

DESIGN AND PLANNING MANUAL

For
**Cost-Effective
Welding**



American Welding Society



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**For
Cost-Effective Welding**



American Welding Society



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SECTION 1

Primary Concepts of Weldability

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Section 1—Primary Concepts of Weldability

Weldability

Welding is used to make large and sometimes complex structures from smaller and simpler metal components. In general, a weld is a localized coalescence of metal that is used to join or repair metal components. Filler metal may or may not be added to the weld. The capacity and ability to join these metal components with available resources help define the term weldability.

The definition of weldability is: *“The capacity of a metal to be welded under the fabrication conditions imposed into a suitably designed structure, which will perform the intended service.”*

When the definition of weldability is reduced to its lowest common denominator, this definition is “it.” To ensure weldability, interaction of countless groups and individuals with specific needs may be involved. For a project to reach a successful conclusion, these needs must be identified, clarified, and, when in conflict, resolved.

All metals may be considered weldable by the very fact that they exist as metals. Depending on whether you are the customer, the welder, the inspector, or the fabricator your definition of weldability may be different. Generally, it is the suitability for service, cost, and weldment aesthetics that determines weldability. With a fundamental understanding of welding and a knowledge of the resources available, “lack of weldability” causing inservice failures, production failures, cost overruns, and schedule delays may be avoided.

In common usage the term “weldability” is somewhat ambiguous and about as varied as the people who use it. The “degree” of weldability can be defined in terms of: weld costs; the capacity of the fabrication to perform its intended service; the ability of the weldment to meet fabrication acceptance standards; or the difficulty of joining a material with a specific process.

Personnel Concerns about Fabrication Projects

Major concerns about a fabrication project and its weldability are expressed by those involved as follows:

- From the customer:

“Does the fabrication perform the intended service and will it last as long as intended?”

“Is the fabrication completed within cost and on schedule?”

“Is it aesthetically pleasing?”

- From the engineer:

“Does the weld and its heat-affected zone meet the critical base metal requirements that are necessary for the intended service of the customer?”

- From the manufacturer:

“How much money does it cost to make the weld (i.e., what’s my profit)?”

“Are there any inspections or requirements associated with the weld that will prevent acceptance of my work?”

“Am I subject to any liabilities if my fabrication is not completed on time or fails in service?”

- From the welder:

“Do I have clearly defined instructions (such as drawings that specify weld size, joint design, material type, material size, stress relief, and welding procedures)?”

“Is there adequate weld joint access?”

“Is there adequate environmental protection?”

“Do I have the proper equipment to accomplish the work?”

“Are the fabrication requirements achievable from the standpoint of accessibility, position, distortion control, weld size, inspection requirements and fabrication sequence?”

“Am I trained and qualified to perform the welding required?”

It is obvious, since the weldability of a metal intersects so many disciplines, that the solution to many weld-associated problems and the ultimate success of a project lies in a *fabricator's ability to coordinate its available expertise*.

There can be no question that people are still the most important resource in the fabrication enterprise. Because of this, it is recommended that a preacceptance bid review group, including production as well as technical personnel, be established to review projects *prior* to acceptance. Formation of this group may be the single most important action taken to ensure a successful and profitable completion for all parties involved. Unless the same project is repeated over and over again, it is obvious that one person cannot resolve all the issues necessary for the project to be a success for all the participants.

Fundamentals of Welding Decisions

One individual in a metals fabrication firm with a varying workload will find it difficult to make good welding decisions for all of the firm's needs. The complexity of welding decisions is immense if the work varies. If an individual makes enough welding decisions, expertise will be required beyond that of filler metals, base metals, and welding processes. This expertise will require a background in, and integration of the technical fields.

Coordination of Expertise

One person normally does not have expertise in all of the areas required to make sound welding decisions. It will benefit a company to have a welding engineer to handle the majority of the welding problems that will arise. However, this individual will find it necessary to coordinate with other available expertise to make the best decisions for the company. If a company is small, this may require hiring a part-time consultant.

Education

There is no substitute for education of personnel involved in welding. Education is needed by the fabrication shop superintendents, the design engineers, the planners and estimators, the production supervisors, and the welding mechanics. Each has different needs. Often, a specification or procedural requirement will not be followed unless there is an understanding of why the requirement is necessary. Understanding the importance of preheats, postheat treatments, and filler metal selection

and how they can affect the safety of personnel and the suitability of the part for service creates a desire by all individuals to follow requirements. Knowing the basics of welding engineering can prevent a company from extensive rework or a customer's refusal to accept a manufacturer's product.

The Welder, Technician, and Production Supervisor

The resolution of many welding problems requires much more than technical solutions. Welding problems require practical solutions as well. For this reason, the practical expertise of the journeyman mechanic and his supervisor can never be overlooked. They are absolutely essential if a company expects to remain profitable. It is for this reason the use of welding engineering technicians is quite common in larger companies. Technicians frequently are trained individuals with journeymen production experience. A balance of welding engineers and welding engineering technicians is most desirable for resolving most welding problems.

The 100% Quality Weld and Weld-Associated Failures

Designers often mistakenly expect the welds they design to have properties that equal or exceed the desired properties of the base metal. The major error in this logic is that the base metal and the weld metal do not perform independently.

Rarely does the weld improve the properties of the metal it joins. The base material, the weld, and the weld's heat-affected zone are not homogeneous regions. They are, in effect, structural and metallurgical discontinuities within the weldment. This is due to the fact that the base materials usually have undergone significant mechanical and/or thermal treatments to optimize their properties, the weld usually performs its service in the as-cast condition, and the heat-affected zone has undergone widely varying heating and cooling rates. In many cases a weld joint lowers fatigue properties and lowers impact properties; in some cases a weld joint also lowers the tensile and yield properties. However, large or complex structures must be welded with high joint efficiency, since large monolithic cast or wrought structures cannot be made in most cases.

Since welds are usually located at changes of cross sections (commonly associated with highly stressed areas), the welds are often in areas where the structure fails. These failures may be wrongly attributed to welds that are perceived as inherently weak or flawed. These

SECTION 1—PRIMARY CONCEPTS OF WELDABILITY

failures are more likely caused by poor decisions on the part of engineers or company management due to a lack of knowledge or training.

Improperly selected joint designs, welding processes, locations of welds, and filler metals are frequently associated with weld failures. The root cause of these types of failures is in the decision-making process and not in the quality of the weld.

Weldability Can Be Determined by the Manufacturer

When a manufacturer *designs* and *fabricates* a weldment, it can truly be said that the manufacturer determines weldability. The manufacturer then controls most of the variables that determine weldability. The weldability of a metal, to a large extent, is determined by the manufacturer's ability to:

- Recognize the cause of existing and potential production problems.
- Properly utilize, coordinate, and develop cooperation of available expertise to make sound welding decisions.

Often weld-associated failures are caused by lack of knowledge about welding and its effect on the base materials. These failures are wrongly viewed as resulting from inherent weaknesses of welds. In most cases, with proper utilization of available expertise, the failures could have been avoided.

Bibliography/Recommended Reading List

Welding Handbook, 8th ed., vol. 1, Welding Technology (WHB-1.8). Miami, Fla.: American Welding Society.

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Section 2—Accepting Metal Fabrication Projects

Background

The critical question asked by a metals fabricator for a completed project to be considered successful is: *Did the project make a profit and was it completed on time?* When large or small companies have repetitive work, they are usually quite successful. They also know the pitfalls. They know what their minimum bid should be and what delivery or schedule times can be met. They probably have experienced the normal day-to-day items that threaten their profit and the quality of their work. Knowing these pitfalls, they can make allowances for them.

However, for a company to be successful when it accepts work that can be defined as a *special project* (meaning a different type of work for the company), the engineer, the fabricator, and the welder need a fundamental understanding of the *weldability of metals* and the basics of *sound welding decisions*. During the acceptance of work, many decisions that seem innocuous to welding end up jeopardizing the weldability of materials and the service suitability of the completed weldment.

Defining Special Projects

The critical first step for a company is the ability to recognize a special project. Nearly all special projects require high up-front costs. There are increased costs in determining:

- Should the company bid on the project?
- What should the bid be?
- To what extent are production instructions required?
- What are the costs to establish these instructions?
- How and when to monitor the work in production?
- Are the company resources adequate?
- Do company equipment and personnel capabilities adequately meet project requirements?
- What additional training/equipment is required to meet project objectives?

Resolving these issues should be accomplished with small review groups with specific tasks in mind.

Special project should be defined as follows:

- (1) Not a repetitive project, even though a company may have procedures that are applicable to the work. This includes work that the company has accomplished before but has not done for a long period of time.
- (2) Any type of field work that is away from the company's home office, and involves a significant number of man hours. Field work limits the company's flexibility for scheduling work accurately. In addition, field work limits the company's ability to combine work activities for economical use of materials, man hours and equipment.
- (3) Any project that requires many different disciplines from the same company to accomplish its task.
- (4) Unusual or complex work requirements (including inspections, paperwork, and records).

Establish a Prebid Review Group (Before Accepting Special Projects)

Since a special project is a nonrepetitive project that may include multiple workshops having new or unusual requirements, the acceptance of such work should be reviewed by a small *prebid review group* before accepting special projects. It cannot be expected that a single person who plans and estimates jobs can assemble and understand all the technical, quality, material, and process requirements of unusual work. When the structure of a company permits, it is recommended that the membership of the preacceptance bid review group consist of comptroller, planner and estimator, design, production lead shop, and quality assurance representatives.

A comptroller or planner and estimator should oversee this group. The primary goal of the group should be to assess the company's limitations and capabilities in regard to technical, quality, and special process requirements before accepting work. The group should also determine the limitations and conditions that should be placed on the project for bid acceptance.

