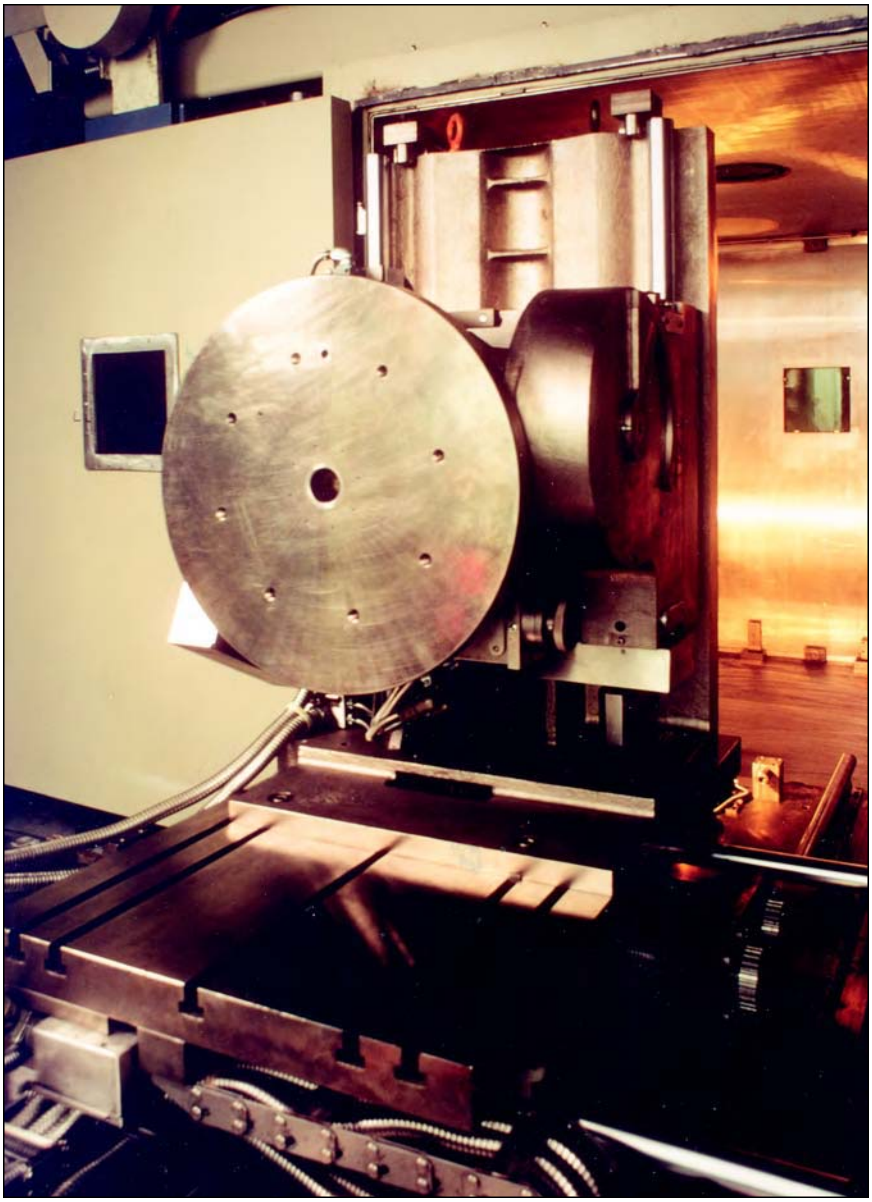


Figure 13.23—Table with X-Y Drive and Rotary Positioner for Electron Beam Welding Chamber

Programmed indexing of the eccentric table from segment to segment can be added.

Multiple-spindle rotary fixtures also are used when making circumferential welds in a group of same components. The components are batch loaded, and then successively indexed into welding position by a motor drive. The joint on each piece can be positioned for welding by linear movements of the worktable on which the rotary fixture is mounted. It is possible to automate the entire operation.

CONTROLS

Since all the operating variables of an electron beam welding system are directly controllable, the process is readily adaptable to computerized numerical control (CNC). Movement of the workpieces or the gun and electron beam deflection can be preprogrammed in any combination. The beam current also is programmable. Thus, the beam can be easily changed from one discrete level to another, or changed at a specified rate. The easy and accurate CNC control of upslope/downslope and the capability of producing various beam deflection patterns enhance the capacity of EBW to produce welds of extremely high quality.

Other variables, including the accelerating voltage, beam focus, emitter power, chamber pressure and other auxiliary functions also can be part of the program for control or monitoring. Electron beam welding systems perform computerized contour welding of intricately shaped components, in which beam power and travel speed must be varied as a function of position along the weld path. The system also is used for components requiring multiple-pass weld programs. Modern CNC controllers continue to replace manual and programmable logic controller (PLC) systems.

MEDIUM-VACUUM EQUIPMENT

The equipment used for medium-vacuum electron beam welding basically is a modification of standard high-vacuum equipment. An orifice, or aperture tube, is added into the gun column assembly. This allows beam passage but impedes gas flow, thereby allowing the separately pumped gun region to remain under high vacuum when the chamber is operated at a medium-vacuum level. As on high-vacuum equipment, a column valve is used to isolate and maintain the gun region under high vacuum during chamber venting, and the added aperture helps to maintain a vacuum of 1.3 10^{-2} Pa (10^{-4} torr) or better in the gun region during beam operation, while still allowing the beam to impinge on a workpiece located in a medium-vacuum environment. Thus, on medium-vacuum equipment, the chamber is cyclically vented as new workpieces are loaded, and then rapidly pumped down to the specified medium-vacuum welding level without exposing the gun region to atmosphere. This permits high-volume weld production. Both low- and high-voltage EBW systems are available for medium-vacuum welding.

