# STEEL CASTINGS HANDBOOK

## Supplement 6

## PRODUCTION WELDING AND FABRICATION WELDING OF CARBON AND LOW ALLOY STEEL CASTINGS

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**STEEL CASTINGS HANDBOOK SUPPLEMENTS**

# PRODUCTION WELDING AND FABRICATION WELDING OF CARBON AND LOW ALLOY STEEL CASTINGS

**By: John F. Wallace,** Professor of Metallurgy and Chairman, Department of Metallurgy and Material Science, Case Western Reserve University, Cleveland, Ohio

**Updated in 2023 By: Barbara Allyn, Dave Poweleit, & Raymond Monroe,** Steel Founders Society of America

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# Preface

This publication is an update of the 1985 Steel Founders' Society Supplement 6, "Repair Welding and Fabrication Welding of Carbon and Low Alloy Steel Castings". The purpose of this publication is to provide detailed welding information that will assist engineers, welders, and weld operators in the production and fabrication welding of steel castings.


# Abstract

Section 1 of this report looks at why steel castings are welded including the two primary ways, production welding and fabrication. The questions designers and users raise "Is it ok to weld steel castings? Will welding negatively affect the properties or production life of the casting?" will be addressed along with the supporting mechanical, toughness, and fatigue properties. Non-destructive testing (NDT) testing is a safeguard to assure quality welds in steel castings, and will also be discussed.

Section 2 covers welder and welding process qualification. This is a critical component of assuring welds that meet the properties required by the customer.

Section 3 explores the welding processes that can be used in welding steel castings (SMAW, FCAW, GMAW, GTAW, SAW, and ESW). After discussing the welding options, this section concludes with a look at how to select a welding process. It compares the strengths and weaknesses of the different welding process options.

Section 4 looks at the various electrodes and fluxes available for welding and explains the American Welding Society classification system.

Section 5 considers the welding operation including the processing of the casting after welding. Topics covered include preheat, inter-pass temperature, residual stress, distortion, heat input, deposition technique, peening, and post weld heat treatment.

To assure a complete set of references for welding steel castings, welding engineers are recommended to gather this publication along with the latest edition of the following publications:

- AWS FMC:2000 FILLER METAL COMPARISON CHARTS, American Welding Society, 2000
- AWS A3.0M/A3.0:2020 STANDARD WELDING TERMS AND DEFINITIONS; INCLUDING TERMS FOR ADHESIVE BONDING, BRAZING, SOLDERING, THERMAL CUTTING, AND THERMAL SPRAYING, American Welding Society, 2020
- ASTM A488/A488-18e2 STANDARD PRACTICE FOR STEEL CASTINGS, WELDING, QUALIFICATIONS OF PROCEDURES AND PERSONNEL, ASTM, 2020
- SFSA Special Report 11: A Review of Welding Cast Steels and Its Effects on Fatigue and Toughness Properties, Steel Founders' Society of America 1974

# 1. Welding of Steel Castings

## Why Steel Castings Are Welded

Welding steel is a practice used to join two steel pieces together for building construction or to fabricate industrial equipment. Welding is also used to clad steel parts for corrosion protection or to reduce wear with a hard overlay. Steel foundries use welding to add steel to the casting, the original additive manufacturing. Castings that are poured may have porosity or inclusions that are unacceptable based on the customer's quality requirements. For an otherwise sound casting to comply with the customer requirements, the casting producer can remove the unacceptable material. The resulting cavity must be filled with steel, and foundries use welding to accomplish this. Since this welding is part of the casting production process, this is production welding.

Steel castings are welded for four reasons:

- **Production Welding** allows the casting to meet customer standards. This is termed production welding; it is a normal part of the production process.
- **Casting Upgrade** is done to upgrade the casting to a higher quality level than the original requirements. This is not to be confused with normal production welding, but rather a casting upgrade is reworking a casting to meet a different quality standard than what was originally called for. This is primarily a term used for valves.
- **Weld Overlay** is cladding made by adding an overlay of a special surface or alloy to areas of the casting to improve wear or corrosion resistance.
- **Fabrication Welding** is adding a casting into a larger fabrication for building construction or to fabricate industrial equipment.