Sometimes accepting a job just to keep the workforce busy can cost you the company. The company's limitations and capabilities should be determined in regard to technical, quality, and special process requirements before accepting special projects. If deemed necessary from this determination, the company should place limitations and conditions on the bid acceptance, or not accept the work.

To determine whether the company should bid or how much it is willing to bid, the prebid review group should evaluate the following items:

- Quality requirements (establishment of special procedures, i.e., quality manual).
- Inspection requirements.
- Record requirements (degree of detail).
- Material requirements certification—receipt inspection.
- Material and labor losses in production (rework).
- Cleanliness and shipping requirements.
- Special process requirements (mockup testing or control samples).
- Personnel availability and special qualifications.
- Special welding equipment and fixtures required.
- Health and environmental considerations.

Establish a Detail Planning Group (Prior to Issuing Job Orders)

After a special project is accepted, a planning group is needed for detailing the job requirements to the production workforce. This detailed planning effort is necessary, because the work is nonrepetitive, may involve multiple trades, and may have different quality requirements than the company normally uses. *The greatest potential for noncompliance and error is when the project is nonrepetitive and has extensive quality and technical requirements.* This detailed planning group should be headed up by a *design engineer*, if possible.

Once a special project is accepted by a company, resources must be expended in advance planning. Work instructions should be clear, concise, and when practical, they should be listed as line items with specific directions and accountability. The referencing of general specifications should be avoided where contract requirements are obscure and can be easily missed. Establishing this group early helps resolve many critical issues that make a project a success. It also establishes early ownership in the project by the participants. It is crucial that this group has authority to make and implement decisions.

During the planning and engineering time of the project, weekly or biweekly meetings should be held to discuss the impact of technical requirements on production with shop supervision. These meetings should be

chaired by engineering. After the production work starts, similar meetings should be held with the lead production shop chairing the meeting, to enable them to receive fast and direct technical resolution to unexpected fabrication problems.

Internal quality reviews or audits should be planned for as work progresses. The first review should take place early in the project. This ensures that the work instructions are adequate to accomplish the work, that contract requirements are clear to the workforce, and the material that is to be received is correct. Trying to recover from incorrect material after a job has commenced is almost impossible without the company experiencing large material and labor losses. Therefore, the prebid review group should also be responsible for material acquisition recommendations. Any project is slated for failure where material requisitions are made haphazardly. Material must be ordered properly and receipt inspected accurately, if a project is to progress within the preestablished schedules. Simple, clear and concise job order instructions should be provided in the following areas:

- Specification (material and fabrication).
- Fabrication documents.
- Quality requirements (receipt inspection included).
- Records.
- Inspection requirements.
- Special process controls.

Summary

If a project has been determined (by a company's definition) to be a special project, a prebid review group should examine all the job requirements. This group will determine whether the company wants to make a bid on the project and what considerations and limitations should be placed with the bid. The group should consist of a designer, a planner and estimator, a production shop leader or project leader, and a quality assurance expert.

After the project has been accepted, a planning review group needs to be established to provide clear and concise work instructions. Job orders should provide details in areas that would be expected to cause production and record problems. Details concerning the receipt of material, quality assurance requirements, and production shop requirements must be provided.

Early in the production cycle, work instructions and receipt inspection of material should be audited, or at least reviewed. During production, work surveillances should be made of workmanship, inspection, and records to ensure work instruction compliance.

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Section 3—Production Welding Cost Analysis

Introduction

The application of welding as a major fabrication process in United States industry began during the late 1930s. Prior to this time period, the welding process did not play a significant role in production applications. Welding was primarily utilized for small-scale fabrication, maintenance, or repair. Its use was accelerated by the military. The U.S. Navy required massive ship construction for deployment during World War II and the U.S. Army needed significant ordnance/weaponry equipment that could only be practically constructed by welding.

Review of Cost Estimating

There are several fundamental variables (costs) that need to be considered prior to submitting a competitive bid for a specific project, in terms of welding costs. For purposes of this review, many of the following terms can apply to repair welding or new construction applications. These cost estimates include *material*, *direct labor*, *overhead*, *fixturing*, and *welding*. Definitions of these five expenses are listed below.

Material Costs

Material costs involve those materials (i.e., steel plate, piping, or other hardware) that ultimately become part of a finished product. These individual components can be traced to the finished project, in terms of a unit of measure expended. Material costs also include consumables used during the manufacturing evolution. Required receipt inspection and traceability documentation should also be included.

Direct Labor

Direct labor is a level of effort or services that can readily be charged or identified towards accomplishment

of specific projects for a customer. As an example, this includes any personnel assigned to a specific end use project. Particular attention should be considered not to exceed the estimated manhours/mandays for project accomplishment.

Overhead Costs

Overhead costs are those costs of indirect services, materials, or other expenses that cannot be specifically identified to a productive effort/customer or do not result in direct productive work. Such examples include paid vacations, health insurance premiums, sick leave, electricity, water, building construction or maintenance, and capital investments not tied to a specific customer.

Fixturing Costs

Fixturing costs are expenditures for tools, jigs, or fixtures that are directly utilized in the manufacturing process, which can be traced or charged to an end product.

Welding Costs

As noted in the AWS *Welding Handbook*, costs for welding basically include the same elements that are applicable to manufacturing costs, i.e., labor, material, and overhead. However, there are other variables that need to be considered:

- Joint design type.
- Weld size.
- Weld type.
- Weld process.
- Electrode deposition efficiency.
- Special weld procedure development or verification of essential elements.
- Heat and fire protection.

Welding Cost Variables

There are a large number of welding variables that can affect the manufacturing costs. For example, the design engineer should be concerned with joint design, weld size or type, and weld process. The welding supervisor should be aware of the setup (field or shop), production welding time, finishing, and inspection costs. The welder holds a very key role. Prior to welding, he/she must be familiar with the applicable weld procedure that lists variables such as type of shielding or required flow rates, welding parameters (volts and amps), travel speed for automated/mechanized welding, preheat or interpass temperatures, and type of filler metals required.

Rework

The welder, in many instances, has major control over the amount of rework. Since rework can be as high as 25% of the project costs, the existence or elimination of potential rework costs deserves a high degree of attention.

Fire Protection

Currently, it is estimated that for every hour of actual welding time, a similar amount of time is required for related fire/heat protection. These costs may include the use of "firewatch" personnel and the installation of flame retardant material or cloth for protection from the welding, or burning evolutions.

Finally, the company owner/management is concerned with all of the above and additionally: utility/labor rates, consumable costs, transportation, and overhead costs. It is very apparent why welding costs make a significant monetary impact in the overall manufacturing costs.

Now, the next obvious question is, "How can these costs be controlled, and yet provide assurances for quality weldments?" Has the designer given adequate thought to "fitness for use," or has the component been overdesigned which increases costs? The remaining portion of this section will attempt to introduce answers/suggestions to aid in solving these questions.

How to Control Costs

Many weldments involve a combination of shop and field fabrication. It is critical to understand that differences exist in job preplanning through project completion. For example, shop fabrication drawings are specific in nature, whereas drawings for field installation or modifications provide sectional views to show the location of numerous components.

If at all possible, it is preferable to accomplish the majority of welding fabrication in the shop vs. in the field. For example, in one case history involving Cres piping, the field reject rate was 420% over those joints welded in the shop. For Monel®, the same reject criteria was 189%, and 107% higher for carbon steel. The average among these three materials welded in the field was 238% higher than the shop welds!

The disparity between shop and field reject rates can be explained by reviewing the complexity behind field conditions. In many situations, the welder will encounter very tight space restrictions, which may require the aid of mirrors to complete the particular pipe weld. Other physical problems might include welding out-of-position, vs. the normal horizontal-fixed or rolled position welds found in shop welding. Some additional negative conditions may involve moisture or contamination in a piping system, or a difficult configuration that restricts the flow of the purging gas for piping welds.

Another variable affecting welding reject rates/costs is the available skilled workforce. Promotion of experienced personnel into management positions, retirements, etc., can cause an increase in the reject rates. Replacement of skilled personnel with inexperienced welders can be one source of higher reject rates/costs.

Regardless of the location of the particular project, job preplanning, definition of scope, and scheduling are essential. These should include an in-depth review of the applicable fabrication specifications, drawings, material lists, work documentation requirements, and schedules. Conduct meetings with the designer, shop supervisor, and other technical support staff to determine the proper direction. A strong preplanning effort will provide a solid project estimate regarding manufacturing costs and successful job accomplishment. As an example of required preplanning, determine what type of variables need to be evaluated prior to making decisions about utilization of a particular welding process for a specific job. The *AWS Welding Handbook* offers the following criteria for consideration:

- Type of welding operation to be performed.
- A clear definition of what physically can and cannot be done.
- Nature of the material to be joined. Is preheating or postweld heat treatment required?
- Joint geometry, thicknesses, and parts fitup/tolerances.
- Weld quality requirements.
- Safety requirements: enclosures, shielding, scaffolding, etc.
- Location/orientation of fixturing (positioners, etc.) is important.

SECTION 3—PRODUCTION WELDING COST ANALYSIS

In his discussion about estimating welding costs, in the *Design of Weldments* (published by the James F. Lincoln Arc Welding Foundation), Omer W. Blodgett states the following:

“The cost of welding is directly affected by the amount of weld metal required. Very few people realize the great increase in weld metal and cost that results from a slight increase in weld size.”

Joint Designs

In a further representation of Mr. Blodgett's words, it has been shown that a decrease of 30° in joint design bevels can result in a savings of almost 50%, which includes the welding time, reduction in filler metal and distortion! In the inverse scenario, an increase in fillet weld sizes by a factor of 50% will require a significant increase in all the above factors. For example, an increase in fillet weld sizes from 1/4 in. to 5/8 in. (using 1/4 in. as 100%) will increase the labor costs by a factor of 500%! This does not include the potential problem of weldment distortion due to the additional welding.