General-purpose medium-vacuum systems, such as the one shown in Figure 13.24, are used advantageously in short production runs. However, most medium-vacuum units are especially tooled for specific weld assemblies. In each case, the work chamber and tooling are an integrated assembly designed for a single application. Figure 13.25 illustrates typical medium-vacuum tooling concepts.

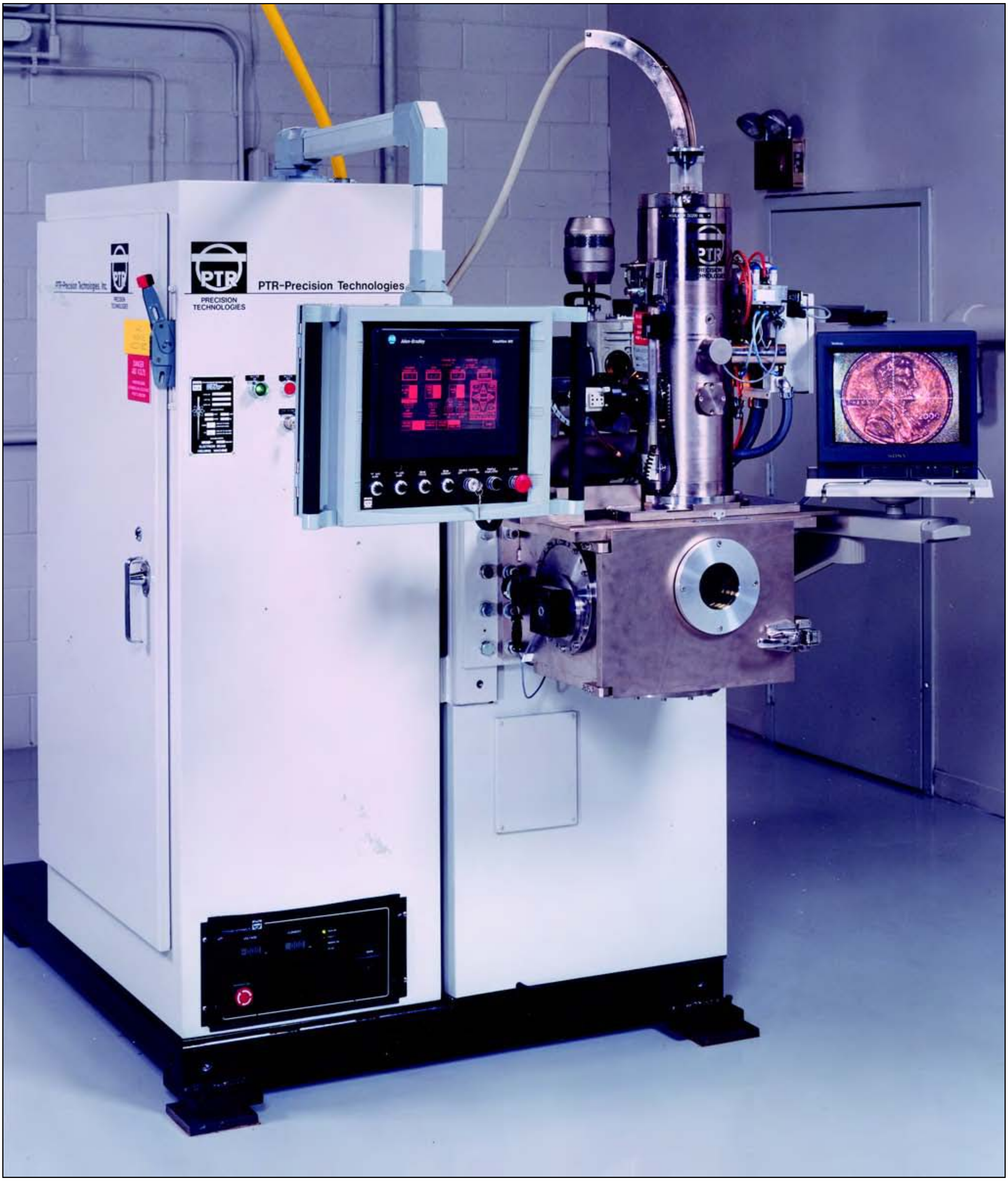
Various medium-vacuum welding systems are used for high-production applications. For example, a machine with a single welding station and multiple-loading stations can have a production capability of welding approximately 200 components per hour. A dual welding station machine could increase that production capability up to 500 components per hour. In the final analysis, production rates are dependent on the design of the weldment.

One method of achieving high production with medium-vacuum equipment is shown in Figure 13.26. This equipment uses a sliding seal to provide intermediate vacuum zones before and after the separately pumped zones in the medium-vacuum welding chamber. This method maintains a series of continuously pumped vacuum zones that eliminate the need to pause for evacuation, thus utilizing the high-production capability of an indexed feed table and allowing production rates in excess of 500 weldments per hour.