### Production Welding

In a steel foundry, welding is required in the process of manufacturing steel castings. ASTM requires new proposed cast grades to indicate capability of the casting to be welded. While minimizing the amount of welding is good practice, welding is a normal part of producing steel castings. This standard everyday process of welding steel castings to ensure they meet the exacting quality requirements of the customer is termed production welding.

Production welding is used to replace certain undesirable features on a casting; it is used to add steel to meet the quality requirements of the customer. Welding to fill a cavity has traditionally been called "repair welding" and the casting conditions removed by welding were called "defects". These terms incorrectly implied that these details were unexpected and that welding on a casting was unusual and outside normal operations. However, it is to be expected that castings will have non-compliant quality details. Depending on their size, location, and the requirements placed on the castings, these quality details may be acceptable according to the customer standard or they may need to be removed and the cavity production welded to bring the casting into compliance with requirements. Today, these casting quality details found during inspection are referred to as indications, which are potential quality non-conformances, rather than "defects". Another common term used in addition to defects is "discontinuities". This term is also not particularly correct or clear. The term proposed, and in this document will be used, is "quality details" for conditions in the casting that are related to quality and must be assessed for compliance with purchase specifications and requirements. The term "defect" should only be used for indications that fail to meet the customer standard in a casting that has been shipped to the customer (ASTM E 1316 Section A Common NDT Terms, 4. Terminology, Defect). Before shipping, indications that are unacceptable are simply nonconformances. The standard process of filling cavities to correct these quality non-conformances is now known as production welding (ASTM A 941). This change in terminology can also be seen in ISO 11970. In paragraph 3, "Terms and Conditions," paragraph 3.2 defines repair welding as any welding carried out after delivery to the end user, i.e., after the casting has been in service. Paragraph 3.1 defines production welding to be any welding carried out during manufacturing before the final delivery to the purchaser including joint welding of castings and finish welding.

Welding is an additional cost like machining, and manufacturing seeks to minimize the welding to keep costs low and improve quality. Even so, welding is used for the production process to manufacture the highest quality castings. [1] For parts requiring extensive welding, foundries may scrap the part and make a new one if that would be cheaper.

### Casting Upgrade

The process of reworking a casting to meet a different quality standard is called upgrading. It is primarily a term used in the valve industry. The term "upgrading" is often used incorrectly to refer to any production welding used to meet the original quality requirements of the purchaser. The difference between normal production welding and welding to upgrade a casting is best shown with an example:

Valve castings can be made to the standard for regular valves or to the standard for special valves. A purchaser who has regular valves in stock and has an order for special valves from the same material and from the same design may upgrade the standard valves to special valves. This process requires additional testing and may require the removal of quality non-conformances and require production welding to fill the cavity remaining to meet the special valve requirements. Sometimes, the difference between a standard and upgraded casting cannot be seen. (ASME/ANSI B 16.34)

### Weld Overlay

In certain places where castings are used, exposure to wear or corrosion might require the addition of a special surface or alloy. It is possible to use welding to apply a special alloy with better wear resistance or corrosion resistance to a casting surface by welding. This process is known as weld overlay, cladding, or facing.

### Cast-Weld Construction

Steel castings can be welded to other steel castings, plates, bars, pipes, or other steel shapes to create a larger fabrication for building construction or to fabricate industrial equipment. In both ASME BPVC Section IX and AWS B2.1, steel castings are grouped with all other product forms that have similar compositions and properties. The development of weld procedures or welder qualification for any material in the sub-groups, qualifies the welder and procedure to weld any steel product in the sub-group to any other product. Steel castings are treated as any other steel product and used in welded fabrications. The welding techniques, electrode and flux selection, preheating and post-heating discussed in detail in this document can be employed for cast-weld fabrication as well as production welding [2].

