this reason, industry associations may prove to be good sources of information on testing procedures.

Aircraft manufacturers in particular have done much toward developing and standardizing the test procedures used throughout that industry; these test procedures may also be followed (in part or as a whole) with other metal-bonding applications where the physical characteristics of the bonded assembly are of critical importance.

For example, such testing in the aircraft industry may be necessary for any or all of three reasons:

1. The evaluation of the strength or environmental resistance of individual elements of the bonded assembly; that is, the face sheet, the core (when used), and the adhesive;

2. The evaluation of the part or structure as a whole to confirm the design application and method of fabrication;

3. The testing of adhesives and finished parts as a necessary function of receiving inspection, process control or final inspection to assure the performance and reliability of the finished product.

TESTING OF INDIVIDUAL ELEMENTS

Normally, the properties of the face sheet or other solid metallic elements of the bonded structure are well known and need not be tested. Suppliers of core materials have published data on the properties of their products. Adhesive manufacturers also have performance data under various environmental conditions. Therefore, testing of individual elements is not normally necessary in order for the designer or manufacturer to develop a satisfactory part.

If an adhesive is to be used with a metal for which no performance data exist, or if it is to be used in an unusual environment, it must be subjected to at least a limited amount of testing. Simple overlap shear specimens can be used to evaluate the compatibility of a metal surface condition with an adhesive system, and to evaluate the effect of any unusual environmental exposure. A standard lap shear test method is given in ASTM D1002.

If an adhesive is to be used in a structural joint under stress in a certain environment, specimen joints should be subjected to both stress and environmental exposure conditions simultaneously. Occasionally this procedure produces results quite different from those obtained by any other method.

PROCESS CONTROL AND QUALITY ASSURANCE TESTING

Process control usually requires 100% inspection of all cleaning and processing equipment, evaluation of all materials and control of storage time and conditions.

Adhesives and primers should be tested to assure conformities to the requirements of the design, to the user's specification or to the adhesive manufacturer's specification. Certified test reports from the manufacturer are generally accepted in lieu of receiving inspection tests.

Periodic tests should be performed using representative coupons to determine that cleaning, mixing and bonding procedures are adequately controlled. Overlap shear test specimens are generally satisfactory for control testing or mixing, priming and bonding. Peel tests should be performed to ascertain the adequacy of cleaning procedures. The "climbing drum" method described in MIL STD-401, MIL HDBK-23 or ASTM D1781 has been found satisfactory for this purpose. Additional government specifications are listed at the end of this chapter.

Such testing is necessary because of the difficulty in inspecting the strength or quality of the adhesive bond in individual parts.

The frequency of testing is dependent upon the volume of parts produced. However, many plants employing adhesive bonding in critical applications perform lap shear tests at least once a day and peel tests at least once a week. In addition, any parts rejected for dimensional reasons or because of damage to a portion of the part should be sectioned, examined and tested.

EVALUATION OF FABRICATED PARTS

After the mechanical and processing properties of an adhesive system have been determined through destructive laboratory coupon testing, the designer remains concerned with the ability of manufacturing departments to duplicate these strengths. Therefore, rather complete testing of the first part or the first few parts of the production run is recommended.

Loads should be applied in the same manner in which the part will be loaded in use. However, actual service conditions are often impractical to simulate completely because of difficulty in holding the parts and in applying loads in different planes at one time. In cases involving multidirectional loads, design limit loads may be applied in each plane individually, with the part then loaded to failure in the most critical load path to determine whether it meets the design ultimate strength.

When it is impossible to load a complete part because of geometry or difficulty in mounting it for test, most companies fabricate test specimens as an integral part of the assembly or as separate panels processed in the same manner as the part. Strength values obtained using such specimens closely represent the actual strength of the part. This procedure also serves to provide close control over materials and processing equipment.

In case of sandwich construction, edgewise compression and beam loading tests, the procedures in MIL STD-401 give the most representative results for determining adequate strength. These tests are also covered by ASTM C364 (edgewise compression) and ASTM C393 (flatwise flexure). When metal-to-metal bonds are involved, overlap shear elements should be tested.

Many of the available nondestructive test methods and proof-loading methods give an indication of a complete bond, and even an indication of the bond strength. Some of these are outlined in paragraph 5.2 of MIL HDBK-23, and include visual inspection for blisters or bulges, tapping or using a spur wheel to detect changes in tone on a panel face and various ultrasonic methods.

INSPECTION METHODS

Ultrasonic Inspection

Numerous research programs are currently underway to develop ultrasonic instruments to measure the integrity of bonded assemblies.

The uses and descriptions of these instruments are complex, and suggested sources of information are: *The Application of Nondestructive Testing or Plastics,* by Alfred M. Anzalone, Office of Technical Services, U.S. Department of Commerce; and *Evaluation of Ultrasonic Test Devices for Inspection of Adhesives Bonds,* Materials Division, Bureau of Weapons, Department of the Navy.

Proof-loading Devices

Proof-loading devices include flatwise tension testing by vacuum, the vacuum-induced concentrated load tester and the Forest Products Laboratory multiple proof loader.

Other Nondestructive Test Methods

Considerable research is currently being conducted on X-ray and other radiographic methods for inspecting adhesive bonds. The major problem with this type of inspection is that radio-gaging techniques have not proven feasible for non-homogeneous materials.

A detailed investigation of these methods shows that considerable time and expense is involved in the more sophisticated methods; the effectiveness of any of the methods is related to the individual skill, experience and interpretation of the personnel performing the testing. Methods and frequency of testing may be simplified or reduced when higher margins of safety are designed into the part, and the bond quality is less critical.

SAFE PRACTICES

Safety precautions must be observed with some types of adhesives. Corrosive materials (e.g., etchants), flammable liquids (e.g., solvents) and toxic materials (e.g., certain resins, hardeners, diluents and solvents) are commonly used in adhesive bonding; therefore, manufacturing operations should be carefully supervised to enforce proper safety procedures and to make sure that workers are provided with all necessary protective devices and clothing.

GENERAL REQUIREMENTS

Flammable Materials

All flammable materials should be stored and issued in suitably labeled safety cans or tightly sealed drums in order to prevent fires during storage and use. Solvents and flammable liquids should not be used in confined areas unless there is adequate ventilation. When solvents are used in trays, safety lids should be provided. Flames, sparks or spark-producing equipment must not be permitted in the area where flammable materials are being handled. Fire extinguishers that are frequently inspected and properly maintained should be readily available.

Toxic Materials

Toxic materials should not be used in confined areas unless ventilation is provided. If ventilation is not adequate, suitable respiratory equipment should be used.

Some uncured adhesives and associated chemicals can cause skin irritation, especially to hypersensitive individuals. For the normal individual, proper handling methods that minimize skin contact with the adhesive should be sufficient. Inasmuch as there is no way of telling, beforehand, which individuals are hypersensitive, it is mandatory that protective equipment, protective creams or both be used to avoid skin contact with certain types of formulations.

The reactive diluents present in, or sometimes added to, many epoxy-based adhesives can accentuate the irritating properties of these formulations. Some amine curing agents (hardeners) are strong bases and can produce chemical burns on contact with the skin. In addition, repeated excessive exposure to vapors may result in skin irritation.

Factors to be considered in determining the extent of precautionary measures to be taken include: the frequency and duration of exposure, the degree of hazard associated with the specific adhesive, the solvent or curing agent used, the temperature at which the operations are carried on and the potential evaporation surface exposed at the work station. All these elements should be evaluated in terms of the individual operation.

Dust

Machining of metals and plastics, associated with the manufacture of bonded assemblies, may introduce various kinds of dust into the atmosphere. Use should be made of an effective exhaust system, respirators or both in order to prevent inhalation of dust particles and to eliminate potential explosion hazards.

Since surface cleanliness is directly related to effectiveness of the bond, it is particularly desirable to avoid doing machining in the area where the bonding operation is performed, if this is possible.

Dust from fibrous glass reinforced plastic laminates can be irritating to the skin, and the use of a protective skin cream is recommended when such dust is present.

PRECAUTIONARY PROCEDURES

A number of measures are recommended in the handling and use of adhesives and auxiliary materials.

Personal Hygiene

1. Instruct personnel in procedures designed to minimize skin contact with solvents, curing agents and uncured base adhesives.
2. Provide workers with showers, wash bowls, mild soaps, clean towels, refatting creams and clean coverall service.
3. Allow adequate time for workers to clean up before break periods (particularly before they eat) and at quitting time.

Protective Devices

1. Plastic or rubber gloves should be worn whenever the possibility of skin contact with potential irritants exists. When gloves become contaminated, they should be discarded or reconditioned by washing first in acetone or methyl ethyl ketone, then in soap and water.
2. Protective clothing (coveralls) should be worn by all who work often or continuously in bonding areas. Heavy-duty aprons should be used as needed for additional protection. Soiled clothing should not be worn.
3. Protective creams may prove effective in certain operations when contact is only occasional.
4. Full face shields should be used for eye protection whenever the possibility of splashing exists.

Handling Procedures

1. Adhesives containing volatile constituents should be mixed under a ventilated hood. In general, it is preferable that mixing operations be done by a limited number of experienced workers.
2. When such adhesives are used, assembly and curing operations should be confined to areas provided with exhaust ventilating facilities to carry off released volatiles.
3. Use disposable paper or film on bench tops or floor areas where drips and contamination may be anticipated.
4. Follow standard good housekeeping practices at all times.

DEFINITIONS*

Adherend—A body which is held to another body by an adhesive. (See also **Substrate.**)

Adhesive, Pressure-Sensitive—An adhesive made so as to adhere to a surface at room temperature by briefly applied pressure alone.

Bond Strength—The unit load applied in tension, compression, flexure, peel, impact, cleavage or shear, required to break an adhesive assembly with failure occurring in or near the plane of the bond.

Catalyst—A substance which markedly speeds the cure of an adhesive when added in minor quantity as compared to the amount of the primary reactants. (See also **Hardener** and **Inhibitor.**)

Cleavage Strength—The tensile load per unit width required to cause separation of a bonded test specimen when stressed normal to the glue line along one edge of the joint.

Contact Bonding—See **Tack, Dry.**

Creep—The dimensional change with time of material under load, following the initial instantaneous elastic or rapid deformation. Creep at room temperature is sometimes called cold flow.

Cure—To change the physical properties of an adhesive by chemical reaction, which may be condensation, polymerization or vulcanization; usually accomplished by the action of heat and catalyst, alone or in combination, with or without pressure.

Curing Agent—A widely used term synonymous with Hardener, Accelerator and Activator. (See **Hardener.**)

Delamination—The separation of layers in a laminate because of failure of the bond, either in the adhesive itself or at the interface between the adhesive and the adherend, or because of cohesive failure of the adherend.

Dry—To change the physical state of an adhesive on an adherend by the loss of solvent constituents by evaporation or absorption, or both. See also **Cure** and **Set.**

Dry Tack—See **Tack, Dry.**

Drying Temperature—See **Temperature, Drying.**

Drying Time—See **Time, Drying.**

*These terms and definitions are presented as a guide to trade terminology. They are not intended to imply acceptance as standard by any recognized society, although they may include those currently approved by ASTM Committee D-14 on Adhesives.

Elongation—The increase in length of a material when it is subjected to tensile stress. It is expressed as a percentage of the original length.

Emulsion—A suspension of fine droplets of one liquid in a second liquid with which it is incompletely miscible.

Extender—A substance, generally having some adhesive action, added to an adhesive to reduce the amount of the primary binder or filler required per unit area. (See also **Filler.**)

Extrusion—A method whereby a liquid or paste adhesive material is forced through a shaping orifice under pressure, as in a flow or caulking gun.

Filler—A relatively nonadhesive substance added to an adhesive to improve its working properties, permanence, strength or other qualities and often to reduce cost. (See also **Extender.**)

Hardener—A substance or mixture of substances added to an adhesive to promote or control the curing reaction by taking part in it. The term is also used to designate a substance added to control the degree of hardness of the cured film. (See also **Catalyst.**)

Impact Strength—(1) The ability of a material to withstand shock loading; (2) the energy absorbed by an adhesive joint when shared by a single blow.

Inhibitor—A substance which slows down chemical reaction. Inhibitors are sometimes used in certain types of adhesives to prolong storage or working life.

Joint—The location at which two adherends are held together with a layer of adhesive. (See also **Bond.**)

Joint, Lap—A joint made by placing one adherend partly over another and bonding together the overlapped portion. (See also **Joint, Scarf.**)

Joint, Scarf—A joint made by cutting away complementary angular segments of two adherends and joining the cut areas in such a manner that one adherend forms a continuous extension of the other. (See also **Joint, Lap.**)

Joint, Starved—A joint which has an insufficient amount of adhesive to produce a satisfactory bond. (This condition may result from too thin a spread to fill the gap between the adherends, excessive penetration of the adhesive into the adherend, too short an assembly time or the use of excessive pressure.) Also called "starved glue line."

Laminate—A product made by bonding together two or more layers of material or materials.

Lamination—The process of preparing a laminate.

Liquid Resin—See **Resin.**

Peel Strength—The average tensile load per unit width of bond line required to produce progressive separation of two bonded adherends where at least one of the adherends is flexible.

Permanence—The resistance of an adhesive bond to deteriorating influences.

Plasticity—A property of adhesives which allows the material to be deformed continuously and permanently without rupture upon the application of a force that exceeds the yield value of the material.

Pot Life—See **Working Life.**

Pressure-Sensitive Adhesives—See **Adhesive, Pressure-Sensitive.**

Primer—A coating applied to a surface, prior to the application of an adhesive, to improve the performance of the bond. (Such a coating may also serve to protect cleaned metal surfaces until the bond is made.)

Resin—A solid, semi-solid or pseudosolid organic material which has an indefinite and often high molecular weight, exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally. (Note: **Liquid Resin**—An organic polymeric liquid which when converted to its final state for use becomes a resin.)