A modern and efficient sequence of operations is employed by automotive industry sectors in Europe and Asia for high-production, medium-vacuum welding of components. A schematic illustration of this system is shown in Figure 13.27. This method eliminates any relative motion between seals and sealing surfaces (a mandatory requirement on the sliding-seal method) and thus avoids the wear that inherently occurs as a result of the sliding motion between these surfaces, but still utilizes the advantages of the index-style of fast transfer of components. As illustrated in Figure 13.27, a segmented chamber is used. Multiple workpieces are placed in the load/unload segment of the chamber. The chamber can be unloaded and loaded and pumped down to a partial-vacuum level while components previously indexed into the processing segment of the chamber are being welded. Thus the chamber is loaded and pre-pumped while the workpieces in the processing chamber are being welded. Then, while under vacuum, the workpieces in the load/unload chamber and the workpiece assemblies in the processing chamber simultaneously lower, index, and lift, thereby interchanging workpieces in these two chambers without exposing the processing chamber to any environment other than a vacuum. While workpieces newly introduced to the processing chamber are being welded, the load/unload chamber can be vented, the weldments removed, and new assemblies loaded. The sequence continues as the chamber is pre-pumped and everything readied for the next full-vacuum interchange of the chamber segments. A finished-product version of the system schematically depicted in Figure 13.27 is shown in Figure 13.28, with a close-up view of the load/unload chamber portion pictured in Figure 13.29.

NONVACUUM EQUIPMENT

The use of nonvacuum EBW means that the beam must pass through a gas atmosphere to perform a welding



Photograph courtesy of PTR—Precision Technologies, Inc.

Figure 13.24—A General-Purpose Medium-Vacuum Electron Beam Welding Machine

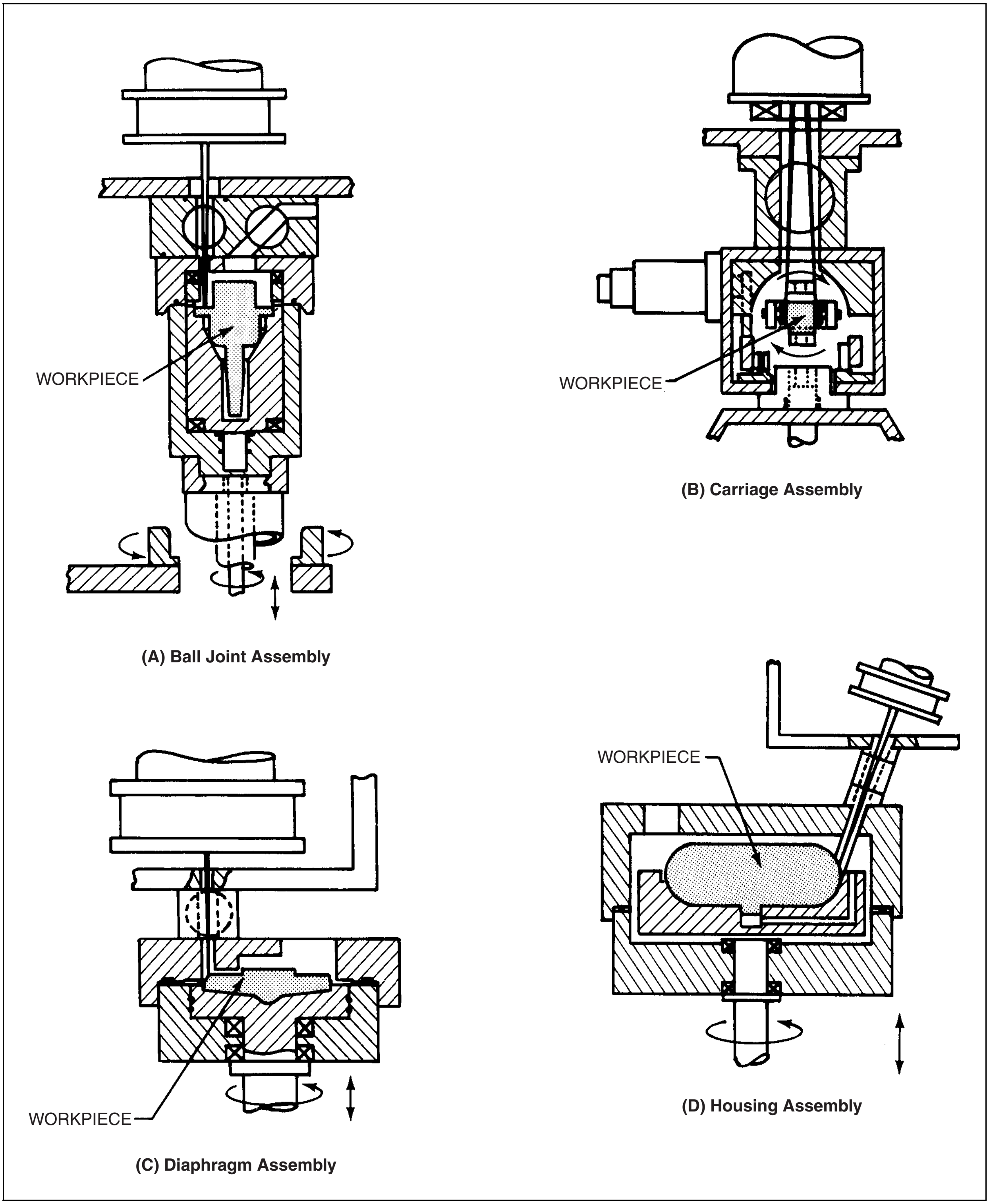


Figure 13.25—Typical Tooling Concepts in Special-Purpose Medium-Vacuum Electron Beam Welding Machines