Cast-weld fabrication is a practical and effective method for joining simple castings to make complex shapes. It is also used to join components of various compositions and properties as well as components made using different processes, such as castings, forgings, plates, bars, and tubes. Advantages include greater flexibility of design, assembly of parts having different physical and chemical properties, increased strength, reduced machining and casting costs, and reduced weight [2].

Cast-weld fabrication techniques can be preferable to producing a very large or complex part as a one-piece casting. Often the combination of standard mill shapes for uniform or thin sections and castings for complex geometries that form connections can be higher quality, less expensive and more capable than a single casting. Castings are typically used to form connections, transferring movement or force to other parts of industrial equipment. Combining the complex geometry of castings with the cost and capability of mill products can make optimal parts. In some cases, the foundry lacks the melting, pouring, or handling capacity for the large castings. Even when the casting size can be managed, sound castings in some configurations are difficult, even impossible to achieve because of coring, feeding, and hot-tearing problems. In many situations, combining castings with other steel products allow the optimal quality and performance.

Cast-weld construction can be used for many designs and configurations. Adding appendages to large cast parts and producing left-hand and right-hand components are among the simplest applications. This cast-weld process is being used to an increasing extent for piping and auxiliary equipment in high-pressure, high temperature, and nuclear-power service. Cast-weld construction also permits joining light sections to heavy sections that would be difficult to cast. One widely employed and significant use is to extend the maximum size of a component that can be produced by conventional casting equipment. Other applications involve combining different metals; for example, separately cast sections of heat, corrosion, or erosion resistant materials are welded to castings of lower alloy composition to provide special properties at selected areas [2].

Castings produced for cast-weld construction can incorporate self-locating devices to facilitate accurate assembly and tapered or “Veed out” areas into which the weld is deposited. The conventional designs of weld grooves and weld preparation are described in Section 5 of this report and are utilized for cast-weld construction in addition to production welding with as much of the grooves, tapers and locating devices cast into the parts as feasible. These designs both improve quality and reduce cost.

## Properties of Welded Steel Castings

It is important when buying steel castings to use a casting supplier with integrity. Many times, when a customer has a requirement for “no weld repair”, it is because they had a bad experience with a foundry. That plant was not doing the required testing of welders, wasn’t following a qualified welding procedure, and wasn’t doing required non-destructive testing (NDT). The problem was not that the casting was being welded, but that the castings were being welded badly, without proper control or oversight. Specifying “no weld repair” doesn’t solve the problem of lack of integrity and significantly raises the price of the product when it is moved to a producer who does have integrity.

Customers may raise a concern regarding production welding of steel castings. However, welding steel is welding steel, whether the steel is cast or wrought. Castings are frequently welded into larger assemblies. If they are fine in service with welding in assembly, production welding shouldn't be a problem. To make sure that the welded steel castings meet the designer's requirements, weld procedures and welders are qualified prior to their use in steel casting fabrication or production. Section 2 of this report will cover what is entailed in welder and process qualification. Welding is another tool in our toolbox to maximize the value and benefit of the steel casting process. Poor in-process welding can result in surface or subsurface quality details that will not pass NDT. NDT is used to verify compliance. [1]

Some pressure vessel purchasers making pumps and valves impose a requirement of no major welds on their castings. This is misguided since major weld definitions limit how deep into the wall a weld can be made before it is considered major. A leaking casting needs to be through-wall welded in order not to leak, so it must be welded.

Welding of steel castings is regulated by ASTM and ISO. ASTM A781 or A957 for structural castings and ASTM A703 or A985 for pressure castings which allows welding in compliance with A488 on the casting. Welding can't be willy-nilly but must meet ASTM A488. ASTM A488 requires welding procedure qualification tests, welder/operator performance qualification tests, and welding procedure specification (all of which will be covered in more detail in Section 2 of this report); it requires that the weld used for qualifying the procedure meet the strength and toughness requirements of the material ordered for the casting. Foundries must have qualified welders, an approved weld procedure, and approved weld filler chemistry to meet the specified grade surface and internal integrity. Often producers will have weld procedures for alloys for use prior to final heat treatment with matching heat treat response and another procedure for welding after heat treatment that may require stress relieve. Some grades in ASTM require the application of a stress relieve after a major weld (for example A487 9.3).