Retarder—See **Inhibitor.**

Scarf Joint—See **Joint, Scarf.**

Set—To convert an adhesive into a fixed or hardened state by chemical or physical action, such as condensation, polymerization, oxidation, vulvanization, gelation, hydration, or evaporation of volatile constituents.

Setting Time—See **Time, Setting.**

Shear Strength—(1) A measure of the ability of an adhesive bond to withstand shear stress; (2) the stress at which an adhesive bond fails in shear.

Shelf Life—See **Storage Life.**

Solids Concentration (or **Content**)—The percentage by weight of the nonvolatile matter in an adhesive.

Solvent—The volatile liquid in which an adhesive is dissolved or dispersed.

Spread—The quantity of adhesive per unit joint area applied to an adherend. It may be expressed in weight per unit area (pounds/1000 square feet) or in area covered per volume (square feet/gallon). (1) **Single Spread** refers to application of adhesive to only one adherend of a joint. (2) **Double Spread** refers to application of adhesive to both adherends of a joint. (Also referred to as **"one-side"** and **"two-side stick."**)

Starved Joint—See **Joint, Starved.**

Storage Life—The period of time during which a packaged adhesive can be stored under specified temperature conditions and remain suitable for use. Sometimes called **Shelf Life.** (See also **Working Life.**)

Strength—See **Cleavage, Impact, Peel, Shear, Tensile.**

Substrate—A material upon the surface of which an adhesive-containing substance is spread for any purpose, such as bonding or coating. (See also **Adherend.**)

Tack—The property of an adhesive that enables it to form a bond of measurable strength immediately after adhesive and adherend are brought into contact under low pressure.

Tack, Dry—The property of certain adhesives, particularly nonvulcanizing rubber adhesives, to adhere on contact to themselves at a state in the evaporation of volatile constituents, even though they seem dry to the touch.

Tack Life—Synonymous with Tack Range.

Tack Range—The period of time in which an adhesive will remain in the tacky-dry condition after application to an adherend, under specified conditions of temperature and humidity.

Temperature, Curing*—The temperature **at the "glue line"** to which an adhesive or an assembly is subjected to cure the adhesive. (See also **Temperature, Drying** and **Temperature, Setting.**)

Temperature, Drying—The temperature to which an adhesive on an adherend or in an assembly is subjected to evaporate the solvent. (See also **Temperature, Curing** and **Temperature, Setting.**)

Temperature, Setting†—The temperature **at the "glue line"** to which an adhesive or an assembly is subjected to set the adhesive. (See also **Temperature, Curing** and **Temperature, Drying.**)

Tensile Strength—The maximum tensile stress which the joint is capable of sustaining.

Thermoplastic—A plastic or polymer which is capable of being repeatedly softened by heat and hardened by cooling.

Thixotropy—A property of adhesive systems to thin upon isothermal agitation and to thicken upon subsequent rest. In the adhesives industry products which remain static in consistency (e.g., pastes, mastics) even when agitated, are frequently (and incorrectly) referred to as "thixotropic."

Time, Curing‡—The period of time during which an assembly is subjected to heat or pressure, or both, to cure the adhesive. (See also **Time, Joint, Conditioning** and **Time, Setting.**)

Time, Drying—The period of time during which an adhesive on an adherend or an assembly is allowed to dry with or without the application of external heat or pressure, or both. (See also **Time, Joint Conditioning** and **Time, Setting.**)

Time, Joint Conditioning—The time interval between the removal of the joint from the conditions of heat or pressure, or both, used to accomplish bonding and the attainment of approximately maximum bond strength. Sometimes called **Joint Aging Time.**)

Time, Setting—The period of time during which an assembly is subjected to heat or pressure, or both, to set the adhesive. See also **Time, Curing; Time, Joint Conditioning;** and **Time, Drying.**)

Vulcanization—A chemical reaction in which the physical properties of a rubber are changed in the direction of decreased plastic flow, less surface tackiness, and increased tensile strength and chemical resistance by reacting it with sulfur or other suitable agents.

Working Life—The period of time during which an adhesive, after mixing with catalyst, solvent or other compounding ingredients, remains suitable for use. (See also **Storage Life.**)

Yield Value—The stress (either normal or shear) at which a marked increase in deformation occurs without an increase in load.

*The temperature attained by the adhesive in the process of curing (adhesive curing temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly curing temperature).

†The temperature attained by the adhesive in the process of setting (adhesive setting temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly setting temperature).

‡Further cure may take place after removal of the assembly from the conditions of heat or pressure, or both.

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MIL-C-7811	Sandwich Construction, Aluminum Alloy Faces, Aluminum Foil Honeycomb Core
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CHAPTER 50

FRICTION WELDING

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CHAPTER 50

FRICTION WELDING

FUNDAMENTALS OF PROCESS

INTRODUCTION

Friction welding is a solid state welding process wherein coalescense is produced after heating is obtained from mechanically induced sliding motion between rubbing surfaces held together under pressure. The friction welding process is based on rotating one part at relatively high controlled speeds against the stationary member to which it is to be joined.

The contacting surfaces are thus heated by this frictional contact to a high temperature and forged together to produce a reliable high-strength weld. The weld is completed within seconds, or a fraction thereof, after making contact. This results in a comparatively narrow heat affected zone.

A wide variety of similar and dissimilar materials can be welded with this process. Some combinations require close control and timing of energy, speed, welding pressure, and forge pressure; others do not. Filler metal, fluxes or shielding gases are not required in a friction welding process and welds can be made with a minimum of work piece preparation.

EQUIPMENT AND PRINCIPLES OF OPERATION

CONVENTIONAL FRICTION WELDING

The current commercial version of friction welding was first described in the open literature by Vill and co-workers in Russia. The equipment involved is simple in principle, but may become quite complex in practice, particularly if relatively large sections are to be welded.

In conventional friction welding the variables to be controlled are: a) rotational speed, b) axial welding force, c) amount of upset or "shortening" of the assembly (the length of welding time may be substituted for this parameter), d) rapidity of stopping the spindle via an external brake, and e) forging force. Since a relatively high rotational speed must be associated with one of the members being joined, it is essential that this section of the assembly have axial symmetry; the other member may, however, have any desired shape as long as it can be held stationary and can withstand the required axial forces. The process is shown schematically in Fig. 50.1.

The specific welding parameters required for any given assembly depends upon the size of the sections to be joined and the physical as well as the metallurgical properties of the materials involved; particularly melting point, thermal conductivity (or more specifically, thermal diffusivity), metallurgical changes that occur during the heating cycle and, in the case of dissimilar metal combinations, the phases that may be produced as a result of alloying. The latter is more important in the case of conventional friction welding than for either the flywheel or inertia versions of the process, since more time is generally required to effect a weld, and consequently, diffusion must be considered as a major consideration in some metal combinations.

Generally, material having a relatively low yield point and either a thin or porous oxide film may be welded with ease, and the specific welding parameters are not critical, i.e., mild steel, commercially pure nickel, annealed austenitic stainless steel, etc. However, high strength materials, or those with a thick tenacious oxide (if not readily soluble in the parent metal), require much more critical welding conditions and almost always necessitate the use of a forging cycle and longer welding time to effect a high efficiency joint. These include such alloys as the heat-treatable aluminum alloys, low alloy steels, martensitic stainless steels, and the high temperature alloys including the "super alloys".

High conductivity material such as copper and aluminum are most efficiently joined by utilizing high rotational speeds, high energy input rates, and minimum weld times to minimize the heat affected zone.

FLYWHEEL FRICTION WELDING

Flywheel friction welding is similar to conventional friction welding and inertia welding in the basic process: The flywheel method, however, stores energy in a flywheel, and this energy can be released in specific quantities through an integral clutch system.

The primary advantage of the flywheel welder is its ability to store energy in the flywheel during the material loading cycle, and thus reduce the total floor-to-floor time per weld. This advantage is most noticeable when large weld areas are involved. The primary disadvantage is the complexity added by the clutch, and the limitation on welding small-area parts.

INERTIA WELDING

As in flywheel friction welding, inertia welding also utilizes the kinetic energy stored in a revolving flywheel-spindle system. It differs from flywheel welding, however, in that all of the flywheel energy is consumed by the weld, since there is not a clutch between the flywheel and the part being welded.

Critical parameters to be controlled are fewer than in conventional or flywheel welding, since the only variables are thrust, rotational speed, and the inertia of the flywheel-spindle combination.

A comparison of conventional and inertia welding parameters are shown schematically in Fig. 50.2. It should be noted from this figure that besides the very large difference in the time cycle required, both exhibit an initial torque peak that is reduced to a relatively constant value in the conventional process until rotation is stopped. However, in inertia welding it again rises to an even higher value at the end of the weld cycle.

Thus, in application, a flywheel with a suitable moment of inertia is accelerated to a predetermined angular velocity to create the desired sliding velocity on the abutting weld members, and to produce the desired amount of heat. The initial torque peak occurs early in the weld cycle when the velocity is at a near maximum, and represents a pronounced peak power consumption at the weld. This peak-power demand is always fulfilled by the decelerating flywheel, as it cannot stall until it has transferred all of its kinetic energy to the weld. The final torque peak occurs as the flywheel slows, and coalescense occurs across the weld interface. Final high torque ("3rd stage" torque), in combination with thrust, displaces material with greater ease than the conventional method, and thereby allows large diameters and difficult-to-forge materials to be welded more readily.

Fig. 50.3 shows shear stresses developed by the torsional and axial forces, and the resultant shear stresses that produces the forging action. The empirical curves for torque and thrust, as a function of bar diameter, have been developed by numerous tests of steel welds. Optimum welds are obtained with specific peripheral speed for a particular material combination and part diameter, i.e., small pieces must be rotated at higher speeds than large ones. As energy and thrust requirements decrease rapidly with decreases of interface areas, the design of a welding machine to cover a broad range of welding areas becomes impractical.

A single model of a machine will span a range of weld diameters of about 3:1, with models available to weld mild steel bars ranging from ⅛-in. to ¼-in. diameters. Thrust forces range from a few hundred to over a half-million pounds. A schematic of the essential design features of an inertia welder is shown in Fig. 50.4.

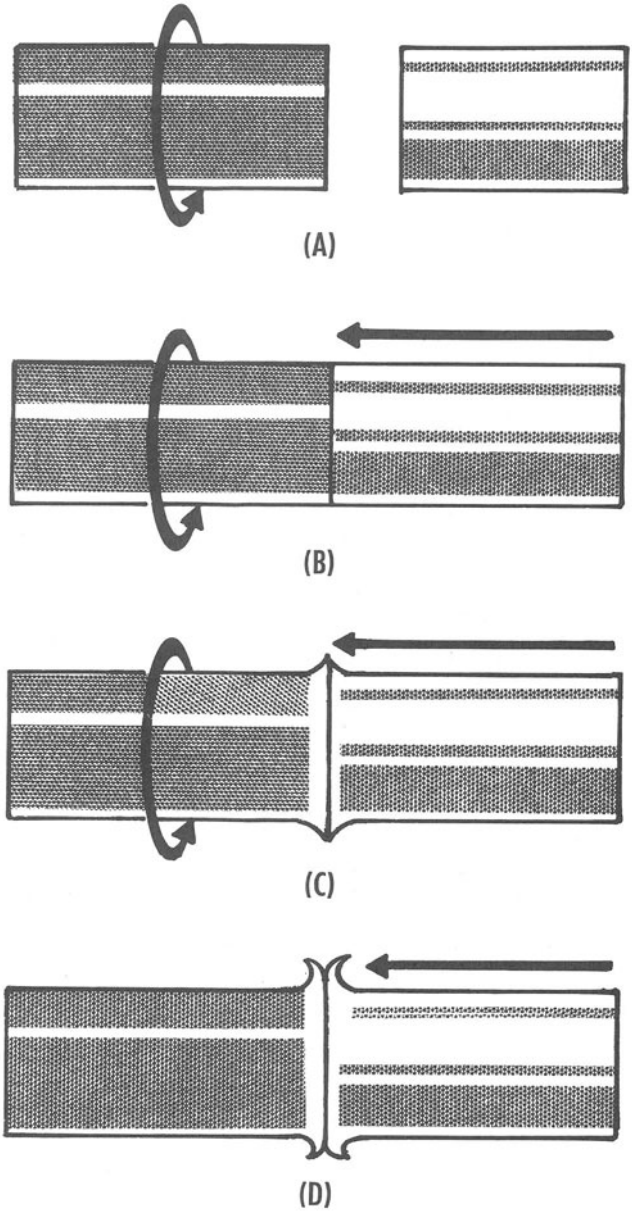


Fig. 50.1.—Basic process of friction welding (A) Rotating member brought up to desired speed (B) Nonrotating member is advanced to meet the rotating member and pressure is applied (C) Heating phase-Pressure and rotation are maintained for a specified period of time (D) Forging phase-Rotation is stopped and pressure is either maintained or increased for a specified period of time
Total welding time — 2 to 30 seconds

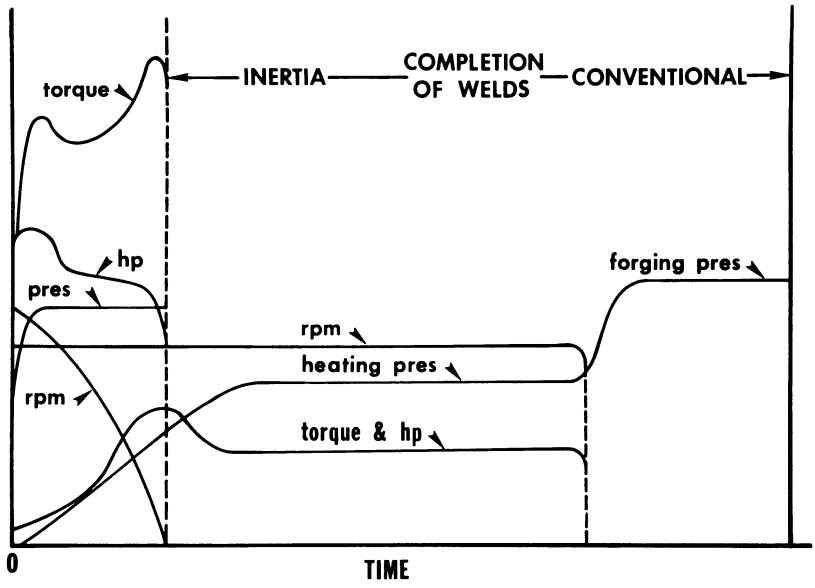


Fig. 50.2.—Schematic presentation of inertia and conventional friction welding parameters