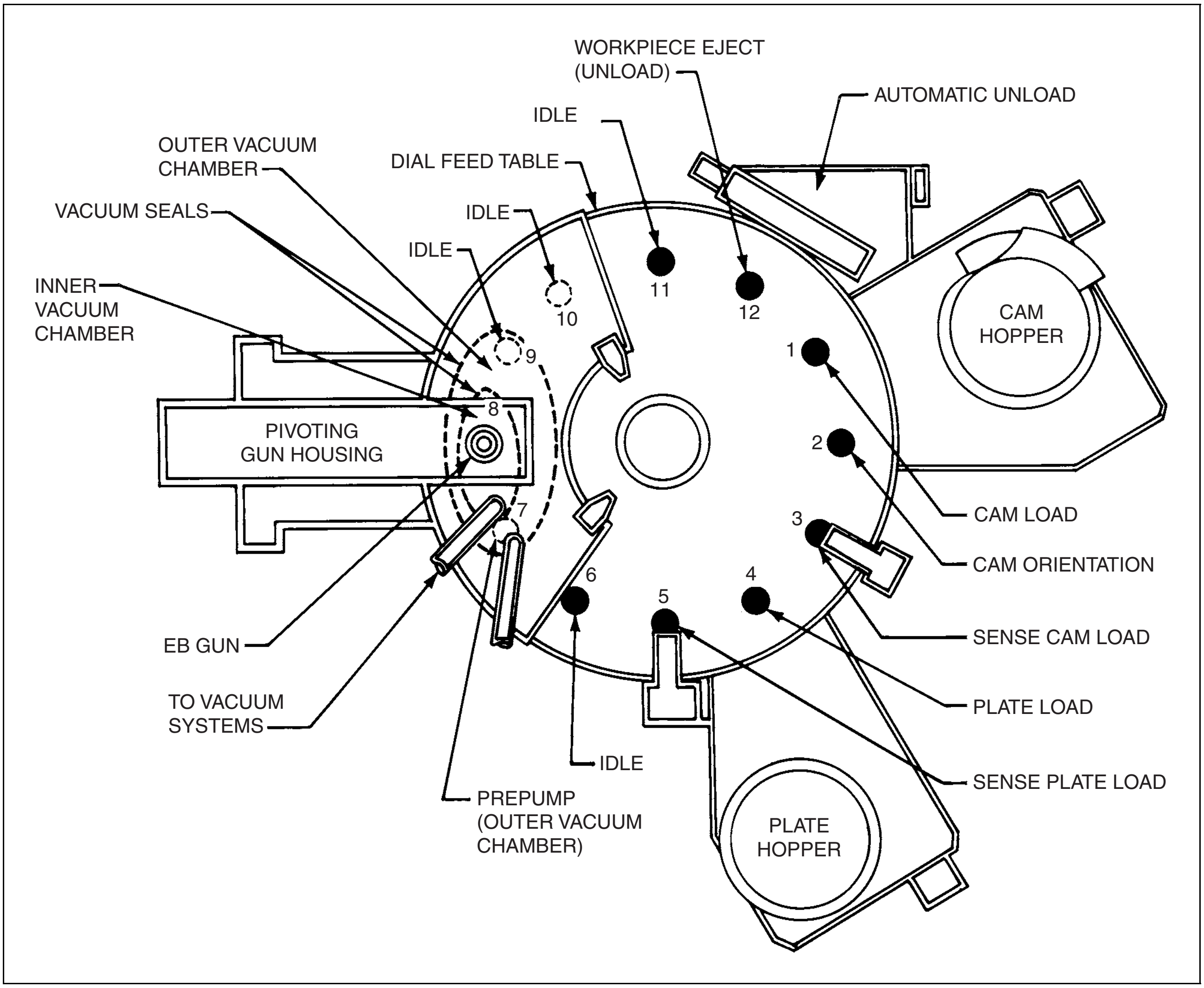
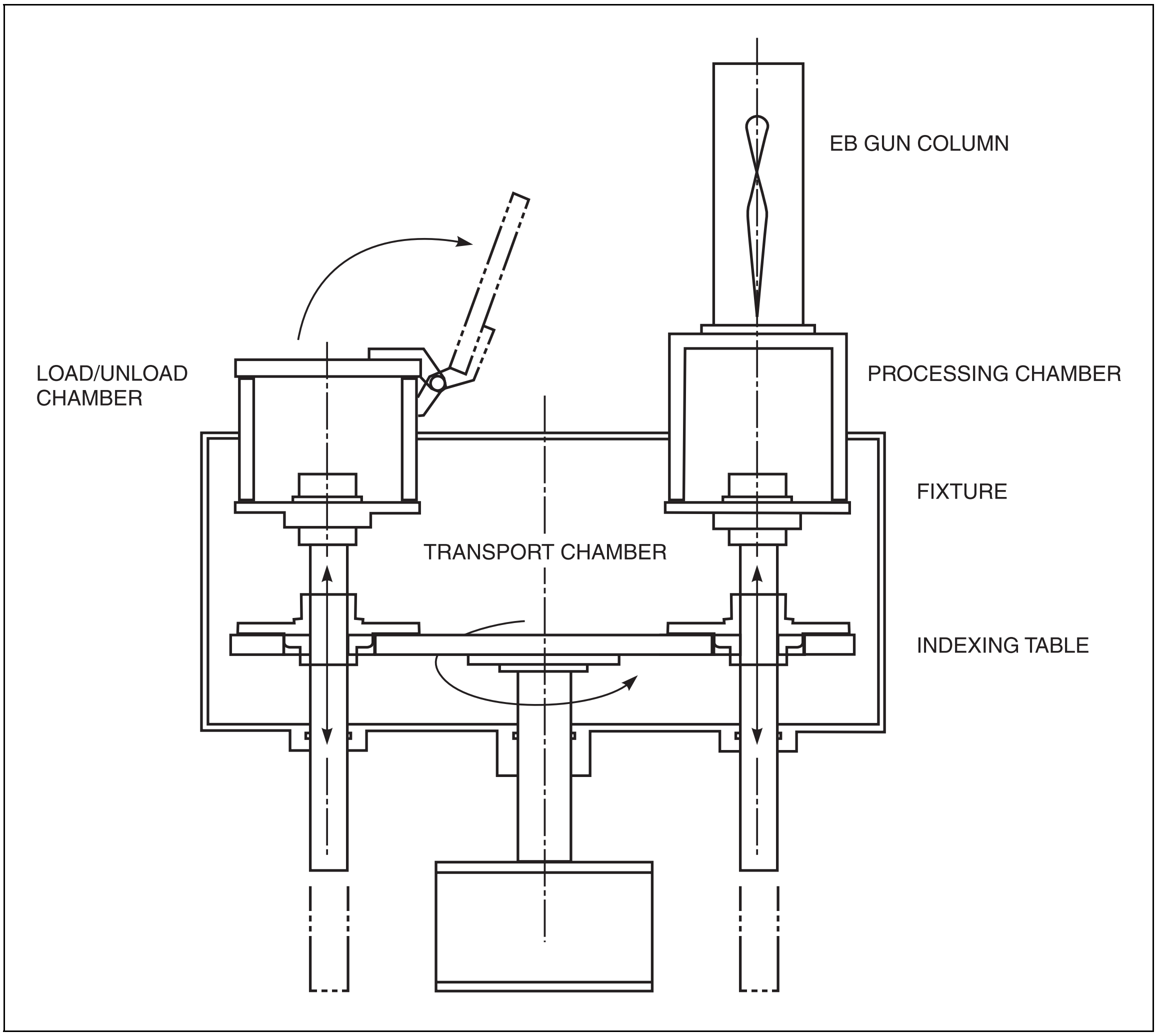