Another factor involving design decisions, or joint design selections, involves the decision of when to utilize fillet or groove welds. There is obviously a significant difference between these designs, and equally so in costs. Based on deposited filler metal costs alone, it is evident that for 1/2 in. plate, fillet welds are the cheapest design per foot, but as the plate thickness increases up to three inches, a 45° double bevel groove joint design becomes the least expensive. The responsibility of the design engineer is very significant in controlling welding or manufacturing costs.

Following a review of joint designs, another “tool” that needs to be evaluated is the applicable welding procedure/process to support fabrication. A welding procedure provides the welding foreman/welder with the essential welding elements including required gas shielding/flow rates, welding current, applicable preheat/interpass temperatures, and type of filler metals required. A careful review of available procedures/processes will afford an opportunity to determine costs, etc.

When considering the filler metal selection, thought should be given to using the largest diameter suitable for the joint design, without violating heat input requirements, to improve the electrode deposition rate. Also, it should be noted when purchasing bare filler metal (spools) for Gas Metal Arc Welding (GMAW), Flux Cored Arc Welding (FCAW), or Submerged Arc Welding (SAW) processes, that the largest available spool poundage be considered if filler metal types do not need to be frequently changed. This will obviously avoid unneces-

sary down time to replace the spooled filler metal containers during the welding operation. Also, ordering filler metal in large quantities, whether it be covered or bare electrodes, decreases the basic costs per pound. Proper planning regarding future needs of specific electrode types, and their proper storage is required here.

Automation/Mechanization of New or Existing Thermal Joining Processes

Another aspect of controlling manufacturing/welding costs, although it involves long-range preplanning with the possibility of only long-term payback on investment, is the introduction of automation or mechanization of new/existing thermal joining processes. However, before serious consideration is given to automate (i.e., use of robots), or to mechanize specific welding processes (GMAW, FCAW), it is critical that fabrication projects exist to support its development. Purchase of complex equipment is a large capital cost, not including associated operator training, engineering support, or maintenance. A projected return must exist. As an example, at one naval shipyard, after a successful development program involving a new welding process (Flux Core—Twisted wire), specific production applications were identified. Utilization of this new process resulted in major labor savings over the previous welding method in reduced joint design preparation, and increased welding deposition rate. The savings can be realized on future thick section weldments.

In addition to the variables previously mentioned during the preplanning section regarding the utilization of welding processes, other variables need to be evaluated prior to making decisions on adapting or purchasing automated welding equipment. Additional criteria for consideration are:

- Processing speed of parts per unit of time.
- Economic requirements: initial investment and operation costs, and payback period.
- Location of the automated equipment should be as close to the prospective work as possible.
- The path between the work area and control unit should be unobstructed.
- Past experiences with similar automated equipment.
- Efficient material handling and fixturing equipment requirements are important with a new process and higher production rates.
- Part programming is a critical time aspect, as there is a need for a flexible software system. The necessary coordination between the welding and actual operation of the automated equipment is important to achieve the desired weld quality.

After review of the above criteria, one of the most crucial decisions remains: is there a high degree of assurance that utilization of the automated welding equipment or new processes will bring about a positive rate of return on the investment?

Records: Accountability for Accomplishment of Work and Inspections

Maintaining accountability for accomplishment of work and inspection—nondestructive examination (NDE), receipt inspections, in-process, personnel qualifications, etc., is a tremendous, but necessary overhead cost. Several commercial code or military codes or specifications that might be referenced on drawings or be included in the contract provisions, require that an extensive quality control system for record origination/retention be established. Some examples of these required records include:

- Vendor certification of welding electrodes, or test results for compliance with the applicable specification/receipt inspection requirements.
- Records that support test data for welding/NDE.
- Records for welder/brazer/NDE operator qualifications.
- In-process inspections or data collection (measurements, etc.).
- Records of NDE inspections (ET, MT, PT, RT, UT, VT).
- Records of casting fabrication, plates, shapes or forgings, and the applicable inspections.
- Verification of thermal joining surveillance inspections.

Before bidding on a project, a thorough review of the required records, specified by the applicable fabrication documents, is necessary. The volume of required documentation may involve hiring of additional staff, thus increasing overhead costs.

Cost Considerations of Nondestructive Examination (NDE)

The requirement to incorporate nondestructive testing during the manufacturing or welding evolution is another cost which has dramatic impact. Utilization of this type of testing has great potential for increasing costs, however, it

provides assurance that the quality level for the product or weldment is being met for critical applications.

Specific definitions/applications of NDE are covered in another section, however, a brief overview of the six available nondestructive inspection/testing methods includes the following: Visual Testing (VT), Eddy Current (ET), Magnetic Particle (MT), Dye Penetrant (PT), Radiographic (RT), and Ultrasonic Testing (UT).

Visual Testing

For all weldments, VT is one of the best and most economical inspections employed. It can be accomplished quickly by qualified inspectors to verify pre or post welding criteria including, but not limited to, adequate joint designs, weld size, appearance (contour, cleanliness, etc.), or detection of surface flaws, (i.e., undercut, cracks, slag, etc.). The most significant disadvantage with this method is that it cannot detect subsurface or minute surface indications. Visual inspection of each weld layer can ensure quality, as it has been shown that if an in-depth VT is accomplished, there can be a 35% decrease in associated NDE inspections.

Eddy Current Testing

ET is an electromagnetic inspection method in which small electrical currents are induced in a material. Flaws are detected by the interruption of these currents. This method can be used on a wide range of electro conducting materials, though the depth of inspection on ferrous materials is restricted to approximately 0.100 in. to 0.200 in., depending on the frequency used. It is excellent for measuring plating thicknesses and can be used on painted surfaces. This is ET's main advantage over MT. The equipment for this technique is not expensive, easily suitable for automation, and the labor costs are minimal.

Magnetic Particle Testing

MT can be accomplished only on ferrous materials. This method is reasonably economical, and serves as an excellent tool in detecting indications on joint preparations (including backgouged roots), root welding passes, and finished weld surfaces. Magnetic particle is basically a surface and slightly subsurface inspection process.

Dye Penetrant Testing

There are two types of dye penetrants: liquid and fluorescent. Both types can only detect defects open to the surface, and can be used on nonferrous and ferrous materials. Dye penetrant inspection is relatively economical,

SECTION 3—PRODUCTION WELDING COST ANALYSIS

although more time consuming than MT. However, PT requires a better surface finish than MT for satisfactory inspection to be accomplished.

Radiographic Testing

Of the six NDE methods, radiographic inspection is the most expensive. This nondestructive method uses the penetrating radiation of X-rays, or the gamma rays of a radioactive source, to penetrate a specific object to reveal discontinuities. It is very labor intensive for the following reasons:

- High cost of equipment and film.
- Stringent controls of the radiation source.
- Skilled personnel capable of producing exposed film.
- Required chemical processing of the exposed film.
- Trained personnel to review/interpret the film.
- Restriction of production efforts in the area of inspection, due to the presence of harmful radiation.

This method can be used on most materials, and provides a permanent record of most surface or internal defects or flaws. RT is widely utilized in inspection of pipe and structural butt welds.

Ultrasonic Inspection

One of the most versatile NDE methods is ultrasonic inspection. UT has several advantages including location of internal flaws in components, and ability to be used on most materials. However, in terms of ease of operation, it is fairly complex, and requires the interpretative skills of trained technicians. In regard to cost, one individual can operate the machine and interpret the ultrasound wave signals. This makes UT considerably less expensive than RT. Because UT produces no radiation, inspection areas need not be evacuated. Though unable to provide a per-

manent record as the radiograph, improved equipment provides computerized printouts for records.

Summary

With ever-shrinking budgets, and strong competition from abroad, controlling costs in the public and private industry is a major concern. As we have seen, there are several variables to consider when welding and related nondestructive testing is involved. This section has attempted to describe some of the welding variables that need to be considered. Table 3.1 is a condensed review. It is not intended to be all inclusive, rather a brief narrative about some of the major subjects which should be reviewed. Table 3.2 is a check-off sheet of costs to remember prior to the bid process.

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Table 3.1
Review of Production Welding Costs

1. Job preplanning, definition of scope, and accurate scheduling are three critical and necessary steps that must be accomplished prior to any project bid submittal or start of production.
 2. Maintaining accountability of work accomplishments or inspections via the use of formal records is a necessary overhead cost that must be factored into the bid.
 3. If at all possible, it is preferable to accomplish the majority of fabrication or welding in the shop vs. in the field.
 4. Increasing fillet weld sizes beyond what is required can be detrimental. Aside from raising the filler metal and labor costs, the additional welding may contribute to serious distortion of the weldment.
 5. Choosing the correct joint design for the particular plate thickness is very important. For example, for thicknesses over 1-1/2 in., the double bevel "T" joint design is more economical to employ than increasing the fillet weld size.
 6. There are several factors that affect the efficient utilization of the many welding processes, i.e., deposition rates, joint geometry, fixturing, etc. Careful considerations must be made prior to utilizing a particular welding process or mode.
 7. The selection of automated equipment requires a close review of several variables, including long-term preplanning and costs. There must be a projected positive rate of return, which will justify the capital expenditures.
 8. Fire/heat protection costs have significantly increased. It has been estimated that for every hour of welding time, an equal amount of time is required for related fire/heat protection.
 9. Weld procedure/personnel qualifications pose two problems. Both are expensive, and can require considerable time to accomplish. Early identification of specific needs is required.
 10. Inexperienced welders or craftsman can affect the reject rates. Maintaining a skilled workforce should be a high priority.
 11. Nondestructive testing during the manufacturing process has potential for increasing costs. However, it ensures that a quality product is being produced, and may in the long run actually reduce costs.
 12. The roles of the design engineer, welding engineer, supervisor, welder, etc., are all varied, with each being critical for successful project accomplishment. Joint meetings to discuss particular attributes or suspected problem areas are necessary for unified direction. The results of these meetings will decrease costs and enhance the product quality.
-