Purchasers are free to add more restrictions to producers. Common restrictions include the requirement for weld maps, prior approval for major welds, and no weld areas in the casting. Weld maps and the definition of major welds are in ASTM A703 S20, A781 S16, A957 S16 or A985 S20. Prior approval for major welds can be required by calling out ASTM A703 S12, A781 S7, A957 S7 or A985 S12. Specific inspection of weld cavities prior to welding is addressed in ASTM A703 S10, A781 S5, A957 S5 or A985 S10.

But what shows us that welding on steel castings is not detrimental to the service of the part? There is more data on welding of steel mill products than for cast steel, since mills make almost 100 times more steel each year than steel foundries. This mill product data has been used to show the acceptability of welds on castings. Steel mill products are also called wrought steel. If welding a steel casting into a fabricated mill-cast assembly works then welding to fill cavities or add stock on a casting shouldn't be a problem. Besides the steel mill data, steel foundries have published work specifically on cracking tendency, mechanical properties, toughness, and fatigue response of welded steel castings.

Published in 1948, [SFSA Research Report 16: Weldability of Carbon-Manganese Steel](#) [3] authored by the SFSA Technical and Research Committee under the direction of Charles W. Briggs, considered the weldability of carbon manganese steels, common ordinary steel. In this research report, wrought steel as well as cast steels were tested. The steels used in this study were grouped into four classes (see Figure 1) each with a different carbon and manganese content. Cast steels were tested in classes 2, 3, and 4 since class 1 was outside the composition for commercial steel castings. One of the conclusions of this study was that "Considering the rolled and cast steels separately, the relation between crack sensitivity and chemical composition was very good. The cast steels cracked much less than rolled steels of comparable carbon equivalent." Figure 1 shows this relationship of underbead weld cracking to carbon equivalent for cast vs mill products. It is of note that, "the welding conditions used in the crack sensitivity test were quite severe, but this was intentional, in order that cracking might be produced in as many of the steels as possible. Under ordinary welding conditions, and without preheat, underbead cracking should not be encountered in any except the Type 4 steels. If low-hydrogen electrodes were used no cracking would be found in any of the cast steel specimens and slight cracking in the wrought type 4 steels." [3] [4]

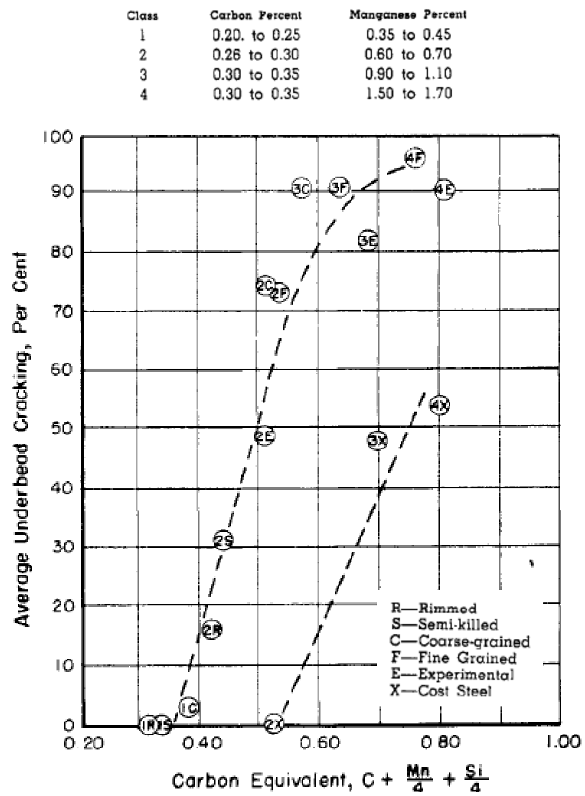


*Figure 1 relation between underbead cracking and chemical composition of 1" plates of carbon-manganese rolled and cast steels. Initial Plate Temperature was 80°F.*