Figure 13.26—A Medium-Vacuum Electron Beam Welding System Capable of Prepumping for Continuous Workpiece Feeding

operation. In applications where the metal is nonreactive, a small shield gas arrangement may be used; in other cases, a larger area of inert gas may be needed to complete welds. A beam of electrons passing through a gas primarily is scattered by the shell electrons of the gas atoms or molecules. As the gas pressure increases, scattering becomes more severe (refer to Figure 13.7). This produces a noticeable broadening of the beam profile and a decrease in the power density of the beam, but not necessarily a loss in total beam power.

An electron beam must be generated in a high vacuum. In addition, the electron velocity (accelerating voltage) must be high enough to minimize the scattering effect of the atmosphere. As a result, to weld with the beam at atmospheric pressure, the beam is passed through a series of chambers or stages operating at progressively higher pressures. The series of chambers operating at successively higher pressures is obtained by *staging* (for example, by differentially pumping a number of chambers). A series of apertures is provided to permit the electron beam to pass through the wall of one chamber into the next, while restricting the gas flow in the opposite direction. This orifice-and-pumping system must be designed to maintain the atmospheric-to-high-vacuum gradient required. The electron beam must be accelerated through a high voltage. If the last stage is in air, this voltage must be a minimum of 150 kV in order to provide a practical working dis-



Source: PTR—Praezisionstechnik GmBH

Figure 13.27—Schematic of a Pre-Pumped, Drop-Bottom Indexing System Used in Medium-Vacuum Electron Beam Welding

tance between the final orifice and the workpiece. The beam power level used and the type of gas comprising the atmosphere through which the beam eventually passes can greatly influence the useful working distance.

Figure 13.30 is a diagram of a conventional nonvacuum electron beam gun/column assembly, including an orifice system. The electron gun in Figure 13.30 is typical of those used with the other modes of electron beam welding, and is capable of operating at accelerating voltages in the range of 150 kV to 200 kV. Beam current, and thus the power, is controlled by the voltage on the bias electrode of the gun. The beam is focused by an electromagnetic lens to the minimum diameter of the orifice system, shown at the bottom of Figure 13.30. It emerges from the vacuum environment into air at atmospheric pressure through the lower orifice. Inert gas shielding can be added, if desired. The workpiece is placed near the lower orifice.

During operation, a high vacuum is continuously maintained in the upper gun area by using an oil diffusion pump or turbo molecular pump on this region. Lesser vacuum levels are maintained in the interim pressure stages by mechanical pumps. In most cases, the workpiece is moved horizontally in front of the gun column, but the entire gun column can be moved if desired. As with the high-vacuum and medium-vacuum

Photograph courtesy of PTR—Praezisionstechnik GmBH

Figure 13.28—Finished-Product Version of the EBW-MV System Diagrammed in Figure 13.27

modes, the gun can be placed in either a vertical or a horizontal position.

Another type of nonvacuum electron beam welding gun unit features a gas-filled, high-voltage power source that can be mounted directly on the gun/column assembly. The unit then can be traversed along the weld joint during operation.

As with the sliding-seal and the modern concepts of medium-vacuum equipment, in which the time for evacuation of the work chamber is effectively eliminated, production rates in excess of 500 weldments per hour are readily attainable with the nonvacuum EBW mode. In addition, since the workpiece need not be enclosed in a chamber and a special atmosphere is not required, workpiece size and surface condition requirements are greatly alleviated.

The welding area for all electron beam processes must be shielded to protect personnel from the X-radiation produced during welding. Health hazards from electron beam radiation are discussed at the end of this chapter in the "Safe Practices" section.