SECTION 3—PRODUCTION WELDING COST ANALYSIS

Table 3.2
Checklist of Project/Welding Cost Variables

-
- ☐ Advance planning costs; i.e., meetings, accomplishment of tasking actions, etc.
 - ☐ Costs of origination/distribution of funding or work standard documents.
 - ☐ Cost of origination/distribution of pertinent engineering instructions or drawings for prefabrication support.
 - ☐ Receipt inspection costs; i.e., issue instructions for base and filler metal inspections, etc.
 - ☐ Weld procedure and welder performance qualification costs.
 - ☐ Material and welding electrode costs.
 - ☐ Special equipment purchases: welding machines, fixtures, etc.
 - ☐ Inspection costs: in-process, nondestructive, and other, such as hydrostatic.
 - ☐ Estimated rework costs.
 - ☐ Formal record costs: origination, tracking, and retention.
 - ☐ Possible post weld heat treatment costs.
 - ☐ Costs for preparation prior to welding; i.e., base metal cleaning, joint designs, fitting, etc.
 - ☐ Rigging or crane costs in the movement of the materials during and after the weldments are completed.
 - ☐ Labor costs associated with welding, machining, casting or forging fabrications.
 - ☐ Distortion control costs during in-process welding, etc.
 - ☐ Fire/heat protection costs (including labor) associated with welding/burning.
 - ☐ Final cleaning, preservation, and shipping costs.
 - ☐ Surveillance and audit costs.
 - ☐ Supervision (labor) costs.
 - ☐ Overhead costs (vacation, electric power, medical insurance, etc.) associated with labor and operation of the required equipment for the fabrication of weldments.
-

SECTION 4

Modular Construction

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Section 4—Modular Construction

Introduction

Modular construction or block construction was a natural evolution of large structures. It became advantageous for structures to be assembled in small blocks followed by joining these small blocks together until the entire structure was completed. This method of construction offered new opportunities to the outfitting trades.

The assemblies could be turned over so work was at a more convenient physical location and much of the welding could be flat position work. Also, machinery and electrical components could be packaged in a less expensive shop environment and landed on the block, reducing the field assembly time. This concept initiated the movement of the design and planning functions toward the zone outfitting approach. By implementing zone methods, the blocks could be preoutfitted prior to erection and joining of additional blocks.

Implementation of modular construction encompasses more than just assembly and fabrication work, it requires the engineering design and production work scheduling to be an integral part.

System Approach

Traditional methods used a systems approach to construction. For example, an entire pipe system would be designed, planned, and scheduled for production without consideration of the other systems that would be fabricated during the same time and in the same location. The systems method enables designers, material personnel, and planners to rapidly define the production of an entire system.

Modular Construction

In modular construction it is essential to change from the systems concept to a zone concept to optimize productivity. The structure and its systems are converted into zones. These zones define work packages that define a quantity of work to be accomplished within boundaries.

Optimizing Resources

By designing and planning for the zone work, the scheduling of people and material is optimized. The amount of time lost for material movement and relocation of people is minimized. A crew of craftsmen can complete a work package that may include portions of multiple systems within a zone, prior to shifting to a new zone.

Productivity Value

The efficiency of a work package can be defined by a “productivity value” which is a function of:

- Time.
- Resources.
- Quality.

These three variables must be balanced to obtain an optimum productivity value. *Each of the variables is a function of the other two* and therefore must be considered together.

Trial and Error Evaluation

Productivity value is a unitless term that cannot be formulated mathematically. Rather, it is an expression that can be used to evaluate performance by comparison. Each work package process and operation can be evaluated by trial and error, until the optimum level of productivity is determined. This may require changes in work package definition until the proper balance of time, resources, and quality is achieved. This process should be repeated periodically to reevaluate the productivity value. As methods change or schedules are readjusted, the variable balance may be shifted and the optimum conditions may no longer be present.

A proper review of a specific zone project must include the prior and following operations after the specific zone function is complete. The processes should be evaluated in relation to resources, time, and quality. The prior process must be included, as it establishes a baseline

condition for the measured operation. Variations in conditions from the prior process or operation will affect the productivity variables. Similarly, the following operation will be impacted by optimizing the evaluated process.

The quality value is a good example of the effect of one operation on the other process steps. Each processing operation must result in a satisfactory consistent level of quality being passed to the following operation. Changes in the quality variable will skew the balance of the three productivity value components and cause less-than-optimum conditions. Starting with a poor-quality product prompts the allocation of additional resources to meet schedule requirements; or when resources are not available, additional time is used to compensate for correction of quality deficiencies. Basically, each operation of the production process will provide a final product to the following operation. This process provides identifiable responsibility and accountability to individuals completing incrementally completed segments. This customer-supplier relationship must be measured and controlled to maintain an optimum productivity value.

Dimensional Accuracy (Process Control)

Successful preoutfitting is greatly dependent on structural dimensional accuracy. Proper implementation of these advanced concepts requires all structural members and platforms to be within predetermined tolerances. The

system components are located by measurements from the nearest structure in lieu of the more traditional compartment or ship centerline. In addition, forcing structural block dimensional control, this now requires the matching blocks to consider the alignment of the distributive systems (i.e., electrical systems) in addition to the structural members.

Deviations from nominal values can become cumulative and the larger block connections must be monitored for dimensional accuracy to ensure proper alignment. In some cases, this will force the use of less than the traditional tolerances. Process control is necessary to ensure that a zone approach to outfitting is successful.

Accuracy Control Program

An important tool for controlling process performance in structural fabrication is an accuracy control program. With the use of statistical process controls, variations in process parameters can be identified and the causes evaluated.

Two of the more common methods of displaying the data for accuracy control measurements are the histogram and the process control chart. Each of these methods utilizes basic statistical analysis.

(1) **Histogram.** Figure 4.1 is a typical histogram. The data shown represent a series of actual measurements

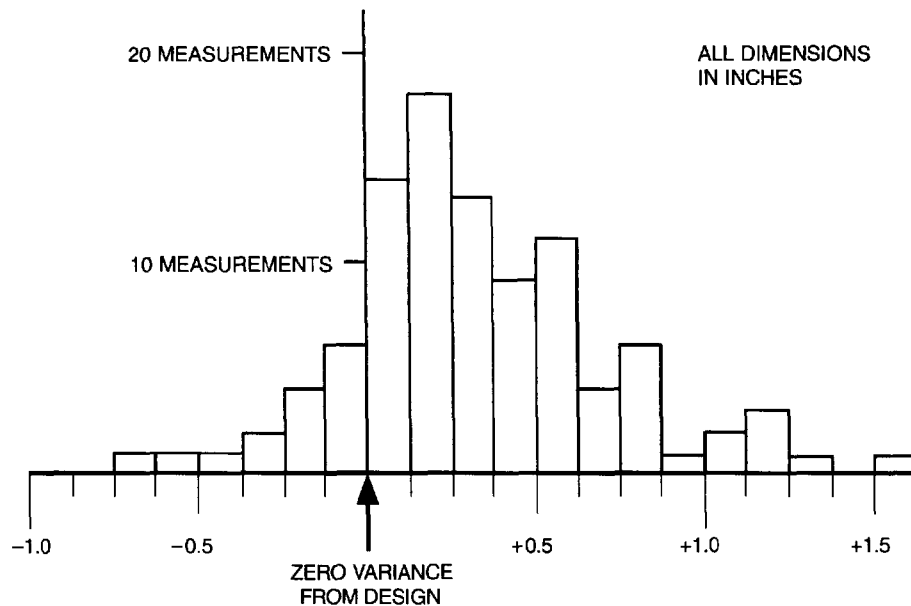


Figure 4.1—Typical Histogram

SECTION 4—MODULAR CONSTRUCTION

taken over a period of time. By collecting the data in the histogram format, the variations in the process can be collected and displayed to provide a meaningful analysis.

The histogram can be used to approximate a “bell curve.” The bell curve is a standard statistical representation of predictable variations in a process. By utilizing the bell curve, normal process inconsistencies can be estimated and a process can be evaluated to determine the frequency and magnitude of deviation from performance to established tolerances.

(2) **Process Control Charts.** The process control chart shown in Figure 4.2 is another tool that is used to measure the performance of a continuous process. The chart is used to monitor an operation by comparing measured accuracy to the accuracy predicted by statistical methods. The variation between the upper and lower control limits are normal and are expected. Excursions beyond the limits are unusual and should be investigated to determine the cause. Adjustments in the process can actually move the upper and lower control limits under controlled conditions, thus redefining normal performance.

Other similar types of charts can be used to assist in monitoring process performance with statistical controls. These methods are valuable tools for management decisions. By implementing a control program, process performance can be measured numerically and decisions no longer need to be based solely on management impressions. Changes in each process can be measured to en-

sure that productivity is being improved and the effects on baseline performance can be determined.

An accuracy control program provides essential information for successful implementation of modular construction. When sequencing work by zones, it is essential that the systems continuing from one zone to another properly align at the boundaries. The structure must be accurate and within predefined tolerances to ensure that the matching systems in two zones are within dimensional tolerances to allow for proper connections.

Preoutfitting—A Major Advantage

One of the most important benefits of modular construction methods is the opportunity to implement preoutfitting work. The objective of this approach is to minimize the outfitting work after erection. Very thorough planning and scheduling is required to optimize this effort. When outfitting does not follow zone preoutfitting concepts, the result may be the erection of empty steel assemblies, which then require the more expensive conventional methods of installing the distributive systems.