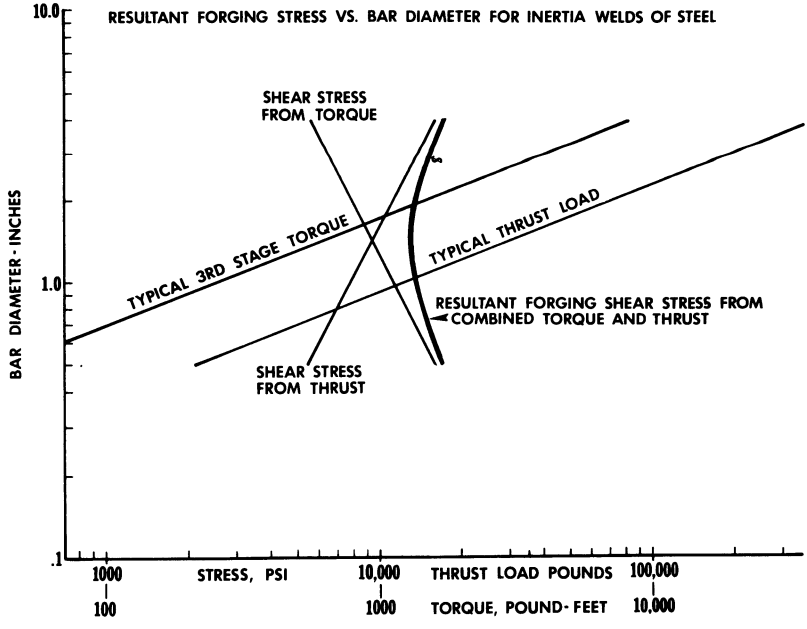


Fig. 50.3.—Final torque peak of inertia welding assists thrust force to produce forging of weld zone

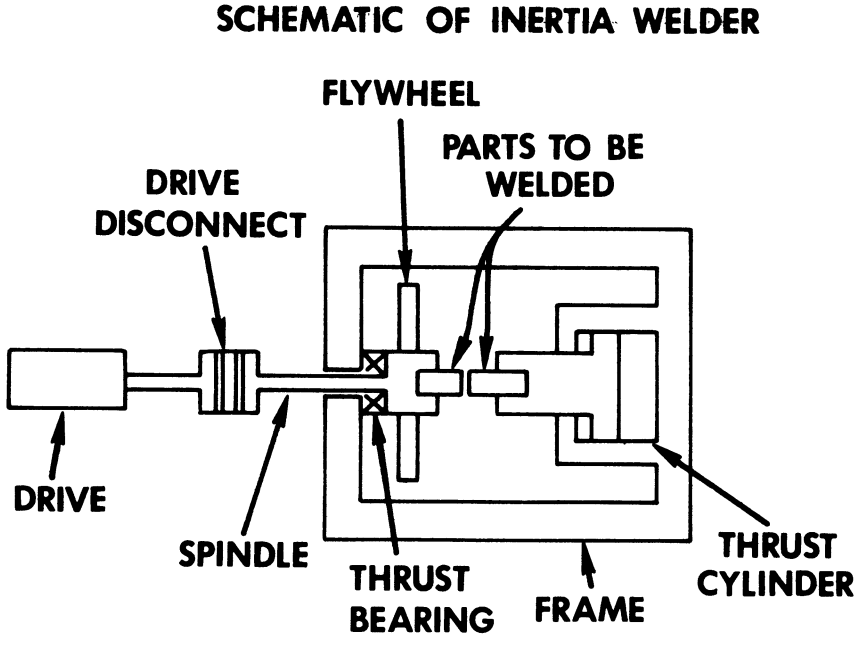


Fig. 50.4.—The basic design features on an inertia welder

TOOLING AND FIXTURES FOR WELDING

All gripping devices used for holding the weld members must be reliable. Slippage of the part in relation to the chuck results either in a poor weld, or in damage to the gripping device.

Thrust supporting and chucking surfaces of the gripping devices must be rigid and located as near as possible to the weld interface to reduce deflection, thus minimizing eccentricity and non-parallelism. Grip diameter must be as large or larger than the diameter of the weld. Serrated gripping jaws are recommended for maximum clamping reliability.

Basic tooling divides into two categories — rotating and non-rotating. Each category, in turn, subdivides into manual and power operated. As a rule, manually actuated tooling is used only for pilot runs, small quantity runs, or custom product runs.

Rotating tooling must be well-balanced, have the smallest possible moment of inertia, have high body strength, and have a high gripping power when rotated at high speeds.

Collet chucks fullfill all of the above requirements and therefore, are most frequently used. (See Fig. 50.5).

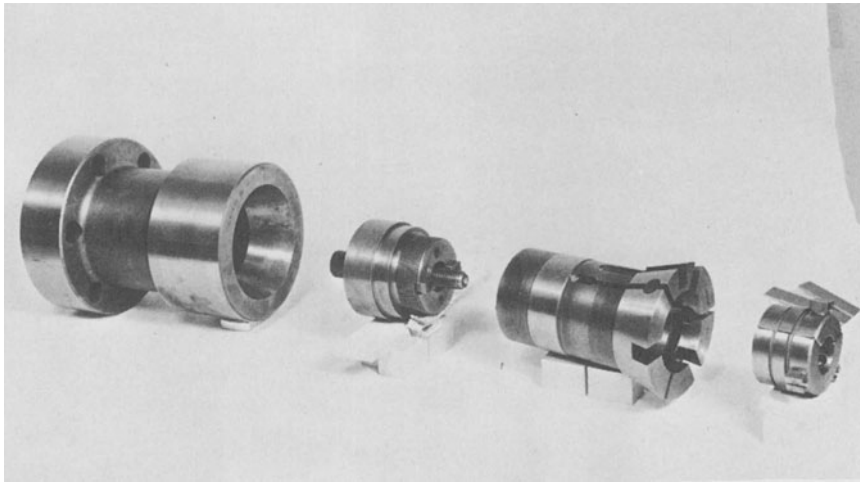


Fig. 50.5.—Collet type tooling as frequently used for gripping the rotating weld member consisting of body, tie bar connector, master collet and insert collet

Since total diametrical movement of a typical collet chuck is approximately 0.020 in., dimensional and ovality tolerances of parts presented must be within this limit. Specially designed collet chucks capable of larger movements are available, but as a rule, they have a larger moment of inertia.

The most commonly used non-rotating gripping device is a self-centering vise-like fixture with a provision for absorbing thrust.

Self-centering of the piece part allows for larger variations of tolerances of the welded pieces, while maintaining concentricity with the piece held in the collet chuck. Non self centering devices may be used where concentricity is of little concern.

Wedge-like fixtures capable of withstanding torque and thrust can be used for welding long pieces; however, if a standard fixture is used, auxiliary anti-buckling fixtures are required.

Weld parallelism and concentricity depends not only on the accuracy of the parts to be welded, but also on the length of overhang from the fixture to weld interfaces, as well as the rigidity of the tooling. As a rule, the larger the pieces welded, the greater the eccentricity, rigidity, and ruggedness of required tooling, shown in Fig. 50.6.

In short tubular welds, tooling can be piloted with considerable improvement of weld concentricity.

When large quantities of the same-shaped parts are welded, machines are built fully automated. Parts are fed into hoppers, from hoppers into gripping devices, welded, and ejected.

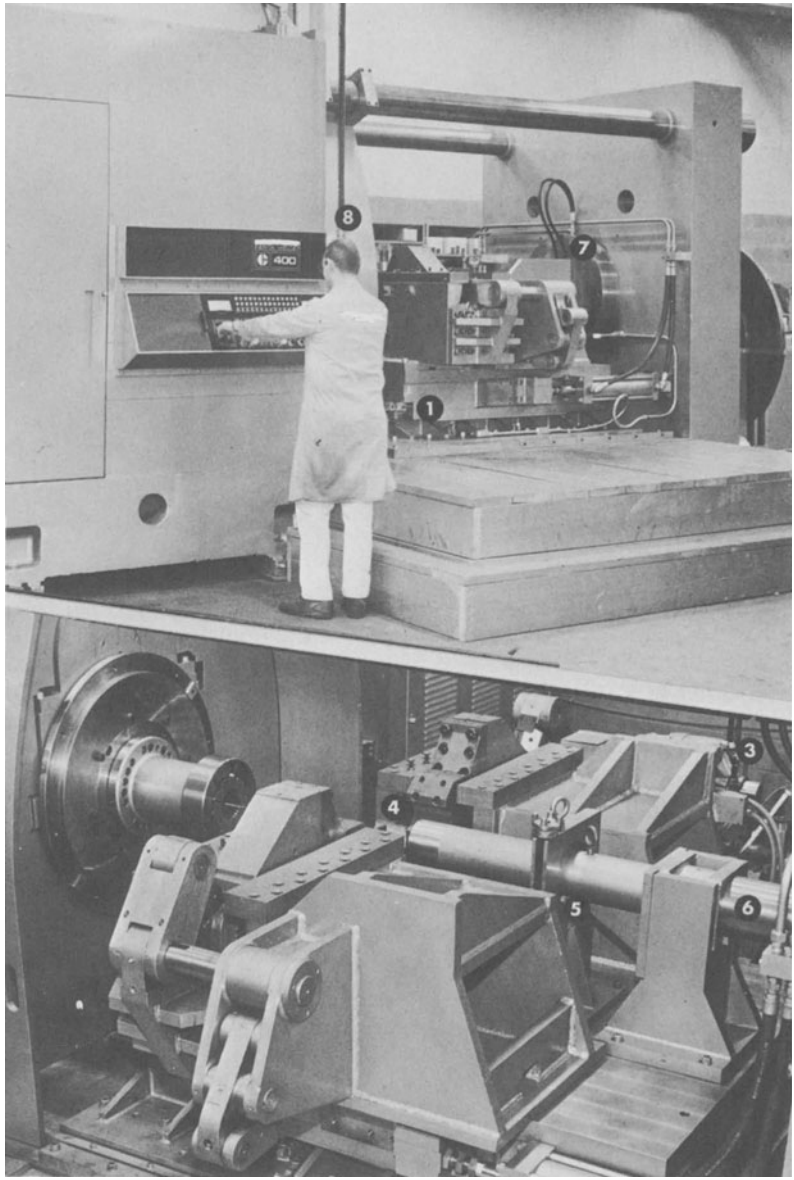


Fig. 50.6.—Tooling for large inertia welder: (1)—Ways, (2)—Retracting Cylinders, (3)—Rotary Actuator, (4)—Replaceable Jaws, (5)—Steadyrest, (6)—Backstop, (7)—Backstop Latch, (8)—Pendant Tailstock Control

WELD PARAMETERS

CONVENTIONAL FRICTION WELDING

Although any of the three versions of the friction welding process involve relatively short welding times, the conventional version is relatively much longer per cycle, frequently as much as ten times that required for either the flywheel or inertia processes for the same material and size combinations. Typical weld cycles used in the conventional process are shown in Table 50.1. However, this table must be used as a guide only, since satisfactory welds can be made with parameters quite different from those shown. The general tendency among current manufacturers of conventional friction welding equipment is to utilize somewhat slower rotational speeds and higher axial pressure than those indicated (the Vill approach), which is conducive to longer equipment life. This table should therefore be used only as a guide to indicate the range of equipment variables that may be desired for experimental purposes.

FLYWHEEL FRICTION WELDING

Flywheel friction welding involves the use of a flywheel in which rotational energy is stored and released to the work pieces in amounts predetermined and gauged by speed. The amount of energy released by the flywheel is determined by its initial contact speed and the speed at which the clutch disengages the spindle from the flywheel. Constant axial pressure is applied to the faying surfaces.

The controllable variables are: a) rotational speed, b) flywheel size, c) cutout speed, and d) axial force. The primary advantage of the flywheel method lies in the welding of large-area parts, since the welding energy is almost immediately available from the flywheel as soon as the parts are loaded. The flywheel is allowed to be brought to its full energy potential by means of the open clutch during the loading of the part to be welded.

Flywheel welders are no longer being manufactured although a number are still in use by industry.

INERTIA WELDING PARAMETERS

There are three welding parameters that are interrelated. These are: initial sliding velocity at the faying surface, which relates to the flywheel-spindle rpm and the weld diameter; the moment of inertia at the flywheel-spindle system; and the axial thrust force in psi at the weld interface. If rpm and inertial mass are thought of as weld parameters, then the weld energy is defined by the equation

$$E_k = \frac{WK^2 (RPM)^2}{5873}$$

where E_k is in foot-pounds (which can be converted to thermal energy as Btu), W is the weight of the flywheel system in pounds, and K is the radius of gyration in feet.