WELDING PROCEDURES

Specifying welding procedures for an electron beam welding application must consider the many variables previously discussed, such as specification of equipment, movement of the gun or workpiece, magnitude of current, accelerating voltage, beam focus, beam deflection, travel speed and distance, emitter power and chamber pressure. Regarding chamber pressure, guidance for converting Standard International and U.S. Customary units of pressure is presented in Appendix C, "Cross-Reference Chart for Various Pressure Units."

Photograph courtesy of PTR—Praezisionstechnik GmBH

Figure 13.29—View into the Load-Unload Chamber of the EBW-MV System Shown in Figure 13.28

Additional welding conditions that must be considered for electron beam welding include joint design, joint preparation, the fitup and fixturing of the workpieces, and the choice of base metals and filler metals. Recommendations for these variables are presented in this section.

JOINT DESIGN

Butt joints, corner joints, lap joints, edge joints, and T-joints can be made by electron beam welding using square butt joints or seam welds. Fillet welds are difficult to make and generally are not attempted. Typical joint designs for electron beam welding are shown in Figure 13.31. Modifications of these designs frequently are made for particular applications.

Square butt welds require fixturing to maintain fitup and alignment of the joint. They can be self-aligning if a rabbet joint design is used. The weld metal area can be increased using a bevel joint, but fitup and joint alignment for bevel joints are more difficult than for square butt joints. Edge, seam, and lap fillet welds are primarily used to join sheet metal of varying gauges.

Joint Preparation and Fitup

When no welding wire is added, fitup of the workpieces must be more precise than for arc welding processes, because poor fitup would result in incomplete filling of the weld joint. The beam must impinge on both members and melt them simultaneously, except for seam welds in which the beam penetrates through the top sheet. Underfill or incomplete fusion will result from poor fitup, and lap joints that are not clamped sufficiently will melt through.

A metal-to-metal fit of the workpieces is desirable but difficult to obtain. The acceptable root opening for a particular application depends on the mode of EBW employed, the type of base metal, the thickness and configuration of the joint, and the required weld quality. Thus, sheet sections being welded in the vacuum mode may require a fitup with tolerance of less than 0.1 mm (0.004 in.), plate sections being welded in the nonvacuum mode may tolerate a fitup more than five times greater. Aluminum alloys can tolerate somewhat larger root openings than steel. Beam deflection or oscillation is used in high- and medium-vacuum welding to widen the fusion zone, but when used in nonvacuum welding, it may permit larger root openings. Consequently, the maximum acceptable root opening and the tolerance for each particular application should be determined and qualified in order to avoid unnecessary joint preparation costs.

In general, roughness of the faying surfaces is not critical as long as the surfaces can be properly cleaned and all contamination removed. Burrs on the sheared edges of sheet are not detrimental unless they separate the faying surfaces of lap joints.

Cleaning

Cleanliness is a prime requisite for high-quality welding. The cleanliness level required depends on the end use of the welded product. Contamination of the weld metal may cause porosity or cracking, or both, and deterioration of mechanical properties. Improper cleaning of the workpieces may excessively lengthen chamber evacuation time, depending on the vacuum mode being employed.

In the past, acetone and methylethylketone were considered to be excellent solvents for cleaning electron gun components and workpieces. However, these