Scheduling and Improved Work Environment

Production defines several objectives of this planning effort. By advance planning, much of the fitting and welding operations can be scheduled to allow flat

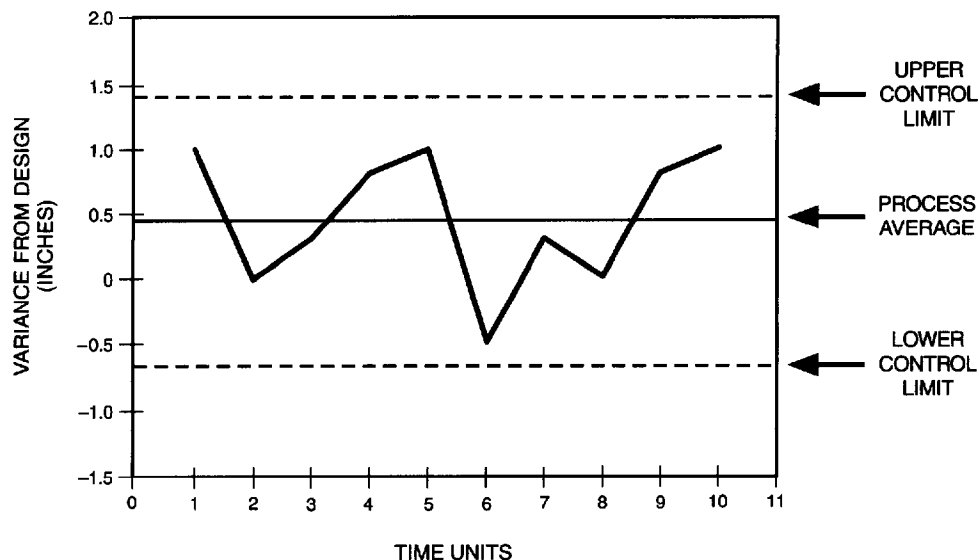


Figure 4.2—Process Control Chart

position welding and horizontal fillets. As this positioning will allow greater use of mechanized and semi-automatic welding processes, labor will be reduced and productivity will be increased. Additionally, the quality of the work will be enhanced.

By early zone planning, components can be identified so that different types of work can be scheduled and kept separate at the earliest manufacturing operation. This will simplify the manning and scheduling problems associated with multiple-operation manufacturing.

Another objective is to schedule work in uncongested and more efficient work locations, rather than having operators perform their tasks in enclosed, high or narrow sites. Quality and productivity will be enhanced by this planning effort which incorporates important production personnel needs to accomplish their work efficiently.

The time span for a production zone work package can be reduced by scheduling multiple tasks, which are not in conflict with each other, to be performed at the same time. This objective must consider work area space allowances to ensure that craftsmen have sufficient room to perform their tasks without interfering with other work. Similarly, compatible tasks can be scheduled to be performed in unison, and considerations of conflicting efforts must be discouraged. For example, it is not efficient to have a blast or paint operation being performed in the same zone as a pipe-fitting operation.

Designing for Zone and Preoutfitting Construction

Effective use of modular construction must incorporate design efforts that enhance zone definition for material and production planning. Design by system has value in defining the capability of each functional individual system and in demonstrating the location and path of the distributive systems. However, the optimum base of zone planning and work packages requires a zone approach to design.

Implementation of preoutfitting will not be optimized without the corollary design package. As stated in the introduction, there are differences between the systems

and zone approach to design. For example, with a zone approach to design, systems arrangement drawings can be eliminated. Also, material lists can be generated to support the zone construction method.

Advancements in the use of computer-aided design (CAD) will soon permit a design to be made with the traditional systems approach and then be converted to a zone configuration. This will maintain the advantages of a system design methodology. From this base, the CAD programming will enable a designer to define zones of a structure and the applicable portions of each system will be broken down into these zones. This will gain the benefits of a zone design concept without a large amount of duplication of effort.

Summary

To reap the benefits of this construction method, changes in many areas must be considered:

- The design effort must support a zone approach.
- Planning must be directed toward a zone work package that is producible, to ensure the proper balance of the key variables (time, resources, and quality).
- An accuracy control program must be implemented to adequately monitor the fabrication process to ensure that the blocks and distributive systems align properly.

Some of the benefits of preoutfitting include:

- (1) A higher percentage of shop fabrication and assembly.
- (2) Less congestion and worker interference for structure installation.
- (3) Reduction in lost material.
- (4) Less on-site rigging and material handling.
- (5) Less on-site cleaning and reduction in fire hazards.
- (6) Improved working conditions on the assemblies.

If properly implemented, preoutfitting and modular construction will be cost effective and improve quality and productivity.

SECTION 5

Welding Process Selection

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Section 5—Welding Process Selection

Common Welding Processes

The most common welding processes used in industry involve arc welding. The electric arc is a very effective and portable heat source for melting most metals quickly. When the base metal and filler metal become molten, they mix together then solidify to produce one solid piece. Most welding processes utilize a consumable electrode, which conducts the welding current and melts as it is continuously fed into the arc and deposited into the joint. The most common manual arc welding process is the Shielded Metal Arc Welding (SMAW) process (see Figure 5.1), in which a fixed length of electrode is hand fed into the joint. Typical semi-automatic arc welding processes include the Gas Metal Arc Welding (GMAW) process (see Figure 5.2) and the Flux Cored Arc Welding (FCAW) process (see Figure 5.3), which automatically feed a spooled electrode filler wire into the joint while the welder manipulates the torch manually. The Submerged Arc Welding (SAW) process (see Figure 5.4) is an automatic process whereby both filler wire and travel speed are controlled by the machine which runs along a preset track. The Gas Tungsten Arc Welding (GTAW) process (see Figure 5.5) uses a nonconsumable tungsten electrode to establish an arc in the weld joint, and typically, a separate hand-held filler wire is melted in the arc and deposited in the joint.

The molten weld pool created with all arc processes must be shielded from oxidation and contamination during the welding process. SMAW electrodes have a thick dry flux coating, which creates a gas shield and also provides many of the alloying elements to the weld. The SAW process obtains shielding and alloying with a similar type of dry flux in a granular form that covers the welding arc and molten pool. Spooled FCAW electrodes also use a dry flux contained in the center of a tubular wire and typically obtain additional shielding from an inert gas shield similar to the GMAW process. Both GMAW and GTAW utilize inert shielding gases that flow around the molten weld pool, while all alloying elements are supplied by the wire electrode alone. For each pro-

cess the weld metal composition is an alloy combination of filler metal and remelted base metal. Weld metal composition varies with each process. It is difficult to predict weld metal composition since many elements are diluted when crossing the welding arc.

Figures 5.1–5.5 describe the most common welding processes and summarize their advantages and limitations.

Process Selection

When selecting a welding process for a specific application, several factors that affect productivity and weld quality must be balanced. This can become a complicated decision, due to the number of conflicting advantages and disadvantages which each process possesses in each situation.

Productivity is usually a very important consideration on most jobs. The deposition rate is a significant part of this factor. Each process can be ranked in terms of its deposition rate in pounds of weld metal deposited per hour. However, there are other factors that must be considered. For example, it usually takes time for a shop to become familiar with a new welding process, new equipment, or even a new brand of filler metal. Until adequate training and acceptance by the shop personnel are accomplished, the actual productivity rate will be less than the average. Reject rates also have a significant impact on actual productivity, since a considerable amount of time is required to remove defective weld metal, replace it, and reinspect it. Therefore, many factors must be taken into account before determining which is the best process for a specific application. Process selection must be made by someone who is very familiar not only with the various processes, but more importantly with the shop's capabilities and the job requirements. As a minimum, the following items should be considered prior to selecting a welding process.

Base Metal Type

Some processes are better suited to certain base materials than others. The maximum heat input must be

limited on some types of materials, i.e., quenched, tempered, age-hardened, and other heat-treated or cold-worked materials. Processes that derive their advantage from high productivity and high heat input may be limited for these applications.

Joint Design and Thickness

As the section thickness increases, welding productivity becomes more important. If possible, the process selection should reflect this. The length of the weld must also be taken into account, since a higher-productivity process may not realize this advantage—particularly if the operator has to frequently stop the process to set up for the next pass, as would be necessary with a small repair. Since some processes require more access to the joint root to avoid lack of fusion defects, the selection of some processes may also require a joint design change.

Welding Position

The weld joint position plays a very important part when selecting a process, since many processes are limited to only a few positions. Whenever possible, the joint should be in the flat position, since the highest productivity and weld quality are attained when welding is accomplished in this position. Since most repair work is done on large weldments that cannot be repositioned and access to the joint is limited, use of high-productivity processes and filler materials is limited.

The four basic welding positions are: flat, horizontal, vertical, and overhead, as shown in Figure 5.6.

Environmental Conditions

Wind and rain are the two field conditions that typically affect welding. It takes very little wind to disturb the gas shield that is critical for high-quality GMAW and GTAW welding. This restricts their use outside of sheltered containments. The SMAW and FCAW processes can also be affected by wind, but to a lesser degree. No process is tolerant of direct rain. Proper placement of tarps, dams, or other temporary containments can rectify this situation. Due to the many problems associated with welding outside (i.e., being exposed to the elements or cramped inside of a structure), shop prefabrication is recommended where practical. Studies have shown that reject rates for field welding increased from 100% to greater than 400% over those for shop welding.

Availability of Equipment

Most large welding shops have access to the welding equipment required for the processes discussed. There are times, however, when new equipment must be evaluated to determine if the increased productivity or versatility would offset the initial cost and training.