Table 50.1—Representative friction welding parameters

Material	Diameter, in.	Relative Rotational Speed, rpm	Contact Pressure		Total Time, sec
			Heating Phase, psi	Forging Phase, psi	
Carbon steel (a)	0.5	3,000	5,000	5,000	7
	1.0	1,500	7,500	7,500	15
Stainless steel (b)	1.0	3,000	12,000	16,000	7
	5.5 O.D. 4.5 I.D.	800	20,000	20,000	35
Stainless steel to carbon steel	0.75	3,000	7,500	15,000	10
Tool steel (c)	0.75	4,000	15,000	20,000	10 (d)
Copper (ETP) (e)	1.0	6,000	5,000	10,000	18
Aluminum (Comm. Pure) (e)	0.75	3,800	4,000	6,500	6
Alloy steels (f)	0.375	5,000	25,000 (g)	40,000	10 (d)
Alloy steel to carbon steel (h)	1.75 O.D. 1.25 I.D.	6,800	2,500 (i)	6,000	42 (d)
	4.5 O.D. 3.25 I.D.	3,000	5,500 (j)	16,000	26 (d)

(a) AISI 1010, 1020, 1030, 1045 steel, etc.
(b) Series 300 and 400
(c) Type T-1 or equivalent
(d) Postheat treatment required
(e) Small amounts of alloys can alter the parameters considerably
(f) AISI 3140 to 21%Cr-4%Ni-9%Mn steel
(g) Pressure built up from 0 to 25,000 psi in 3 seconds
(h) AISI 4140 to 1035 steel: preheat the AISI 4140 to 600°F
(i) Pressure built up from 0 to 2,500 psi in 20 seconds
(j) Pressure built up from 0 to 5,500 psi in 26 seconds

Establishing correct weld parameters for inertia welds begins by using values such as those shown in Table 50.2. These parameters may be varied considerably and still produce good quality welds. Fig. 50.7 illustrates changes in the flash formation and the shape of the heat affected zone as the weld parameters are varied over wide ranges, but without impairment of weld quality. Rules-of-thumb can generally be applied for selecting weld parameters as weld sections change.

Among these is to vary the unit thrust pressures (psi) as a function of the square root of the diameter. For example, a two-inch diameter bar will require $\sqrt{2}$ times the unit pressure of a one-inch bar. The same function applies for selection of unit energy. Peripheral velocity remains constant as bar diameter changes; thus spindle rpm varies inversely with bar diameter. Under these conditions weld time and weld upset values vary approximately linearly with bar diameter.

Tubular sections generally have peripheral velocities about 50% greater than bars. Unit energies and unit pressures of tubular sections vary as a function of the O.D.-I.D., in the same manner that these weld parameters vary as a function of bar diameter. Bar or tube to plate welds require about 10% more energy and pressure than bar or tube welds.

Table 50.2—Representative conditions for inertia welding one-inch bars

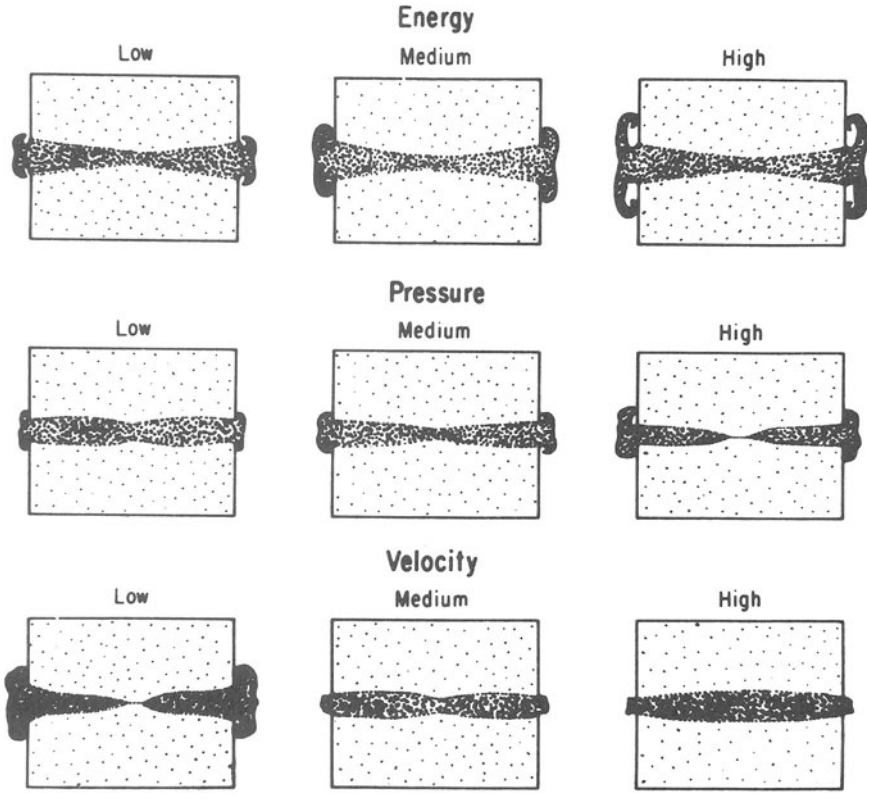
Material	Weld Parameters			Resultant Weld Conditions		
	Speed, RPM	Thrust Load, Pounds	Inertial Mass, Lb-Ft^2	Energy Ft-Lbs	Upset, Inches	Weld Time, Sec.
Low Carbon Stls.	4600	12,000	6.7	24,000	.10	2.0
Med. Carbon Stls.	4600	14,000	7.8	28,000	.10	2.0
Low Alloy Stls.	4600	15,000	8.3	30,000	.10	2.0
Superalloys	1500	50,000	130	50,000	.15	3.0
Maraging Stls.	3000	20,000	20	30,000	.10	2.5
Stainless Stls. (Ferritic)	3000	18,000	20	30,000	.10	2.5
Stainless Stls. (Austenitic)	3500	18,000	14	30,000	.10	2.5
Copper	8000	5,000	1.0	10,000	.15	0.5
Brass	7000	5,000	1.2	10,000	.15	0.7
Titanium (6-4)	6000	8,000	1.7	16,000	.10	2.0
Aluminum (AA1100)	5700	6,000	2.7	15,000	.15	1.0
Aluminum (AA6061)	5700	7,000	3.0	17,000	.15	1.0
Copper-Carbon Stls.	8000	5,000	1.4	15,000	.15	1.0
Tool Stls.-Carbon Stls.	3000	40,000	27	40,000	.10	3.0
Superalloys-Carbon Stls.	1500	40,000	130	50,000	.15	2.5
Stainless Stls.-Carbon Stls.	3000	18,000	20	30,000	.10	2.5
Sintered Stls.-Carbon Stls.	4600	12,000	8.3	30,000	.10	2.5
Aluminum (6081)-Stainless Stls.	5500	5000*-15,000*	3.9	20,000	.20	3.0
Copper-Aluminum	5500	5000*-15,000*	3.9	20,000	.20	3.0

* The lower thrust load is applied during the heating stage of the weld then increased to the higher load near the end of the weld.

Departures from the above weld parameters are often required for particular applications. When the flash is not removed, weld energy may be decreased to minimize its volume. For example, less than usual weld energy was used in the example of Fig. 50.8 which produced only 0.020 in. upset of the weld members. Other situations call for more than the usual amount of energy to broaden the heat affected zone. This decreases the cooling rate following the weld cycle and, consequently, lowers the hardness of the flash material. This may be important where machinability in the as-welded condition is of concern. Normally alloy steels, unless they are low carbon content, will require a post-weld anneal to lower the hardness of the flash material to machinable levels.

METALLURGICAL STRUCTURES PRODUCED

The metallurgical structures produced by conventional and inertia welding are generally those expected from general consideration of the time-temperature cycles for materials of similar compositions welded to each other. However, as pointed out earlier, time at temperature is short, and the temperatures achieved are generally below the melting point for all friction welding processes. Thus, in materials such as mild steel, changes in hardness are negligible across the entire weld zone. On the other hand, for hardenable steels, severe structural changes occur in the heat affected zone. Such relatively hard (and hardenable) materials also require more welding time and produce an increased width of the heat affected zone.



50.7.—Heat affected zones and flash formations of inertia welded steel bars steel as affected by changes in the weld parameters

The interface structures of dissimilar metal combinations are drastically affected by the particular friction welding procedure employed. The longer the welding time, the greater the consideration must be given to the importance of diffusion at the interface. Proper weld parameters will usually prevent undesired diffusion or compound formation such as shown in Fig. 50.9, where the interface between aluminum alloy and stainless steel shows no discernable diffusion zone when welded by the more rapid inertia process.

JOINT DESIGN AND PREPARATION

The very nature of friction welding is such that the joint face of at least one of the members must be essentially round. The revolving member should be somewhat concentric in shape as it must be revolved at relatively high speeds. Fig. 50.10 illustrates the basic joint designs, consisting of combinations of bars, tubes and plates. Where bars or tubes are welded to plates, most of the flashing occurs from the more easily forged bar or tube member.

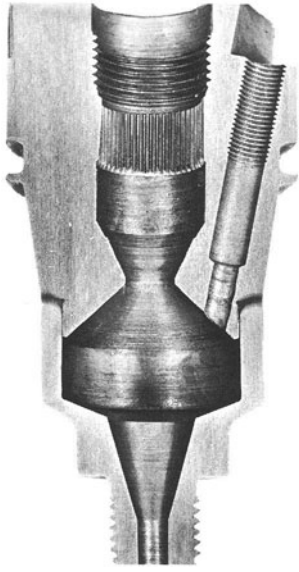
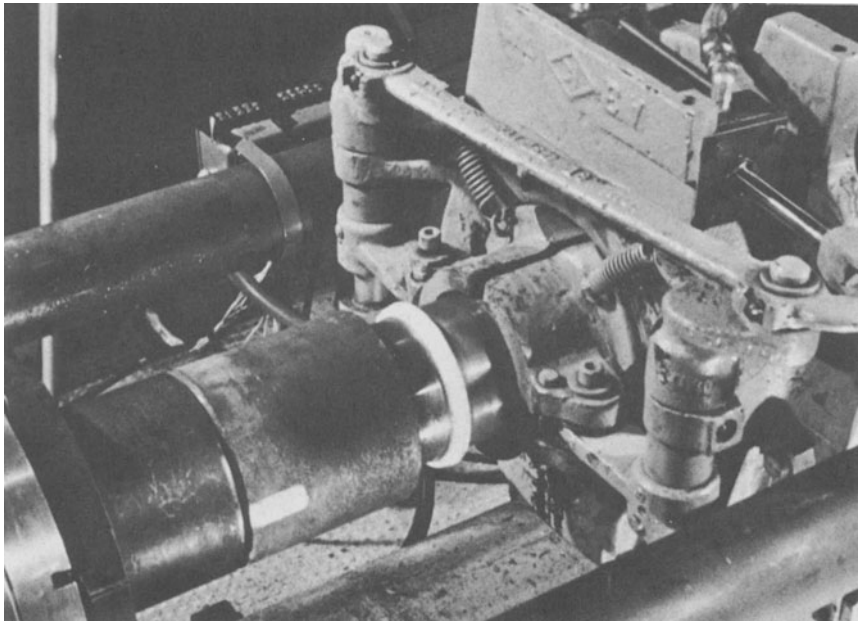


Fig. 50.8A.—Left, Cross section of diesel engine pre-combustion chamber in as-welded condition showing heat affected zone and flash trap. This weldment of free machining SAE, 5120 steel is subsequently quenched and tempered for best fatigue strength

Fig. 50.8.—Below, Closeup of friction weld being formed (upset stage) between an alloy steel tool and an oil well drill pipe



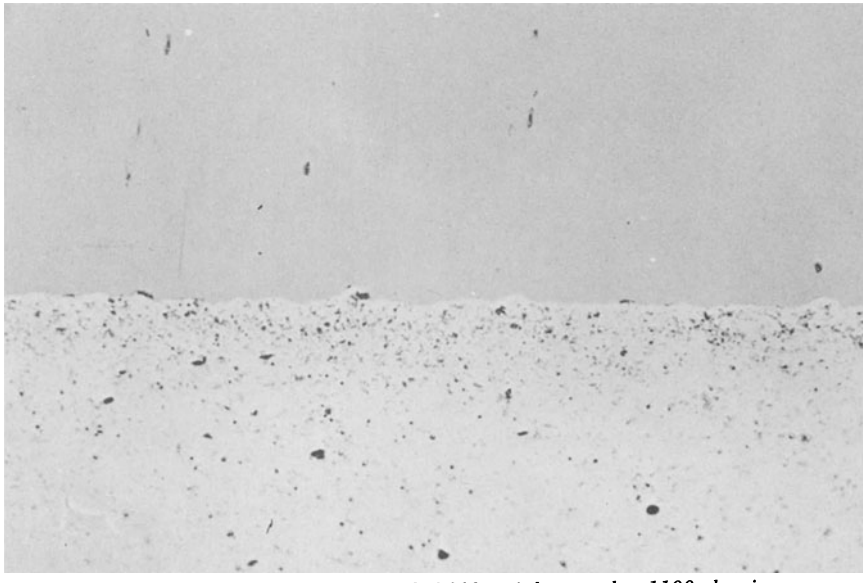


Fig. 50.9.—Weld line of inertia welded 302 stainless steel to 1100 aluminum

Fig. 50.11 illustrates "special" joint designs consisting of simultaneous welds on concentric cylinders. The requirements here are to produce both welds within suitable speed limits, and to insure that both welds contact at appropriate times during the weld cycle to distribute energy proportionately. In addition to the square butt welds, angular or taper welds are feasible.

Angle joints are usually designed with faces 30° to 45° from the center line, although angles as low as 8° have been made. For the more easily forged materials, the greater angles are preferred to prevent pushing the one part through the hole. Some other special joint designs are shown in Fig. 50.12. The "flash trap" joints are intended for applications where the flash is not accessible for removal, and it must not be exposed for functional or aesthetic reasons. Non-circular members have been welded successfully, although the flash produced is very rough and unsymmetrical, and presents problems if it must be removed.

A requirement for non-circular joints is that the area of the mating member must be sufficiently large to completely accept the sweep of the non-circular rotating member. Plate-to-plate welds are not feasible by rotary friction welding. However, such a joint can be produced, as illustrated in Fig. 50.12, by rolling a tube into a plate section.

Some welds between dissimilar materials with widely different forging temperatures or thermal diffusivity values require relative size adjustments at the interface, to produce proper balance of forging and upsetting of each member.