The 1983 T&O paper [Weldability of Cast Steels](#) by Dr. Lundin and Dr. Menon from the University of Tennessee [5] replicated the research of SFSA Research Report 16 to measure if wrought steel had a greater susceptibility to underbead cracking compared to cast steel at the same carbon equivalent. They found "under similar high hydrogen conditions, wrought C-Mn-Si steels welded parallel to the rolling direction (PRD) cracked to a greater extent and required higher preheat temperatures to remain crack insensitive than comparable C&N (cast and normalized) C-Mn-Si steels. However, when tested normal to rolling direction (NRD), preheat temperatures to prevent cracking were found to be similar to those for equivalent C&N steels." In this study they also recorded the effect of welding cast steel and applying post weld heat treatment (PWHT) on weld Charpy values. "Charpy blanks were subjected to a thermal cycle corresponding to a peak temperature of 2400°F using an energy input of 50 KJ/inch in a 1" plate, welded at 80°F. The blanks were then post-weld heat treated at 1200°F for one hour. Charpy samples from the as received C&N base materials were evaluated to have baseline data." For steels with a CE greater than 0.45, the toughness for the thermal cycled and PWHT condition was equal to or greater than the base metal values. Steels with a carbon equivalent (CE) less than

0.45 showed a decrease in toughness in the thermally cycled and PWHT condition compared to the base metal values. "The decrease in toughness of the low C.E. C&N C-Mn-Si steels is attributed to the presence of high temperature transformation products contributing to a mixed microstructure, whereas the higher C.E. materials essentially have a tempered martensitic structure, which possesses high toughness." The overall conclusions of this paper were that:

1. "Cast steels can be welded provided adequate preheat temperatures are used; these preheat temperatures are established based on the C.E."
2. "The level of preheat temperature required appears no different from those already established for equivalent wrought materials i.e. the fabricability of cast steels is as good, or even better, than that of comparable wrought materials."
3. "Maintaining the preheat after welding can help in reducing the preheat level required to prevent cracking."
4. "Whenever possible, welding should be performed on normalized steel rather than as-cast steel."
5. "The melting practice (acid or basic) does not appear to have any effect on cracking susceptibility."
6. "Fully deoxidized cast steels appear to have better weldability characteristics than partially deoxidized cast steels; however, the above observation has to be tempered with the realization that excessive aluminum deoxidation may give rise to the problem of aluminum nitride embrittlement."
7. "As far as possible, low hydrogen electrodes should be used. The methods of storage and bake out recommended by the manufacturer should be adhered to."
8. "Greater HAZ impact toughness than that of the cast steel can be realized using post-weld heat treatment, provided the C.E./heat input combination is suitably chosen."

Steel Foundry Facts 78-10 Production Control for Welding by P.J. Neff looked at process control for production welding of steel castings. [6] In it, the author points out that "Five factors to be controlled are 1) solidity of the welds, 2) mechanical properties of the weld, 3) chemical composition of the weld, 4) hardness of the heat affected zone, and 5) the welder operator and his technique. The means by which these items may be controlled are: 1) chemical analyses, 2) hardness testing, 3) radiographic examination, and 4) magnetic particle testing." To show that the mechanical properties of the welds on castings were acceptable, cast plates 10" x 12" x 1.25" were made. A weld groove with 60-degree angle 1.5" deep was made in the cast plates and welded following their casting production welding process. Tensile tests were taken from 100% weld metal and transverse to the weld so as to include some base, HAZ, and weld metal. The 100% weld metal behaved as you would expect based on the weld filler material properties.