Fabrication and Inspection Standards

Most welding and inspection is governed by welding standards that often limit the use of some processes on certain materials, and also may limit the maximum heat input used to ensure that specific mechanical properties are met. A high-productivity process such as SAW would lose much of its advantage if the heat input were restricted down to the range achievable by GMAW.

Table 5.1 is a general comparison guide for the most commonly used processes in the industry, relative to some of the factors discussed above. While some of the ratings are subjective, they do provide a general comparison for many applications.

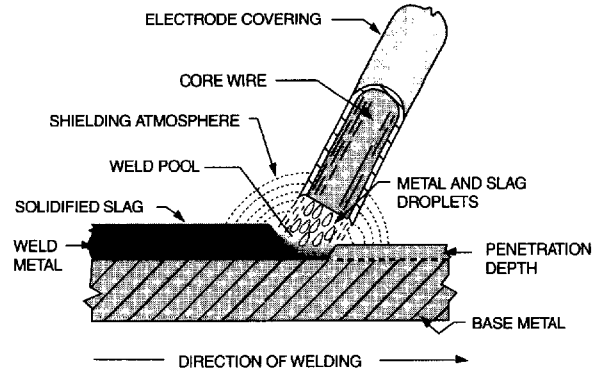
It can be seen from this chart that many variables must be taken into account when selecting the best welding process for a given job. In practice, it takes experience to identify and accurately weigh all of the variables involved. Some factors, such as the attitude and perception of shop employees toward a new process or procedure change, may be more difficult to analyze than others.

Another factor complicating process selection is the rapid change brought on by the computer age, which is taking place in the electrical power sources used for arc welding. It takes a considerable amount of study to take full advantage of the wide variety of machines available today and all of the functions each one is capable of performing. The GMAW and FCAW processes are probably the most influenced by these advances, in the form of “synergic” power sources that manipulate the waveform of the welding current through complex electrical circuits. These advanced machines automatically adjust all of the waveform parameters to optimize the mode of metal transfer across the arc with simple operator controls. Since productivity and weld quality are greatly affected by many aspects of the metal transfer across the arc, these machines offer a significant advantage over the previous generations of power sources.

SECTION 5—WELDING PROCESS SELECTION

SMAW

Shielded metal arc welding is a manual arc welding process. A covered electrode is used to deposit the filler metal and supply shielding to the molten weld pool. The 12-in. to 18-in. long electrode has a dry flux coating that decomposes in the arc to form a gas shield and a solid slag covering on the cooled weld deposit. The flux coating often provides alloying and deoxidizing elements.

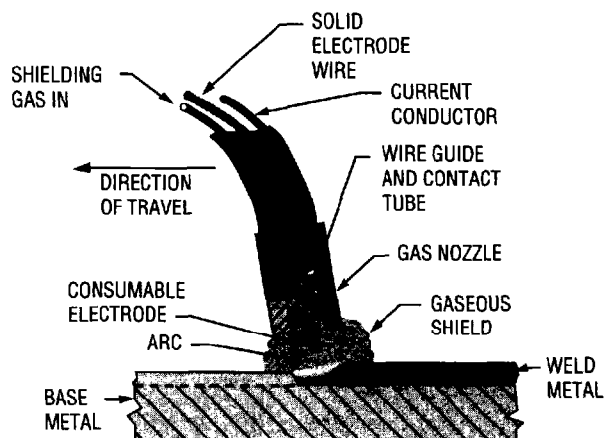


Advantages	Limitations
All-position capability. Many alloys are weldable. Thick sections are weldable. Excellent for field and repair work. Equipment is simple, low cost, low maintenance, and is easy to set up. Good accessibility in space-restricted areas. Arc visibility is good. The process is fairly tolerant of environmental conditions. Electrode travel, which helps to control heat input, is required.	Higher potential for weld contamination than for other processes. Welding is frequently interrupted due to the short, fixed length of electrodes. The process creates spatter and smoke fumes and leaves a slag that must be removed before the next layer can be deposited. Not suitable for thin material but is suitable for thin-wall repairs on thick material. Poor usability for aluminum and most bronzes. Special electrode care is required since most flux coatings absorb moisture. Foreign material exclusion for nuclear applications is poor. Severe arc blow can be a problem when using direct current (dc)

Figure 5.1—Shielded Metal Arc Welding

GMAW

Gas metal arc welding is a semiautomatic or automatic process. A small-diameter, continuous consumable electrode is melted in the arc and deposited in the joint. Shielding is provided by a gas that flows through the weld torch. Depending on the amperage and wave form used, four modes of metal transfer are possible: short circuiting, globular, pulsed spray, and spray transfer.



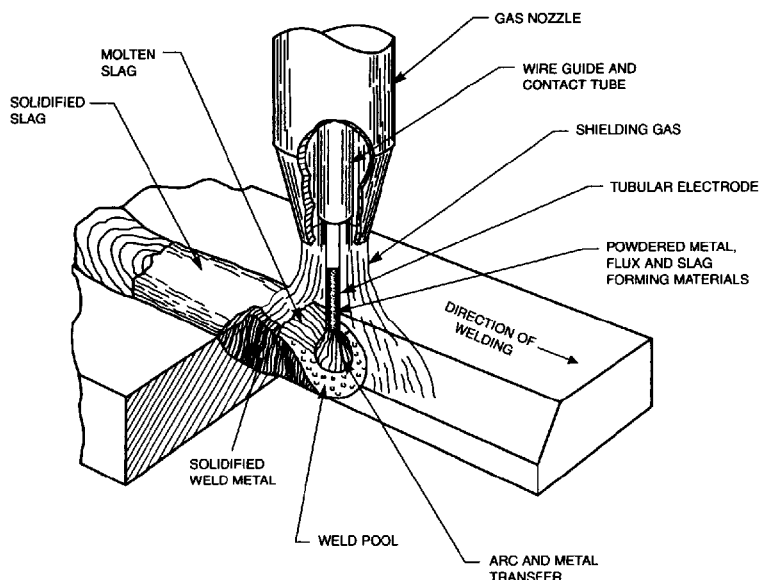
Advantages	Limitations
High-quality welds.	Gas shielding is easily disturbed during field work.
High deposit rates (three times that of SMAW).	Handling gas bottles for field work can be expensive.
Most metals are weldable.	Equipment is complicated and expensive.
Minimal stub loss.	Flash burns easily obtained.
All-position welding with some GMAW processes.	Excessive weld spatter with CO ₂ shielding.
No slag removal and minimum interpass cleaning.	Not used for thin metals except with pulsed spray and short-circuit transfer welding.
Easily adapted to robotics.	Limited accessibility.
Good weld puddle visibility.	Spray transfer limited to the flat position.
	Restriction on the use of short circuiting transfer welding.

Figure 5.2—Gas Metal Arc Welding

SECTION 5—WELDING PROCESS SELECTION

FCAW

Flux cored arc welding uses equipment similar to GMAW. The main difference is that the electrode is a tubular wire with a flux core. Some electrodes provide adequate shielding with the flux core alone, but others require the addition of gas shielding.

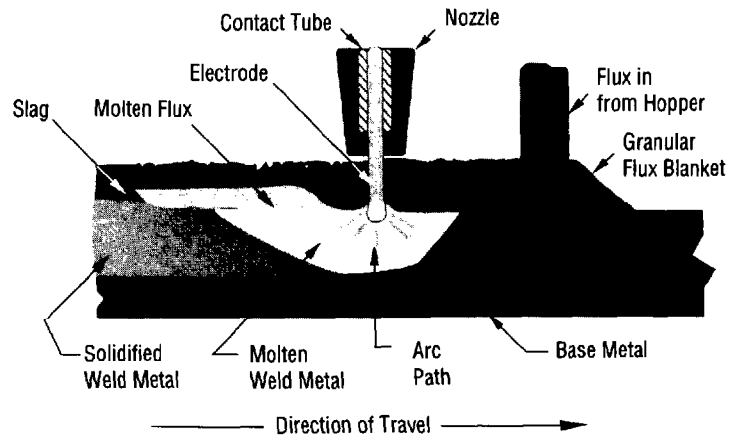


Advantages	Limitations
Large single-pass fillets possible.	Large amounts of smoke and fumes.
Tolerant of mill scale.	Weld spatter can clog nozzles.
Self-shielded process is good for field work.	Self-shielded process has lower-quality welds than external gas shielded.
High deposition rates possible.	Flash burns easily obtained.
All-position welding possible.	Slag coating must be removed between layers.
Less joint preparation required than for SMAW and GTAW.	The flux core is susceptible to moisture pickup, which may cause porosity and worm tracks.
Good penetration with gas shielding.	Equipment is bulky, and accessibility can be a problem.
	Equipment is complicated and expensive.

Figure 5.3—Flux Cored Arc Welding

SAW

Submerged arc welding is very similar to GMAW except the weld pool is shielded, deoxidized, and alloyed with a granulated flux that melts in the arc. The flux is fed through a hopper and a guide tube and deposited in the joint ahead of the welding arc. Two or more electrode wires can be used in tandem or metal powders can be added to increase deposition rate to obtain optimum mechanical properties.



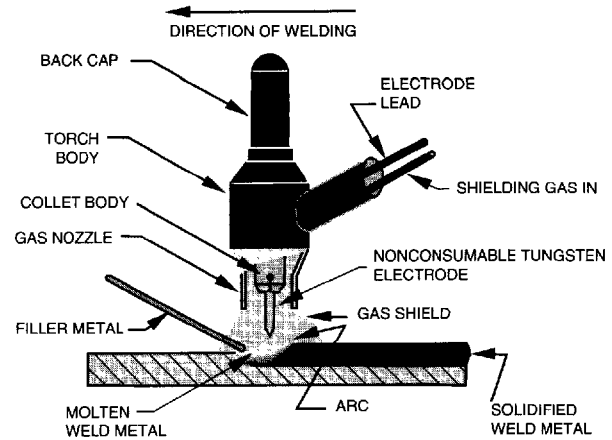
Advantages	Limitations
High deposition rates.	Welding positions limited to flat and horizontal.
Excellent weld quality.	Limited to ferrous metals and high-nickel alloys (no age-hardenable alloys).
No flash burns.	Best suited to long welds and thick sections.
Less angular weld distortion.	Special care required for the flux, since it absorbs moisture easily.
Weld appearance excellent.	Slag and unfused flux must be removed.
Maintenance relatively low.	High toughness properties are hard to obtain.
Smoke and fume quantities are low.	Joint fit-up and design are critical to penetration control.
Penetration is excellent.	
Less weld joint preparation.	