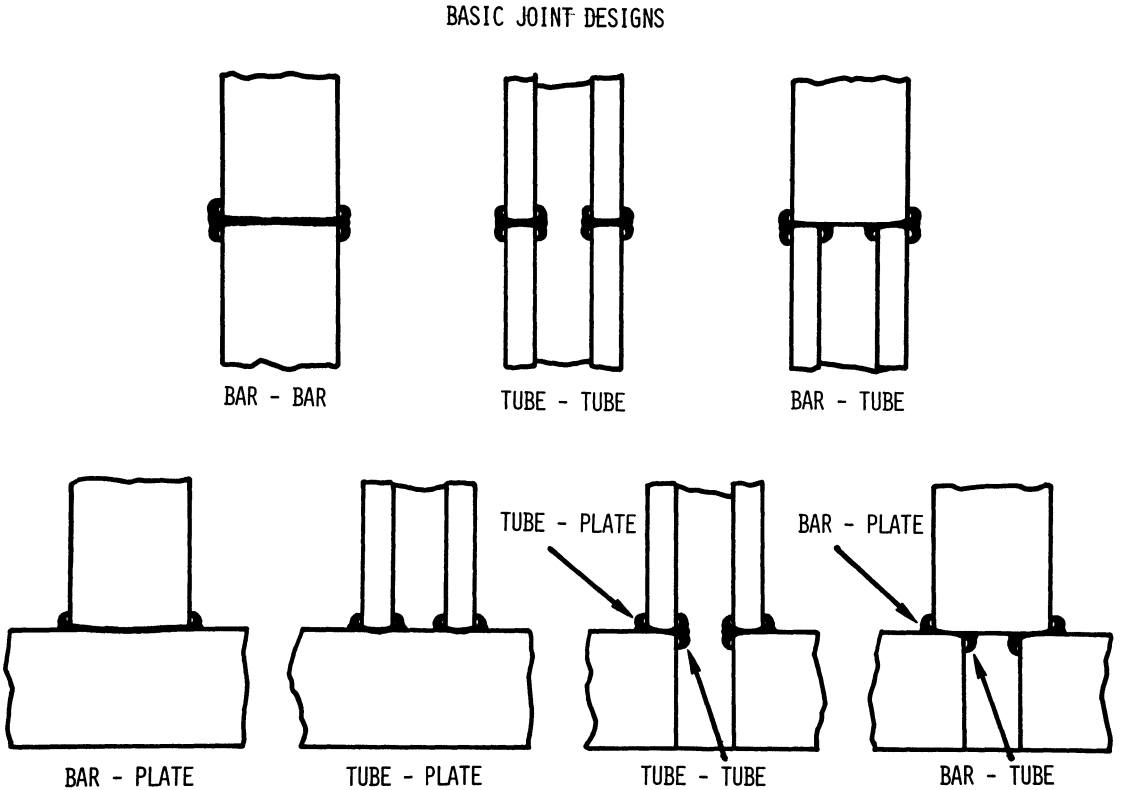


Fig. 50.10.—Typical joint designs showing flash formation and HAZ

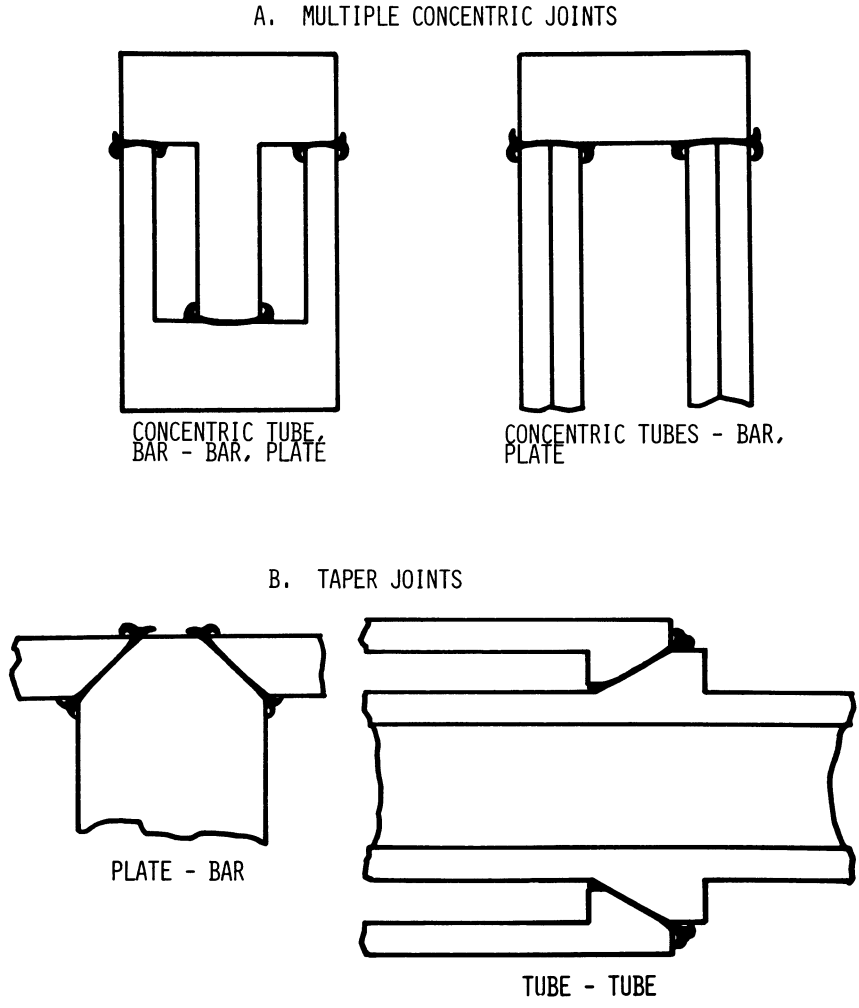


Fig. 50.11.—Special joint designs showing multiple welds and welds made on a taper

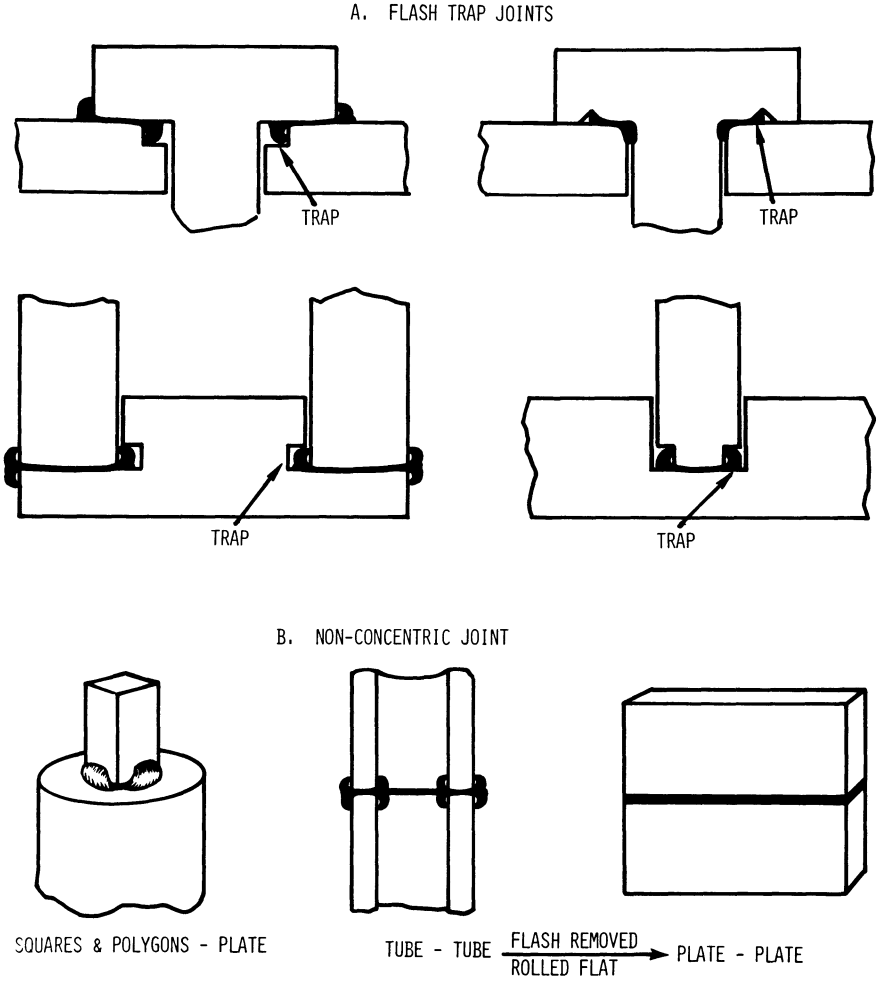


Fig. 50.12.—Special joint designs utilizing traps to contain the flash, and joints of non-circular geometries

Since the original butting surfaces of most welds are completely forged away in the process, joint surface preparation is not critical. Sheared, flame cut, and sawed surfaces are usually satisfactory if adequate energy is provided to correct for out-of-squareness and the excessive flashing is not detrimental. Excessive out-of-square faces, however, may produce radial forces affecting weld concentricity. A rule-of-thumb would be to maintain squareness within 0.010-in./in. of weld diameter. Center projections left by cut off tools present no problems. However, pilot holes or concave surfaces should be avoided to prevent entrapping of air and oxides in the weld. Heavy forge or mill scale should be removed, as it acts as bearing surfaces and sometimes cannot be flashed out of the weld interface. Carburized, nitrided, and plated surfaces should usually be avoided.

CONTROL OF WELD QUALITY

Weld quality is primarily dependent upon the proper selection of weld parameters; fortunately, most materials are tolerant of wide variations. Because it is a solid state process without the use of filler materials or fluxes, defects such as gas pockets, slag inclusions, and brittle compounds are virtually non-existent. Fracture or bend tests, micro examination, visual examination of the size and nature of the flash, ultrasonic, magnetic particle or dye penitrent tests may all be employed to establish that weld integrity has been established.

Once correct weld conditions have been established, based on approximate tests such as suggested above, the physical measurement of the weldment is the basic quality control technique. Spot checking the amount of weld upset by length reduction of the weldment is an effective means to assure that malfunction of the welder or changes in the work pieces have not occurred. The good reproducibility of the process, which in the case of inertia welding involves controlling only speed (hence energy with an established flywheel size) and thrust force, allows maintaining upset within 5% of the nominal value.

Defective welds can result from various causes. For example, when inertia welding, tearing of material at the peripheral edge of the heat affected zone, as shown in Fig. 50.13, can occur from the use of an excessively large flywheel and lower than adequate speed. These conditions did not create sufficient weld zone temperatures, and caused excessive twisting of the weld zone following coalescense across the interface.

Another type of defect at the center of welds may occur for various reasons. The welding parameters used may not have created sufficient heating of the center for coalescense. Concave surfaces which prevent contact of the mating surfaces during the early stages of weld will limit center heating and entrap oxides, therefore producing defects. Fig. 50.14 shows a center defect resulting from one member having a centering hole.

If a center hole must be used, it must be sufficiently deep to contain the flash, with sufficient volume remaining to prevent entrapped air from being forced out of the cavity into the weld plane. Center holes, providing they have adequate depth, can be an effective means of increasing the cross-sectional area that can be welded, since parameters for tubular sections rather than solid sections apply. This, of course, lowers the unit pressure requirement that normally is the limiting factor for rating machine capacity.

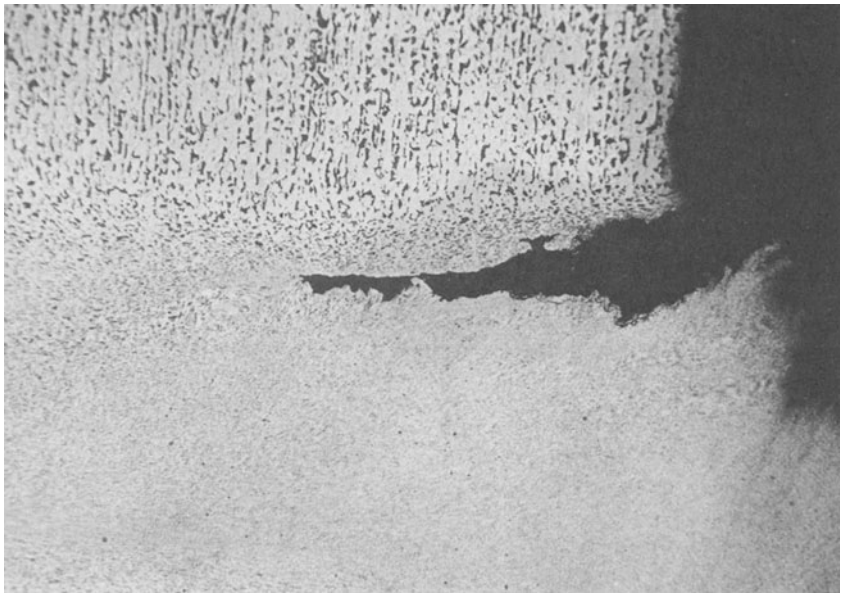


Fig. 50.13.—Tearing at edge of HAZ of inertia weld through use of too large a flywheel and too low an initial velocity

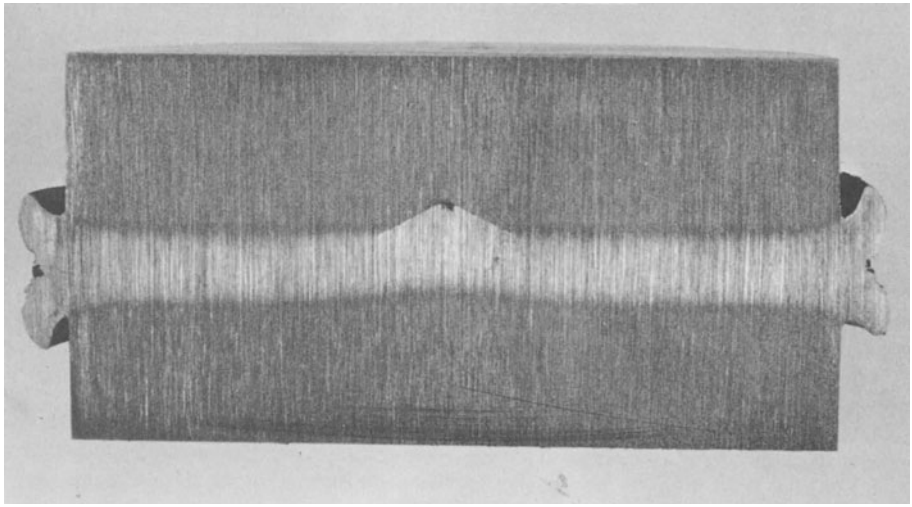


Fig. 50.14.—Center defect in 2 in. diameter weld resulting from a small center hole in one member

Weld defects, as shown in Fig. 50.15 will sometimes occur at the center of bars from lack of upset. These are inertia welds, all made with the same speed and inertial mass, but with a decreasing pressure from left to right. The two defective welds that exhibited center defects upon deep-etching resulted from the less than adequate upsets of 0.136-in. and 0.064-in. Normally 0.2-in. upset for 2-in. bars will adequately insure against such defects. Lack of center bonding may also be obtained in conventional friction welds if inadequate speed or weld time, as well as insufficient heat or forge pressures, are used.