*Table 2 Mechanical properties for tensile tests taken transverse to the weld*

Transverse Test Bars

| | Yield Strength | Tensile Strength | Elonga-tion-% | Reduction of Area-% |
|---|---|---|---|---|
| Parent Metal | 50,000 | 80,000 | 30.0 | 54.7 |
| 1/2" Weld | 44,000 | 73,800 | 23.0 | 69.0 |
| 1" Weld | 42,100 | 71,500 | 27.0 | 71.2 |
| 1-1/2" Weld | 42,100 | 71,000 | 28.0 | 70.8 |
| 2" Weld | 41,000 | 70,000 | 30.0 | 72.3 |
| All Weld | 47,700 | 70,300 | 31.5 | 73.5 |

*Table 1 Elongation in weld vs parent metal based on weld length.*

| Length in Weld | Elongation in Weld | Elongation in Parent Metal |
|---|---|---|
| 1/2" | .40 | .06 |
| 1" | .44 | .10 |
| 1-1/2" | .45 | .11 |
| 2" | .60 | .00 |

Hardness test values taken on single pass welds on Grade "B" steel plates containing 0.28 carbon and welded with Murex 0115 electrode (0.50% carbon, 0.30% molybdenum) were as shown in Table 3.

*Table 3 Un-tempered hardness values of weld, HAZ and parent metal*

| | Weld | Heat Affected Zone | Parent Metal |
|---|---|---|---|
| 1/2" Plate | 230 Brinell | 220 Brinell | |
| 1" " | 240 " | 230 " | 160 Brinell |
| 2" " | 270 " | 250 " | |

Data for the transverse tensile test bars with various weld sizes of ½" to 2" are shown in Table 1. Table 2 shows how much of the elongation in the tensile was seen in the parent metal vs the weld. Table 3 shows hardness values in the weld and heat affected zones were higher than the parent metal hardness if left un-tempered. The author noted that "Tempering did not change the hardness of the welds but reduced the heat affected zone to 180-190 Brinell. By renormalizing the heat affected zone came down to the hardness of the parent metal." This data shows a slight decrease in yield and tensile in the welds as compared to the parent metal but with a corresponding increase in reduction in area. This paper was published in 1948 and there is no mention of low hydrogen considerations while welding.

In Steel Foundry Facts 249-02 Metallurgical Effects of Welding 3- to 4- Inch Sections of WCB Steel published in 1964 by R.W. Carter and Nick Wukovich [7], the authors were researching how best to production weld heavy section steel castings. They used three different compositions of WCB steel (see Table 4) to cast 3.5" thick plates. These plates were welded using three different types of electrodes and in different conditions including as-welded vs stress relieved and preheat vs no preheat. Mechanical testing and bend tests were performed. Test specimens were taken transverse to the weld (so they contained some of the weld, HAZ, and base metal). Tensiles were taken from the bottom (the root of the weld), middle, and top of the weld. Bend tests were taken near the bottom and top of the weld. See Figure 2 for locations of test specimens taken from the cast then welded test block.

*Table 4 Steel Compositions*

| Type | Remarks | C | Mn | P | S | Si | Ni | Cr | Mo | Cu | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WCB | Standard A-216 | .26 | .67 | .021 | .029 | .46 | .12 | .17 | .08 | .13 | .086 |
| WCB | Composition A | .29 | 1.00 | .023 | .025 | .48 | .29 | .25 | .22 | .11 | .072 |
| WCB | Composition B | .28 | .70 | .023 | .025 | .48 | .32 | .27 | .24 | .11 | .078 |
| 8627 | AISI | .24/.30 | .60/.95 | — | — | .20/.35 | .35/.75 | .35/.65 | .15/.25 | — | — |
| 1029 | AISI | .25/.31 | .60/.90 | — | — | .20/.35 | — | — | — | — | — |