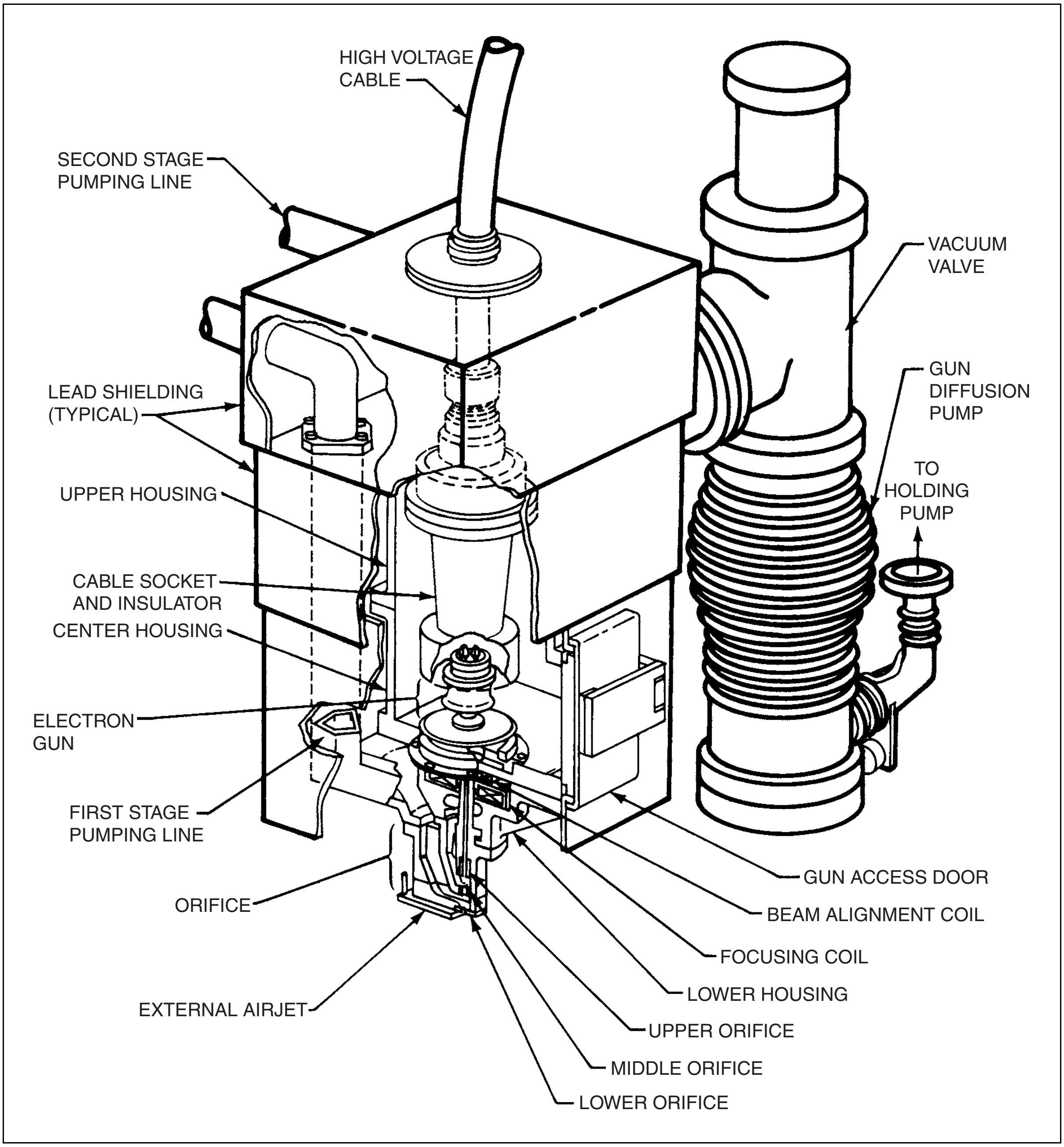


Figure 13.30—A Nonvacuum Electron Beam Gun Column Assembly

chemicals have since been considered to be possible hazardous substances, thus most facilities use pure alcohol instead.

Chlorinated hydrocarbon solvents should definitely not be used because of their detrimental effect on the operation of high-voltage equipment and because of their potential for forming phosgene gas when exposed to ultraviolet light. If a vapor degreaser containing a chlorinated hydrocarbon solvent must be used for heavy degreasing tasks, the components must be thoroughly washed in pure alcohol afterward. An alternative would be to use a fluorocarbon-type solvent for degreasing. After final cleaning, the joint area should not be touched by hands or tools.

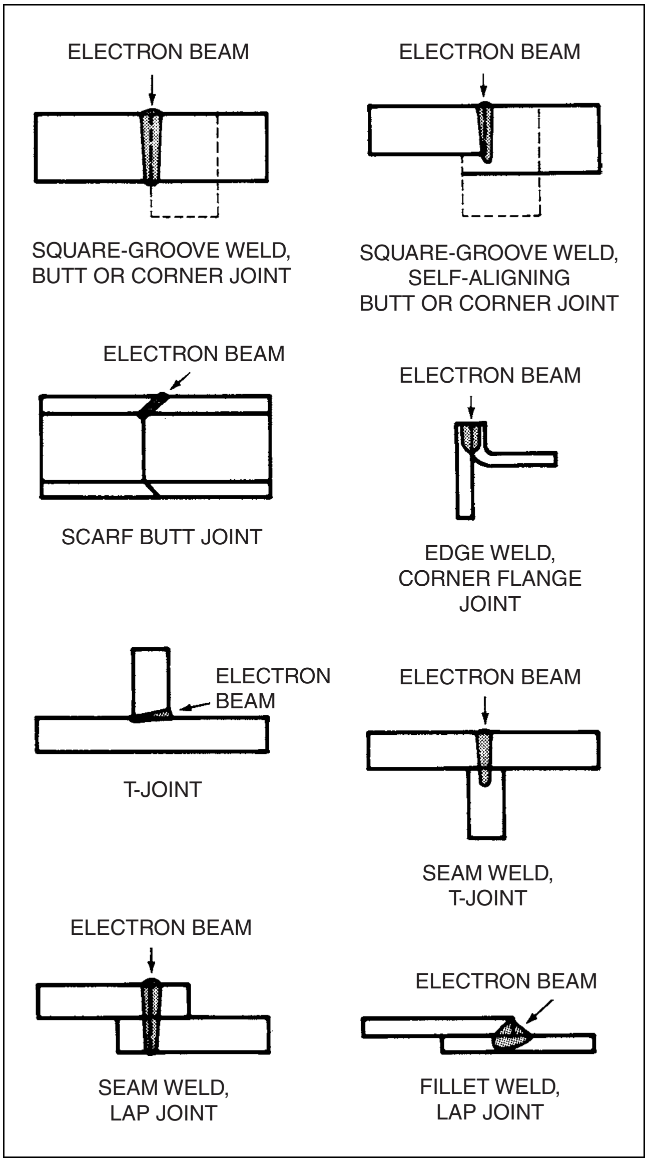


Figure 13.31—Typical Joint Designs for Electron Beam Welds

Surface oxides and other forms of contamination that cannot be dissolved by solvents should be removed by mechanical or chemical means, such as brushing, scraping, machining, or chemical etching. Flat surfaces of soft metals, for example, magnesium, aluminum, or copper can be scraped by hand. Machining without a coolant is preferred for all but very hard metals, where grinding must be used. Surfaces that are not prepared by machining should be chemically cleaned.

Grit blasting and grinding are not recommended for soft metals, including soft steels, because grit may become embedded in the surfaces. Wire brushing generally is not recommended because it also tends to embed contaminants in the metal surface. Nonvacuum welding generally will require less stringent precleaning than vacuum welding.

FIXTURING

Electron beam welding can be accomplished by manually or automatically controlling the functional operation of the system. The workpieces must be fixtured to align the joint, unless the design is self-fixturing; then either the assembly must move or the electron beam gun column must be moved to accomplish the weld.