The fabricated compressor wheel, shown in Fig. 50.16, represents a weldment where close tolerances must be maintained in the finished product. Blank preparation was carefully controlled and rigid tooling used to hold concentricity to within 0.015-in. T.I.R., and upset to within 0.010-in. This 24-in. O.D. compressor wheel of Inconel 718, a high temperature nickel alloy, was designed to operate at a temperature of 1000°F and at approximately 80,000 psi centrifical force. The 14-in.^{2} joints were inertia welded in 2.5 seconds.

HEAT TREATMENT OF WELDS

Pre-weld heat treatments of the weld members generally have little effect on their weldability, but may affect the mechanical properties of the heat affected zone, even though the over-all properties of the weld are not significantly altered. The heat treated condition of the alloys being welded may, however, alter the welding parameters, particularly in conventional welding.

Pre-weld heat-treatment is sometimes employed, however, to produce the desired properties in the materials remote from the weld areas, or to solve processing problems that may be inherent in treating the weldment. Steel-aluminum weldments should not be heat-treated (other than an aging treatment of the aluminum) after welding, since thermal treatments above 600°F will cause a severe embrittlement at the weld line by the formation of iron-aluminum compounds.

Fig. 50.17 illustrates the softening that occurs in 6061-T6 aluminum when inertia welded to steel. This softening is due to annealing or solution treatment near the weld interface, and over-aging near the edge of the heat affected zone. Similar softening in the heat affected zone has been observed in 2024-T4 aluminum when welded by the conventional process.

Several of the super alloys, such as Inconel 718, have been welded in the following conditions:

a. Solution treated + aged + inertia weld + solution treated + aged.
b. Solution treated + inertia weld + aged.
c. Solution treated + aged + inertia weld + aged.

Mechanical property tests made on specimens taken from these weldments do not show any variations. The electron micrograph shown in Fig. 50.18 shows the weld line to be free of defects. These welds produced equal or greater strength than the parent material. It may therefore be concluded that the hot forging action of the inertia welding process has a solutioning effect on age hardening alloys that allows re-aging after welding.

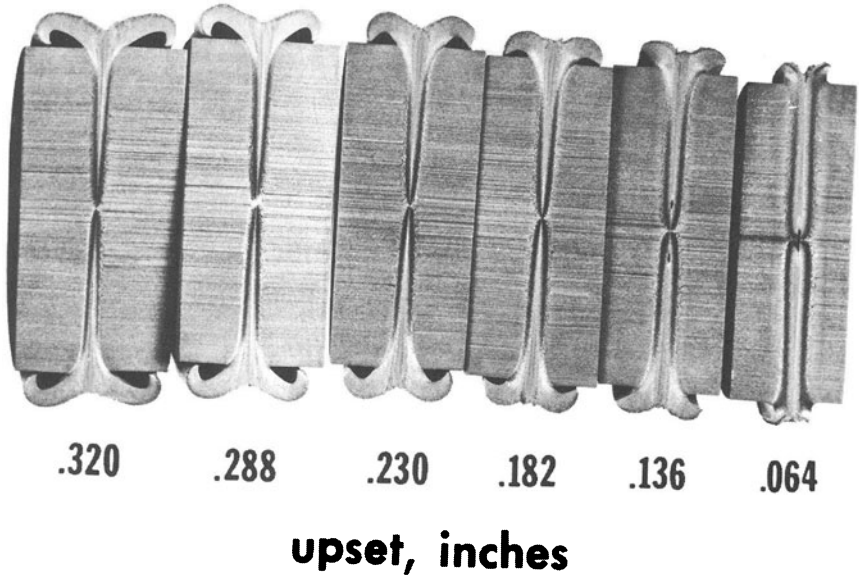


Fig. 50.15.—Deep etched sections of inertia welds showing center defects resulting from inadequate upset. Etch pattern denotes the re-orientation of the flow lines

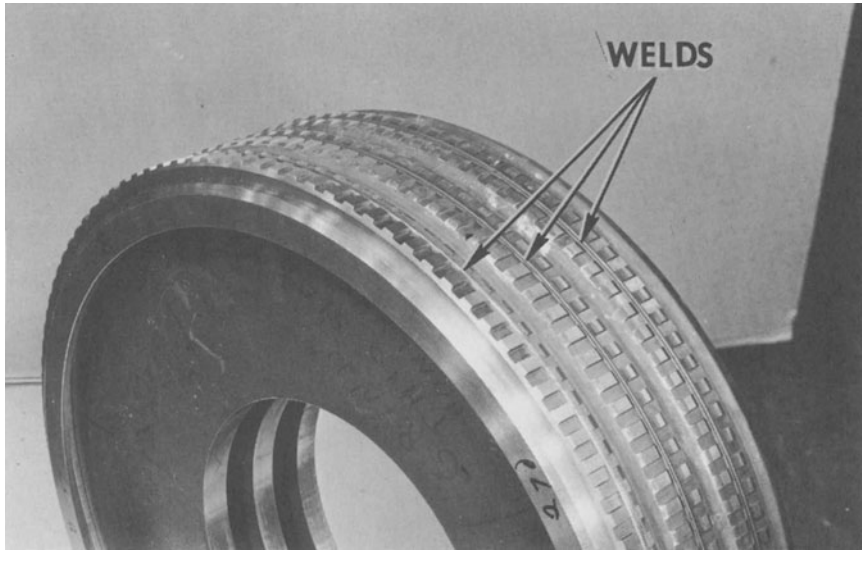


Fig. 50.16.—Inertia welded compressor wheel of Inconel 718. The 14 in. 2 welds joining each 24 in. O.D. wheel, was made in 2.5 seconds

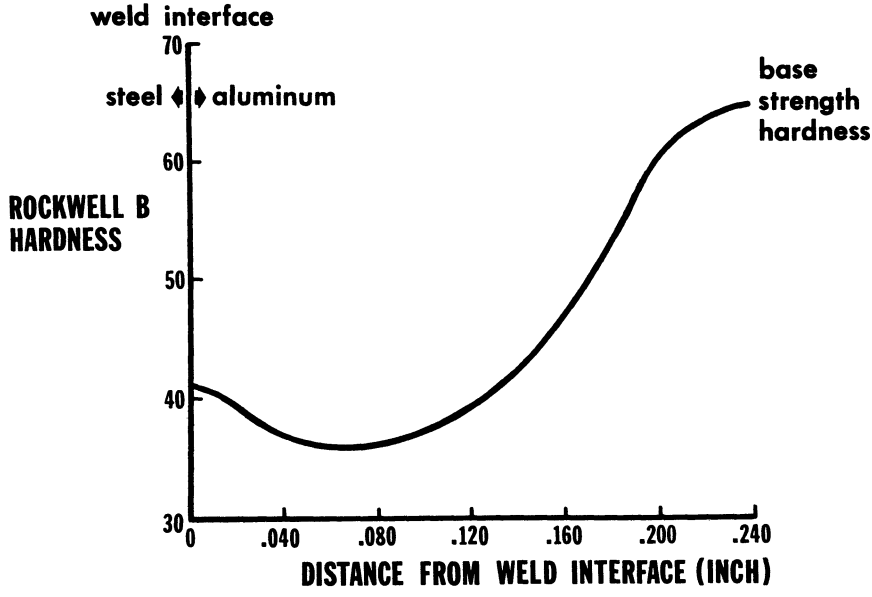


Fig. 50.17.—Softening of 6061-T6 occurred when welded to steel because of overaging and re-solution temperatures of weld

Table 50.3—Tensile properties of various inertia welded alloys

Alloy	Condition	Temp. °F	UTS Ksi	.2% Y.S. Ksi	Elong. %	Failure Location
4340 Steel	Weld	R.T.	220	206	12	Parent
321 Stainless	Weld + Stress Relief	R.T.	87	34	65	Parent
Ti-6-6-2	Weld +	R.T.	182	177	12	Parent
	Stress Relief	600	147	120	16	Parent
Ti-6-2-4-2	Weld +	R.T.	145	133	14	Parent
	Stress Relief	900	110	83	18	Parent
200 Grade Marage	Weld + Age	R.T.	227	218	12.5	Parent
Udimet 700	Weld +	R.T.	189	135	13.5	Parent
	Heat Treatment	1400	144	125	15	Parent
Inconel 718	Weld + Age	R.T.	210	172	13.5	Parent
	Weld + Age	1200	162	146	8	Parent
Ti-6-4	Weld (A)	R.T.	144	131	12	Parent
	Weld + 1750°F + 1300°F (B)	R.T.	136	125	14	Parent
	Weld (A)	600	104	84	16	Parent
	Weld + 1750°F + 1300°F (B)	600	104	83	17	Parent

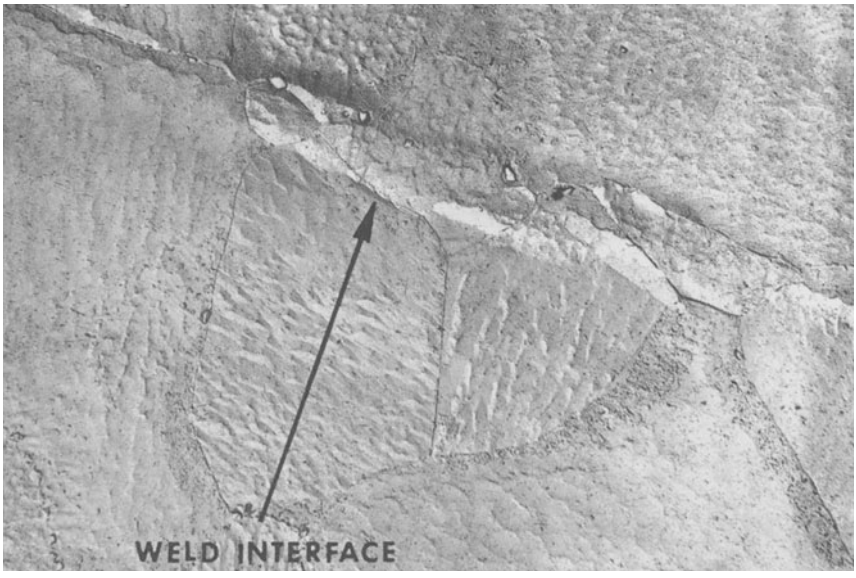


Fig. 50.18.—Electron photo micrograph inertia weld interface in Inconel 718 and 5000 MAG

Table 50.3 shows the tensile properties of both age and non age hardening alloys. These tests indicate full strength in the weld with the various post heat treatments given.

A post weld anneal is often applied to lower the hardness of the flash material to render it machinable and to stress relieve the joint. The weldment of SAE 1141 steel, shown in Fig. 50.19, is an example where the weld zone area is induction tempered to facilitate machining of the I.D. flash, and to toughen and stress relieve the joint. Steels with carbon contents below about 0.20% would normally not require post weld heat treatments except where maximum fatigue properties are required.

Alloy steels of medium and high carbon contents will harden from the rapid cooling rate that follows the weld operation.

Fig. 50.20 shows the resulting hardness in the heat affected zone of an inertia welded 2¼-in. diameter bar of SAE 86B30 steel. The as-welded hardness is maximum on each side of the weld line. The somewhat lower hardness at the weld line is presumably due to less hardenability of very fine grained material at this location. A post weld quench and temper heat treatment will produce uniform grain size and hardness through the weld area and parent material. The micro-structure of the weld area is not discernable from the parent material when weldments are re-austenitized, such as shown in Fig. 50.21.

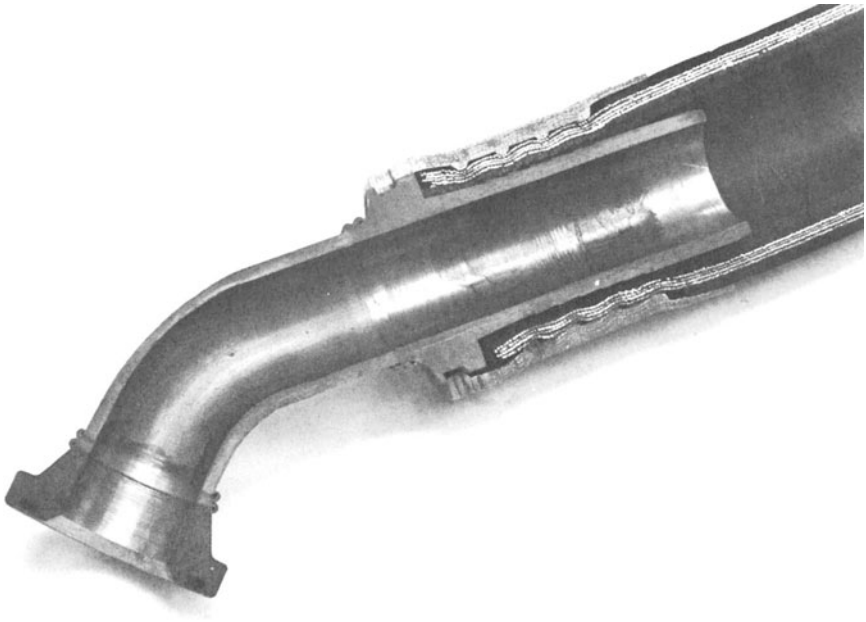


Fig. 50.19.—Induction tempering of the HAZ of the welds was employed to soften the I.D. flash for machining and to toughen the welds in this hydraulic hose coupling assembly

In such situations welds are located by deep etch treatments or sulfur prints that serve to detect re-orientation of flow lines at the weld. Pre-hardened tool steel welds should be tempered at a minimum of 400°F but preferably higher, depending on the type of steel. In general, good metallurgical judgment will dictate when pre- and post-weld heat treatments are required if it is kept in mind that the thermal history of friction welds consists of a rapid heating and cooling cycle. Because it is a solid state joining process, the heat affected zone responds to heat treatment in a manner identical with the response of the non-heat affected material remote from the weld area.