Figure 5.4—Submerged Arc Welding

SECTION 5—WELDING PROCESS SELECTION

GTAW

Gas tungsten arc welding is a gas shielded manual or automatic process that uses a nonconsumable tungsten electrode to establish the arc. The filler metal is added to the weld pool separately. Shielding of the weld pool and electrode is provided by predominately inert gases. Autogenous welding (no filler wire added) is possible with some materials.



Advantages	Limitations
Excellent arc visibility.	Lower deposition rates compared to SAW, GMAW, or SMAW.
Precise filler metal placement.	High-amperage, water-cooled torches are heavier and bulkier than air-cooled torches.
The best undercut control.	Both hands must be used to hold the torch and filler wire, which limits accessibility.
Wide range of thicknesses can be welded.	Shielding gas is easily disturbed by gusts of wind.
Very clean welds can be achieved with no significant slag, spatter, or smoke.	Flash burns are easily obtained.
Excellent weld quality on most metals.	Very limited for outdoor field work.
Amperage can be controlled by remote foot or hand switches.	Difficult to monitor heat input.
The process can be used either manual or automatic.	
All-position welding possible.	
Filler metal is not always required.	

Figure 5.5—Gas Tungsten Arc Welding

SECTION 5—WELDING PROCESS SELECTION

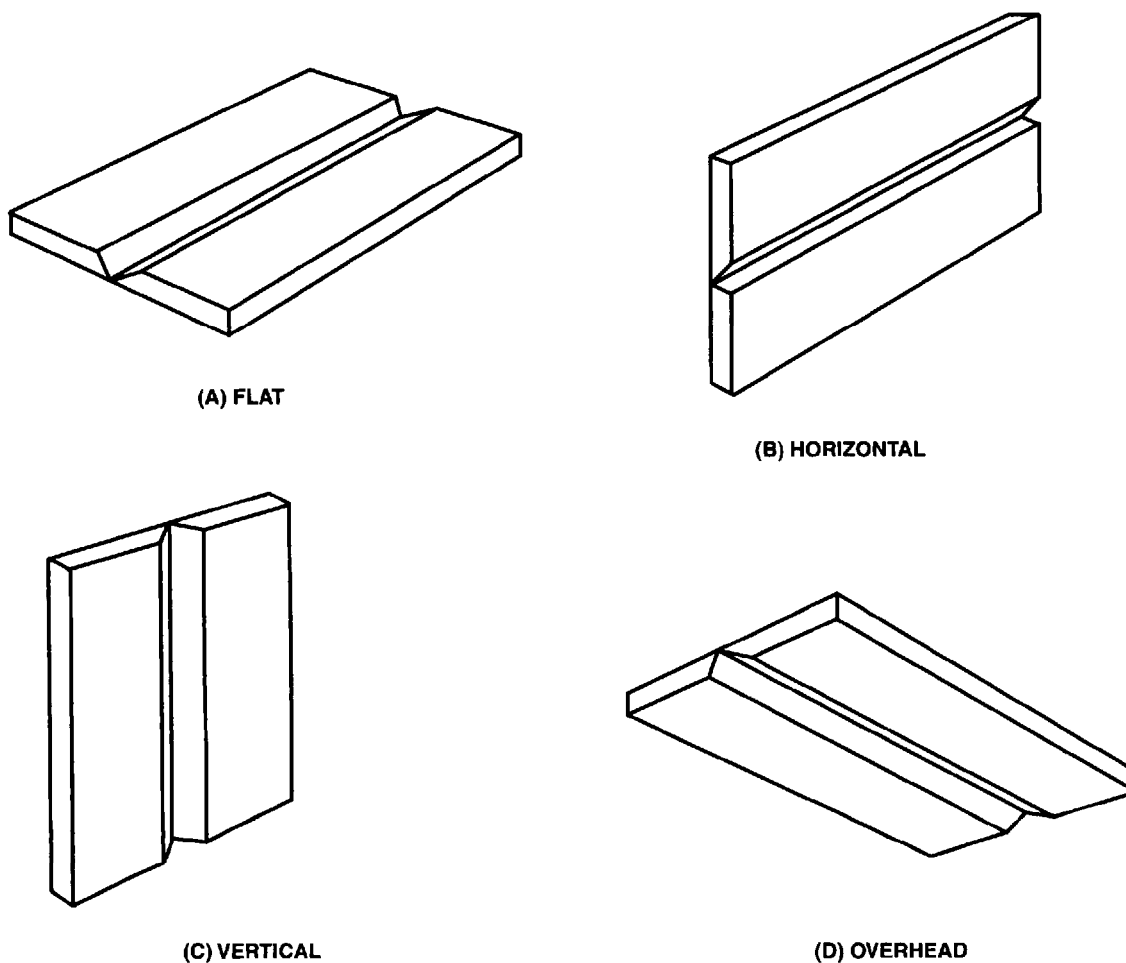


Figure 5.6—Four Primary Welding Positions

Table 5.1
Process Comparison Chart

Process	SMAW	GTAW	GMAW	FCAW	SAW
Quality	Good	Excellent	Excellent	Good	Excellent
Deposition Rate	Fair	Poor	Good	Good	Excellent
Field Work	Excellent	Poor	Fair	Excellent	Poor
Equipment Maintenance	Low	Low	Medium	Medium	Medium
Smoke/Fumes	High	Low	Medium	High	Very Low
Heat Input Control	Excellent	Poor	Good	Good	Satisfactory
Arc Visibility and Filler Metal Placement	Good	Excellent	Satisfactory	Satisfactory	Poor
Variety of Metals Weldable	Satisfactory	Excellent	Good	Good	Fair

SECTION 5—WELDING PROCESS SELECTION

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SECTION 6

Primary Concepts of Welding Design

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Section 6—Primary Concepts of Welding Design

Introduction

Inexperienced engineers frequently believe that if their design can be conveyed to paper as a drawing, it can be welded. Welding is the most common means of joining two pieces of metal, but it requires special consideration if it is to be done economically. What appears to be a good design on a computer or drawing board may be a disaster when it hits the production floor if the fabrication requirements are not properly considered. Using quenched and tempered steel in a complex design for strength-to-weight savings may appear to provide cost savings. However it may be more expensive to fabricate than heavier section mild steel.

The term “designer” is used in this section to address any engineer, technician, draftsman, or other person issuing instructions regarding metal fabrication requirements. These individuals are engineering type employees with cognizance of structural, machinery, piping, and pressure vessel fabrication. The intent of this section is not to provide detailed welding design information but to provide basic welding design concepts. Recommended reading is provided at the end of this manual for more detailed information on welding design specifics.

What the Designer Should Know About Welding

Welding design must not be based on isolating the weld alone. The designer must understand how the weld and the heat-affected zone (HAZ) next to the weld will affect the structure’s service. Many factors influence the effect of the weld on a structure’s performance including the filler metal type, the welding process and parameters, and *how* and where the filler metal is placed in the structure. It is essential for the design engineer to review the actual production site prior to and during fabrication, and to review the finished product. This provides some practical perspective to weld design that would be missed if the designer were primarily an analytical type.

Service Requirements

Service requirements are the first item that must be clear in the designer’s mind before making welding design decisions. Welding decisions will be less than fully adequate without clear definition of the service requirements, and the weldment may be subject to premature, in-service failures.

Service requirements may be very simple or quite complex. Weldments experience high and low temperatures, high pressures and stresses, corrosive environments, and fatigue and impact loading. Often more than one of these conditions is involved simultaneously.

The designer should consider only the service requirements that make the weldment (the combination of weld, HAZ and base metal) suitable for the expected service. Some of the service requirements the designer may consider are:

- Tensile, compressive, and shear stresses and strains.
- Corrosion resistance.
- Erosion resistance.
- Abrasion resistance.
- Impact resistance (stress and temperature dependent).
- Creep strength.
- Temperature (high and low temperature).
- Fatigue resistance.
- Aesthetics (color match, anodizing, appearance).

It is rare that a designer would be concerned with more than a few of these service requirements for a specific design.

It is poor practice to seek to achieve certain properties from a weldment, based upon the material’s ability to achieve these properties, even though the properties are not related to the service. If a quenched and tempered material is used for its strength-to-weight ratio properties, and impact loading is not of concern, the designer should not impose requirements of impact properties just because the material used has the ability to achieve high impact resistance. If 300 Series stainless steel is used because of its high-temperature yield and oxidation

resistance, as required in steam boilers, the designer should not be concerned about weld sensitization of the base metal during fabrication. In many cases, boiler components will operate in the sensitizing temperature range in service anyway.

Base Metal Selection

Weldments should be made from the most economical and readily weldable base metals available that are suitable for in-service requirements. Mild steel is much less expensive to purchase and to fabricate than the quenched and tempered steel alloys or the heat-treatable steels and will usually require considerably less rework. Steels designed for special applications frequently require pre-heat, and interpass temperature controls during welding, and sometimes stress relief. Special electrodes and electrode care may also be required. Since fabrication is much more expensive with quenched and tempered steels, special consideration should be given to their use.