Self-fixturing joints should be used when practical. A pressed or shrink fit can position circular components for welding. However, these methods require close-tolerance machining, which may not be economical for high-production welding.

Fixturing for electron beam welding need not be as strong and rigid as that required for automatic arc welding. The reason is that electron beam welds generally are made with much lower heat input per unit length of weld than arc welds. Therefore, stresses in the weldment caused by thermal gradients extend over a smaller volume of metal. However, fixturing used for EBW must not introduce magnetic effects that adversely affect the beam. The close fit-up and alignment required for joints in electron beam welds generally call for fixturing made to the same tolerances. Copper chill blocks plated with nickel can be used to remove heat from the joint.

Worktables and rotating positioners should have smooth and accurate motion at the required travel speeds. All fixturing and tooling should be made of nonmagnetic metals to prevent magnetic deflection of the beam. All magnetic metal workpieces should be demagnetized before welding.

The entry and exit of the electron beam tends to produce underfill at both ends of the welded joint. To minimize or eliminate underfill, weld tabs of the same metal as the workpieces should be fitted tightly against both ends of the joint so that the beam can be initiated on the starting tab, traversed along the weld joint, and terminated on the runoff tab. When the weld is completed the tabs can be removed flush with the ends of the workpiece.

FILLER METAL

Filler metal normally is not needed to obtain a weld with complete joint penetration when the faying surfaces of butt joints are fitted together with acceptable tolerances. As welding progresses along the joint, weld metal flows from the leading edge to the trailing edge of the keyhole. As the weld progressively freezes, thermal contraction usually produces a welded joint free of underfill when proper welding procedures are used. Certain joint designs use the thermal contraction of the weldment to produce an autogenous weld from multiple weld passes; these welding procedures use a narrow tapered root opening and a low-power-density beam to produce welds with complete joint penetration. These welds tend to exhibit few of the discontinuities sometimes encountered with single-pass autogenous welds.

For some applications it is desirable or necessary to add filler metal to obtain an acceptable welded joint. Filler metal may be needed to obtain certain physical or metallurgical characteristics in the weld metal. Characteristics of the weld metal that may be altered or improved by the addition of filler metal include ductility, tensile strength, hardness, and crack resistance. For example, preplacing a thin aluminum shim in the joint can produce a deoxidizing action in mild steel, which will reduce porosity in the weld.

When filler metal is added to the joint for metallurgical purposes, filler metal in the form of welding wire is often used, but not employed exclusively. The dilution obtained from a dissimilar filler metal added as wire at the joint surface does not occur uniformly from top to bottom of the weld. For a single-pass weld in heavy plate, filler metal may take the form of a thin shim. The presence of the filler shim requires that beam oscillation or a large-diameter spot be used to melt the shim and the base metal on both sides of the joint. This is not the case with weldments in thin metal, where welding wire can be added at the surface and dilution will occur throughout the entire joint. Typical examples of filler metal additions for metallurgical reasons are the welding of Type 6061 aluminum alloy using Type 4043 aluminum filler metal, and the welding of beryllium using aluminum or silver filler metal.[8]

Filler metal may be added at the surface to fill the joint during a second pass after the penetration pass has been made. This is done to obtain complete joint penetration in thick plate. Welding wire-feeding equipment usually is either a modified version of that used for gas tungsten arc welding or a unit specially designed for use in a vacuum chamber. Welding wire diameters generally are small, 0.8 mm (0.030 in.) and under, because the wire feeder must uniformly feed the wire into the leading edge of a small weld pool. The wire-feeding nozzle should be made of a heat-resistant metal.

When welding in a vacuum chamber, the welding wire drive motor must be sealed in a vacuum-tight enclosure or otherwise designed for use in a vacuum. Outgassing from an open motor will greatly increase the work chamber evacuation time. Provisions must be made for adjusting the wire-feed nozzle so that the welding wire is positioned relative to the electron beam and to the weld joint over the entire length of the joint.

8. Aluminum classification designators are defined by the Aluminum Association, 900 19th Street N.W., Washington, D.C. 20006.

SELECTION OF WELDING VARIABLES

The rate of energy input to the workpiece during EBW commonly is expressed in joules per inch, or joules per second.[9] The formula for this expression is the following:

$$\text{Energy input, J/mm (J/in.)} = EI/S = P/S \qquad (13.2)$$

where:

E = B-Beam accelerating voltage, V;
I = Beam current, A;
P = Beam power, W or J/s; and
S = Travel speed, mm/s (in./s).

Data for welding various thicknesses of a specific material can be plotted to permit interpolation of welding variables for that material over the range of values covered by the data. A curve relating energy input with thickness for a particular group of alloys can be determined from a few tests to establish the welding conditions for untested metal thicknesses. Figure 13.32 provides sample curves for several metals. These figures are particularly useful to determine starting-point conditions. The following factors make this possible:

1. Electron beam welding machine settings usually are regulated by closed-loop servo controls that ensure stability and reproducibility; and
2. The adjustment of each variable is independently controlled to permit flexibility in selection.

Assuming the vacuum level and electron beam gun-to-workpiece distance are held constant, only four basic variables need to be adjusted: accelerating voltage, beam current, travel speed, and beam focus. Beam deflection may constitute a fifth variable, if an oscillating beam motion is employed. These variables combine to make the process of establishing the welding schedule relatively simple.

9. Energy input to the weld from a heat source is discussed in more detail in American Welding Society (AWS) Welding Handbook, 2001, *Welding Science and Technology*, Miami: American Welding Society, Vol. 1, Chapter 2.