MECHANICAL PROPERTIES

Since friction welding is a solid-state welding process, it is not affected by some of the factors that lower weld strength in fusion welding, i.e., cast structures, coarse grain size and atmospheric contamination. As a result, weld strength is usually equivalent to that of the parent material. Steel to 6061 aluminum welds are notable examples where friction welds (by the inertia method) have produced full-strength welds where both the static and the fatigue strength of the weld exceeded the strength of the aluminum.

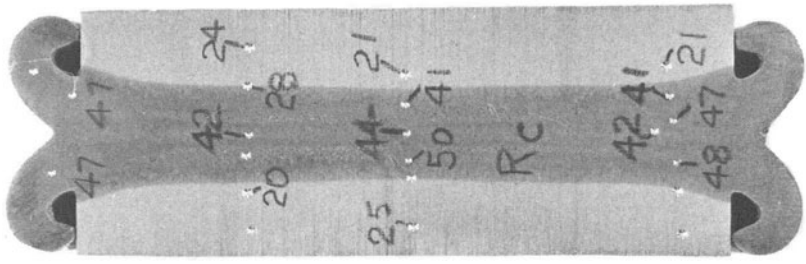


Fig. 50.20.—HAZ zone 2¼ inch diameter weld of SAE 86B30 steel. Numbers represent Rockwell C hardness values in the aswelded condition



Fig. 50.21.—Microstructure of SAE 14B35 steel at the weld line after a quench and temper treatment-magnified 500X

This solid state bonding process does not produce the embrittlement that would normally be found in fusion weld processes. The weld is essentially free of iron-aluminum compounds, at least to the extent that it cannot be detected by electron-probe and electron-microscopy investigations. The fatigue curve shown in Fig. 50.22 shows these steel-aluminum alloy welds to have a fatigue limit of ± 15,000 psi, well within the scatter band for the unwelded aluminum. Hot-short aluminum alloys such as 2024, when welded to steel, would not be expected to exhibit 100% weld efficiency. This also holds true for hot-short steels, such as those that are highly resulfurized. These steels exhibit a strong directional effect and, as a result, lose a significant portion of their static and fatigue strengths, presumably because of the transverse flow line direction in the weld zone.

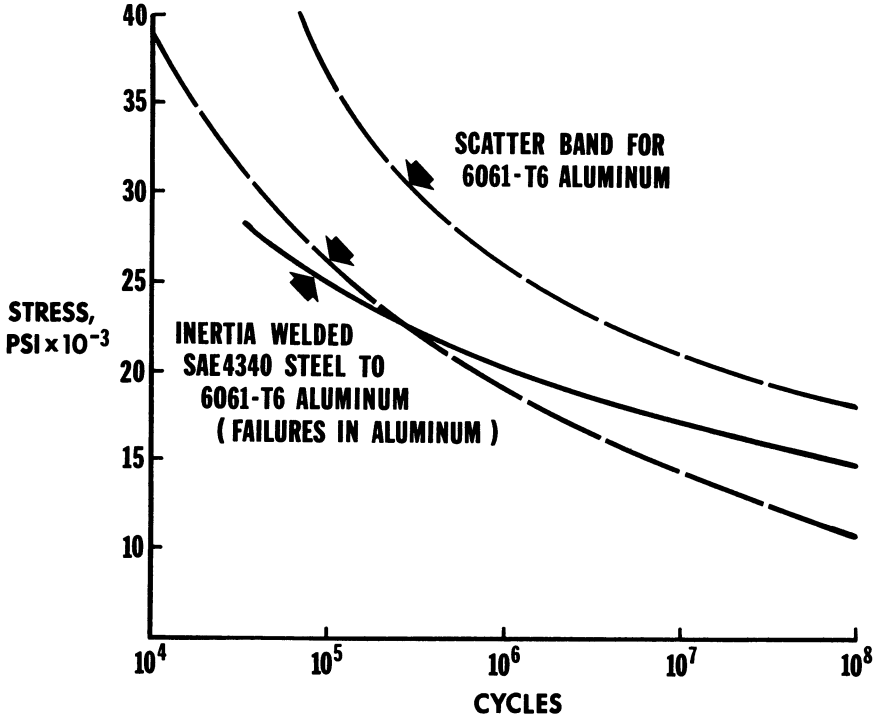


Fig. 50.22.—Failures occurred away from the weld interface where the hardness was a minimum in the aluminum, as illustrated in Figure 17

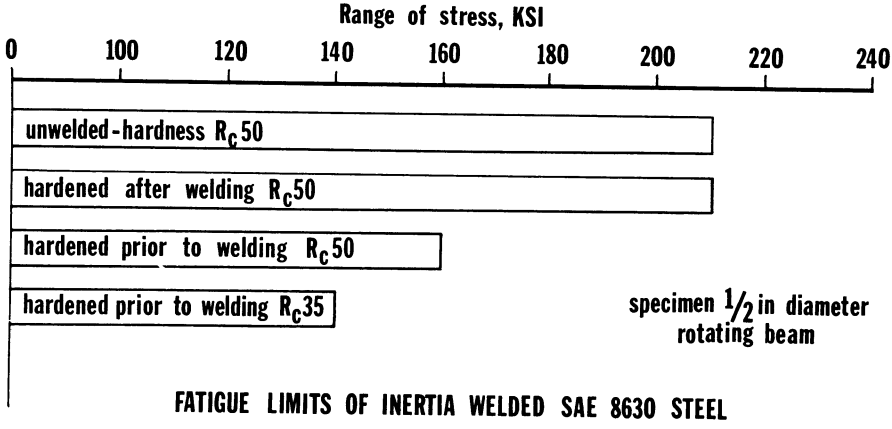


Fig. 50.23.—Full strength of inertia welds occurred when heat treated after welding. Less strength results when tested in the aswelded condition because of tempering which occurs in the HAZ (see Fig. 26 and 27)

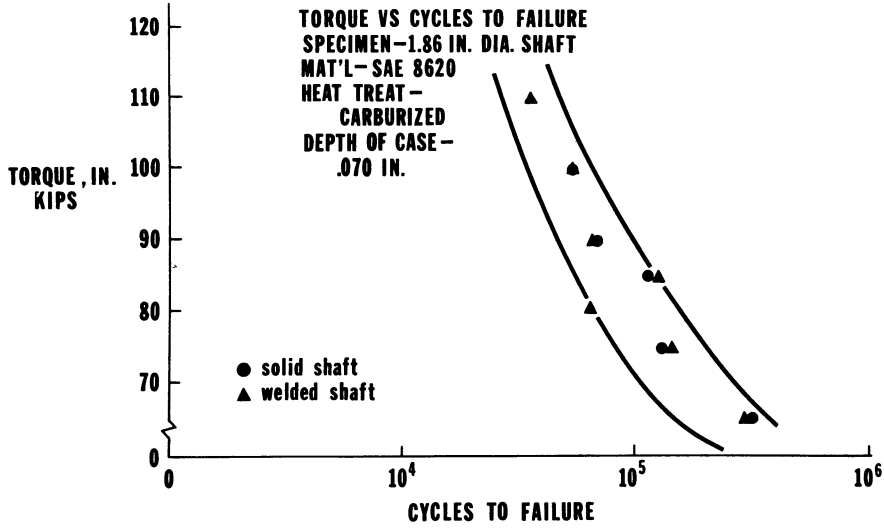


Fig. 50.24.—Fatigue tests comparing non-welded (solid) and inertia welded shafts

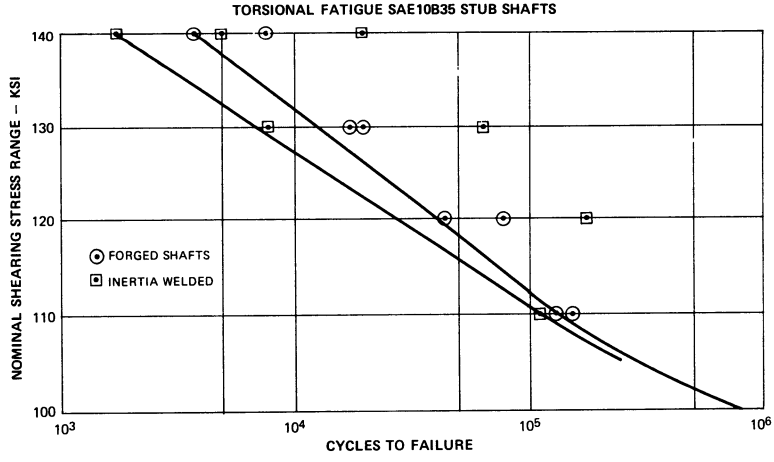


Fig. 50.25.—Fatigue tests comparing forged shafts (non-welded) and inertia welded shafts. These 2-inch diameter specimens were heat treated to Rc 50 hardness

Fatigue results of inertia welds of SAE 8630, carburized SAE 8620 and SAE 10B35 steels, shown in Figs. 50.23, 50.24 and 50.25 respectively, match the unwelded specimens fatigue limit. In the finite life range, inertia welds may show a loss of about 10% when steel hardnesses exceed approximately Rc 45.

Best fatigue results of friction weldments will be obtained when a quench and temper treatment follows the weld operation. The lower fatigue strengths shown in Fig. 50.23 is a result of the tempering of the pre-hardened weld members in the heat affected zone, as shown in Figs. 50.26 and 50.27. It is mandatory to machine away the weld flash to remove the notch effect, and to heat treat after welding if maximum fatigue strengths are required.

Fig. 50.28 shows fatigue results of torsion tests of a composite weldment. The flange portion of these specimens is from a low carbon alloy steel plate, while the shaft portion is from a medium carbon boron steel bar. Heat treatment followed welding to produce a machinable hardness (Rc 35) in the low carbon steel flange, and Rc 50 in the pre-machined shaft for good fatigue strength.

This composite part represents a broad category of applications for the weld process to eliminate costly forgings, to facilitate easier heat treatment or machining, and produce parts with specific properties where needed.

MATERIALS WELDED

The ferrous based materials, from mild steel to high-speed tool steel, can all be welded. The mild steels are relatively easy to join and have a wide range of parameters. Highly alloyed steels, such as high-speed steels, can also be efficiently joined, but with a much narrower operating band of parameters and more axial thrust force, commensurate with their higher forging flow stress. Their lack of toughness and their sensitivity to notches and thermal shock may dictate that weld flash be removed prior to thermal quench treatments to prevent crack propagation from the flash.

Titanium can be easily joined. Titanium's ability to diffusion bond to itself at relatively low temperatures and pressures, when the surface contaminants are removed and because of its low thermal diffusivity, makes it a natural candidate for inertia welding. For the alpha-beta titanium alloys, the weld joint will generally be made in the beta temperature range, but since the heat affected zone is small and the beta structure is heavily worked, the weld joint strength will generally equal or exceed the wrought properties of the parent material.

The stainless steels and rust resisting chromium alloys generally are comparatively easy to join with good properties without much care being given to the joining parameters. The heat treatable stainless alloys, as with other highly alloyed steels, are more sensitive to processing variables, in that the heat affected zone will require further processing to produce the desired properties.

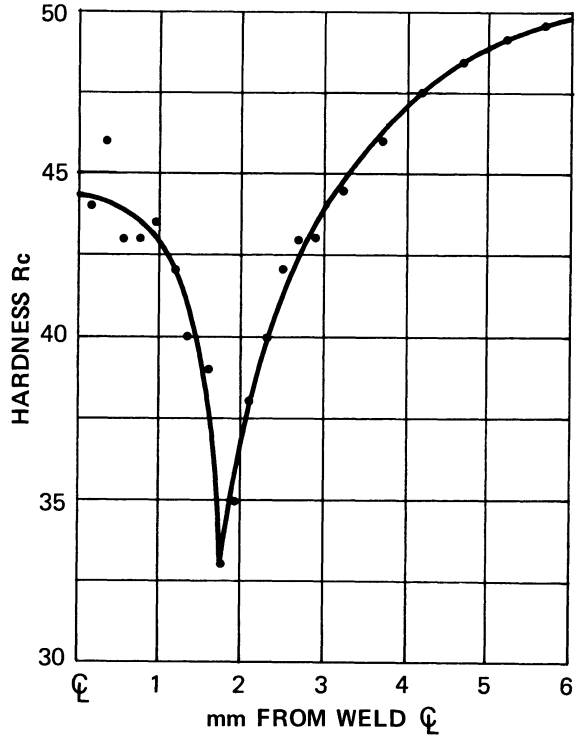


Fig. 50.26.—Hardness traverse through HAZ of SAE 8630 steel, hardened to Rc 50 prior to welding

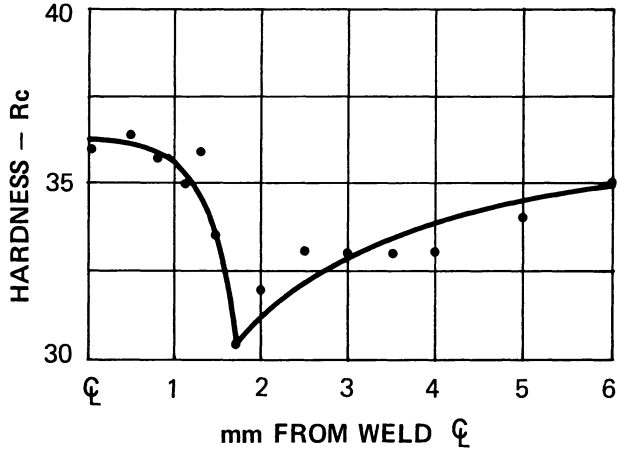


Fig. 50.27.—Hardness traverse through HAZ of SAE 8630 steel, hardened to R35 prior to welding