From a design prospective, in some instances, quenched and tempered steels offer little advantage. Fatigue stress ranges are not improved with these steels, only the maximum allowable fatigue stress or static loads. If complete reversal of service stress is expected, these steels offer little advantage for fatigue. These steels also have lower buckling stability for similar cross sections of mild steel, because they are typically used for higher loads and will most likely require additional stiffening.

Welds Create a Discontinuity in the Base Material

The designer always must keep in mind that a weld does not create a monolithic structure that has uniform properties throughout. Welds do not act the same as the base metal and they have different properties. Welds are, in fact, a discontinuity (a stress riser) in the structure—caused by their metallurgical, chemical, and mechanical property differences. Because welds are different than the base metal, they must be given special design consideration.

Weld vs. Base Metal Properties

Welds are used to join base metals because they are economical, have high joint efficiencies, and reliability relative to other fabrication processes. Service areas where welds can perform favorably toward base metals are:

- Allowable stress.
- High-temperature service.
- Impact loading.
- Fatigue loading.
- Leak tightness.
- Corrosion resistance.

Welds Rarely Improve upon Base Metal Properties

As compared to base metals, welds will cause the weldment to have:

- Lower fatigue resistance than the base metal.
- Lower impact properties than the base metal.
- Higher residual stress than the base metal.

The weld is a discontinuity which is both a geometric and metallurgical notch that decreases the suitability for service below that of the base metal alone.

Keep Weldment Designs Simple

Weldment design should be kept as simple as possible. Weldments that involve multiple crossing of stiffeners on the same plane, multiple intersecting “I” beams, or complex patterns of stress flow should be minimized. Complex designs are expensive to fabricate and can lose serviceability, due to high residual stress and distortion. Complex designs also limit welding access and may cause the inability to meet post-weld inspection requirements.

Standardize Component Welding Design

Standardization of design is necessary for automation and mass production of similar items. Standardization also reduces engineering analysis time and may include complete foundations, stiffeners, pad eyes, weld joint designs, or even the size and shape of structural members. Unique welding processes, specialty items, varied member size, and different materials are not economical in terms of fabrication or engineering time to analyze each structure. Standard design details will simplify fabrication and reduce costs.

Minimize the Number of Welds

Welding and its related processing is one of the most expensive operations in fabrication. Shaping plate by pressing or breaking is usually preferable to welding one

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or more pieces of plate together. Reducing the number of component parts by improving the design or purchasing standard shapes is usually more economical than welding.

Location of Welds

From a design point of view, a structure's ability to carry service loads is only as good as the weakest part of the structure. In most cases, the weakest link is the weld deposit and the localized effects on the structure (especially for fatigue applications). The allowable loads that welds are permitted to carry are determined in many instances by a standard or code to which the item is fabricated. Examples of such controlling codes are the AWS D1.1, *Structural Welding Code—Steel*, and the American Institute of Steel Construction (AISC) Code.

Welds should be located according to the cost of making the weldment, inspection requirements and the service requirements.

Because welds represent a metallurgical notch and are stress risers, welds should be kept in the lowest stressed areas as practical. When fatigue, impact, or creep is a primary concern, the welds should be placed in low-stressed areas.

When possible, the designer should arrange for the welds to be made in the flat position. The most economical, fastest and highest-quality weld is achieved in the flat position with standard welding processes. Flat position welding with simple designs allows high deposition rate mechanized, semiautomatic, or automatic welding processes at substantial cost and time savings.

The location of welds should always provide the welder easy and open access. The most costly welds to make are predominately those where proper welding access has not been provided for by the designer. If welding access is difficult, then Nondestructive Examination (NDE) will usually be difficult, as will any necessary follow up repairs. Snipes or "rat holes" should be as large as practical to provide access for welding and NDE.

Designs should avoid welding across flanges under tension as drastic reductions to allowable service loads are imposed by most codes.

Avoid welds on edges of members subject to tensile fatigue. Edges of members subject to tensile loads usually experience higher loads than the rest of the member and, since a weld acts as a stress riser, premature failure of a component could occur due to unanticipated loads.

Weld Deposit Mechanical Properties

The as-deposited mechanical properties of a weld in a fabrication should always be considered to be different

than the welding filler metal specification requirements. In production the weld metal properties are dependent upon the base metal chemistry, how much it has been diluted into the weld metal, and the rate of weld metal cooling. The cooling rate of the weld can also affect the mechanical properties of the weld and the heat-affected zone. The cooling rate can be drastically affected by base metal type and thickness, the amount of weld deposit, the technique used to deposit the filler metal, and the temperature of the base metal prior to each weld pass (i.e., the preheat and interpass temperature). In general the designer should use the lowest possible yield strength filler metal compatible with the design.

Designers will frequently use filler metals that produce a deposit that exceeds base metal properties. Often these higher-strength deposits, in combination with the base metal HAZ, result in the weldment having:

- Decreased fatigue resistance.
- Decreased impact resistance.
- Increased distortion.
- Increased base metal cracking.
- Increased amounts of residual stress.
- Increased costs.

Joint Designs—Amount and Type of Weld

The type and direction of loading of the weldment will determine the type and amount of weld. The least amount of weld should be used to meet the necessary design service requirements. Specific weld joint design selection is discussed by another section of this manual. However, it will suffice to say the primary reasons for selecting a joint design are to provide the desired service requirements (i.e., the ability to accommodate service stress/strain and corrosion) and to accommodate welder accessibility.

There are many other secondary factors that affect joint design selection, such as available processes and skill levels, cost, aesthetics, environmental conditions, system status, base metal thickness and properties, location of the weld, position of the weld, the number of welds, the schedule of the project, etc.

Partial Penetration Welds

A partial penetration weld is a weld that intentionally does not completely penetrate through the thickness of a joint (see Figure 6.1). Partial penetration welds can often be used for tension, compression, and shear stresses that act parallel to the longitudinal axis of a weld and for

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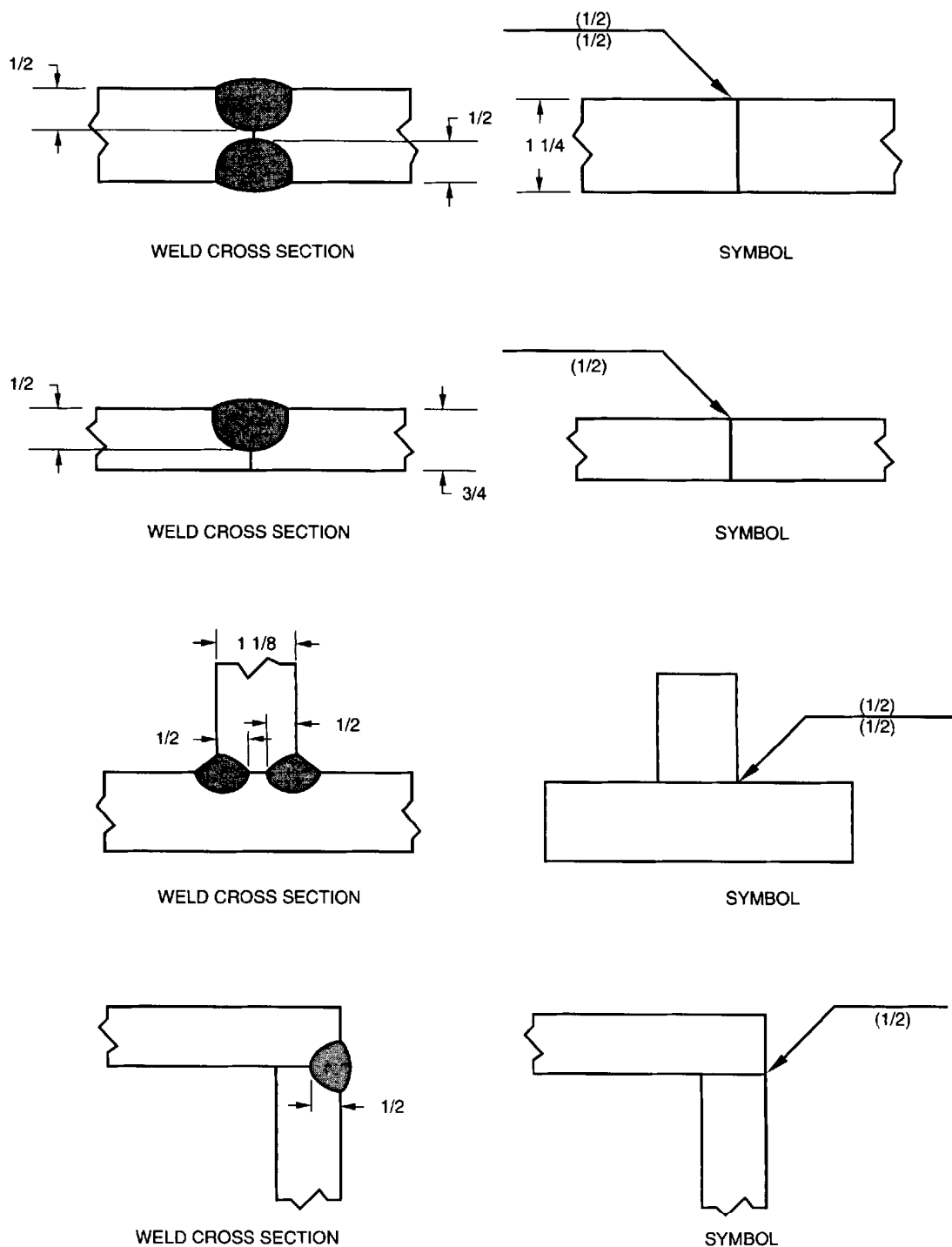


Figure 6.1—Partial Joint Penetration with Joint Geometry Optional