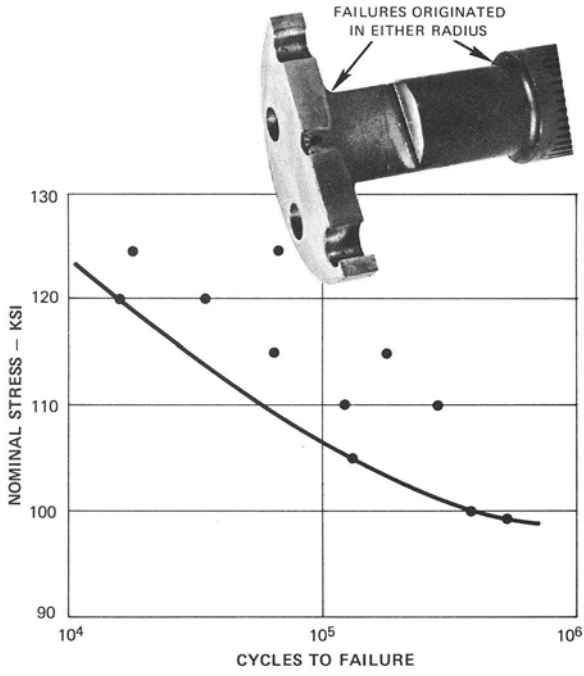


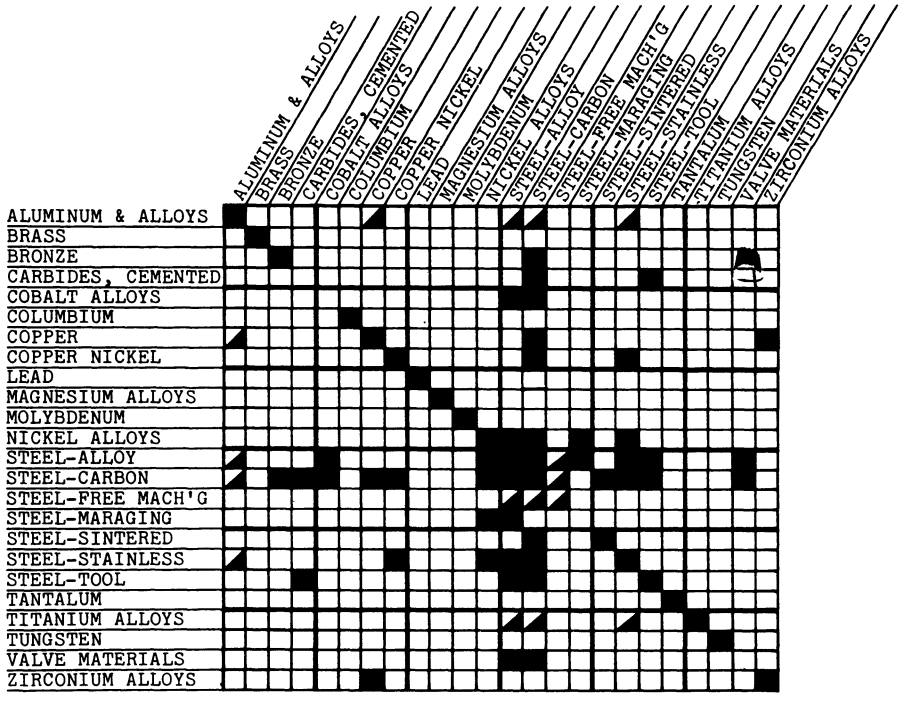
Fig. 50.28.—Fatigue test date of composite inertia weldment of low carbon steel flange and medium carbon steel shaft

Material with high thermal diffusivity values, or materials that tend to seize and cold work at the faying surfaces, require high speeds to produce high heat input rates while limiting the torques. Copper and molybdenum are two examples of materials that require high speeds.

Table 50.4 lists most of the metals and alloys that have been inertia welded to date. It may be assumed that many more of the combinations may be welded with various degrees of success. Materials such as a leaded-bronze alloy, or that exhibit hot shortness cannot, as a rule, be welded.

Cast irons cannot be welded with any degree of success. Any incipient welding that may occur with cast iron is of such a brittle nature that it has no commercial value. As a general rule, at least one of the weld members must be of a forgeable nature at the welding temperature if it is to be successfully welded.

Table 50.4—Most of the metals and alloys that have been inertia welded to date



APPLICATIONS

It may be generally stated that the various versions of the friction welding process are frequently replacing pressure or flash welding where these welding processes have, in the past, been considered the standard method of joining. As previously stated, one important restriction with the friction welding process, however, is that one of the members being joined must have the essentially axial symmetry, because of the high rotational speeds involved.

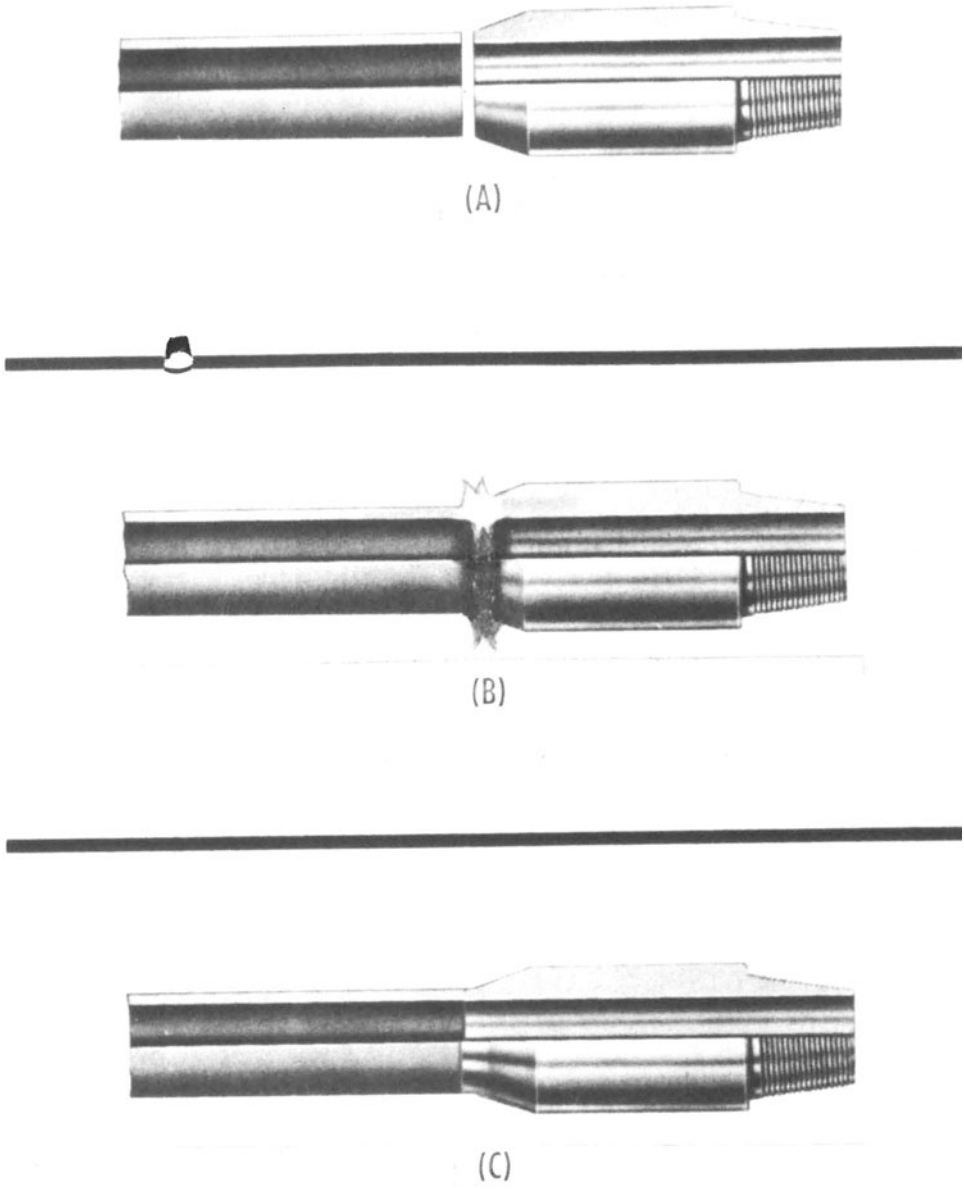


Fig. 50.29.—Cut-away view of friction welded tool joint (A) Pipe and pin connector before welding (B) Friction welded joint showing upset (C) Upset metal turned off and bored out

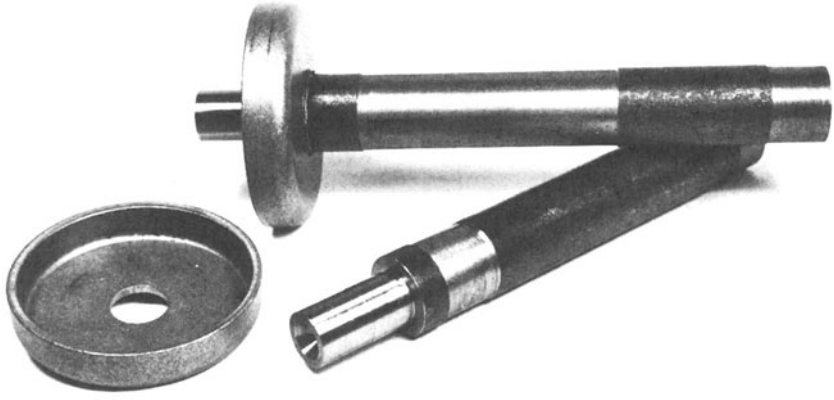


Fig. 50.30.—Inertia welded input shaft.

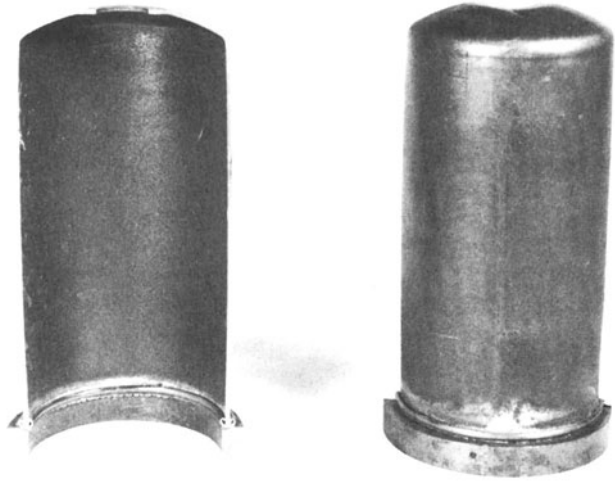


Fig. 50.31.—Thin walled tube welded to thick ring.

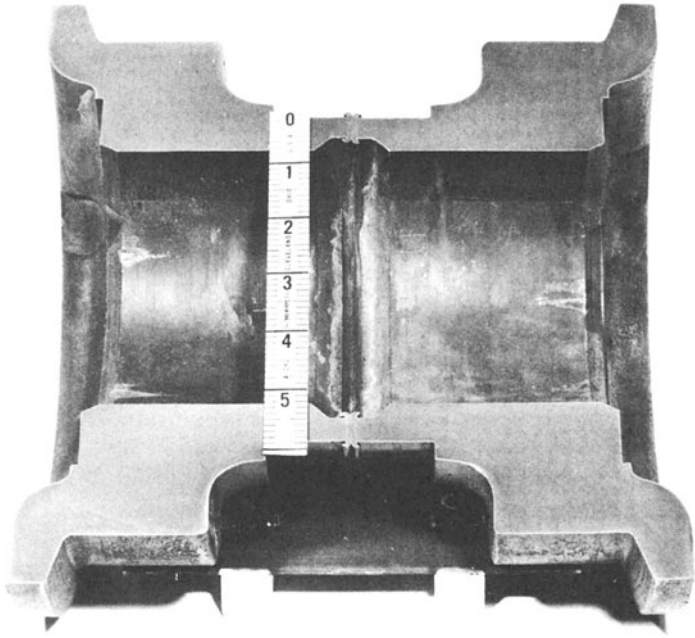


Fig. 50.32.—Track roller weldment of SAE 1046 steel.

A typical application of the conventional friction process, as well as the inertia procedure, is shown in Fig. 50.29. This is an example of joining low alloy to plain carbon steel, where both members have tubular cross-sections.

The automotive transmission input shaft shown in Fig. 50.30 is fabricated by welding an SAE 1010 steel stamping to a bar of SAE 1141 steel. This part was put into production as an inertia weldment because no other method produced satisfactory fatigue strength. Actual weld time for this weld is 2 seconds, with a floor-to-floor time of 30 seconds. The thin walled (0.060 in.) tubular container, shown in Fig. 50.31 welded to a base of greater thickness, is made in an 8 second floor-to-floor weld cycle with an actual weld time of 1 second. The difference in floor-to-floor time between these two welds is mostly a result of differences in tooling.

This assembly was formerly made by copper brazing. The process was changed to inertia welding to lower cost and to produce a more reliable and consistent part.

The photograph in Fig. 50.32 illustrates a tube-to-tube type weld of approximately 7 square inch area made in about 2.5 seconds weldtime with a floor-to-floor time of 30 seconds. This weldment of SAE 1046 steel is welded without benefit of pre-heat, and is subsequently heat treated to the desired hardness level. This process replaced the submerged arc process previously employed.

The maximum cross-sectional area of mild steel that can be welded with current conventional friction welding equipment is 10 sq. in. At present, the largest inertia welder has the capacity to weld 4-in. diameter bars, or tubes of 24-sq. in. cross-sectional area. The maximum sizes that can be welded with any given piece of equipment varies: it depends upon the properties required of the particular application.

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