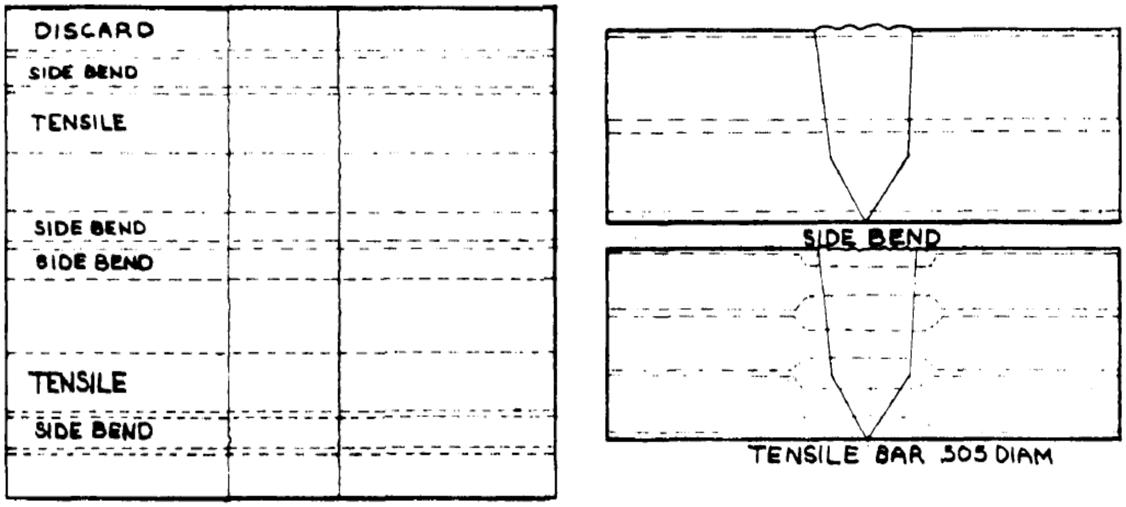



*Figure 2 Bend and tensile test specimen locations*

Table 5 shows hardness traverses of the WCB weldments. The HAZ has the highest hardness as expected. Stress relief did lower the HAZ hardness without significantly changing the weld metal or base metal hardness.

*Table 5 Hardness transverse of WCB weldment*

| | Hardness, BHN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Preheated | | | | Preheated | |
| | As Welded | Stress Relieved | As Welded | Stress Relieved | As Welded | Stress Relieved | As Welded | Stress Relieved | As Welded | Stress Relieved |
| Weld Plate | 1 | | 7 | | 9 | | 8 | | 10 | |
| Welding Electrodes | E6010 | | E6018 | | E6018 | | E6012 | | E6012 | |
| Base Metal | 149 | 149 | 197 | 192 | 201 | 192 | 212 | 192 | 217 | 186 |
| Heat Affected Zone | 183 | 174 | 235 | 212 | 235 | 223 | 235 | 212 | 248 | 201 |
| Weld Metal | 143 | 156 | 170 | 167 | 170 | 170 | 167 | 174 | 163 | 163 |

Table 6 shows the mechanical property data. The ends of the weld plates were acid etched; the plates welded with E6010 and E6012 showed areas of slag inclusions and/or porosity while the plates welded with E6018 or E7018 were sound. E6018 and E7018 are low hydrogen electrodes and as such did contain a higher manganese and silicon content. The reduction in area values especially show the benefit of using the low hydrogen

*Table 6 Mechanical properties of welded cast plate. Tensiles were taken transverse to the weld near the bottom (root of the weld), middle, and top of the weld.*

| Plate | Electrode | Preheat | Stress Relief | Tensile Location | Tensile Strength, psi | Yield Strength, psi | Elongation % in 2" | Reduction of Area, % |
|---|---|---|---|---|---|---|---|---|
| 1 | E6010 | None | 1200°F | Top | 63,700 | 54,700 | 38.0 | 49 |
| | | | | Middle | 65,200 | 54,000 | 22.5 | 43.5 |
| | | | | Bottom | 64,700 | 50,200 | 19.5 | 38 |
| 7 | E6018 or E7018 | None | 1200°F | Top | 73,200 | 61,700 | 31.7 | 78.3 |
| | | | | Middle | 71,700 | 59,700 | 26.5 | 70.2 |
| | | | | Bottom | 71,700 | 61,000 | 25.0 | 71.5 |
| 9 | E6018 or E7018 | 400°F | 1200°F | Top | 65,000 | 54,000 | 34.5 | 78 |
| | | | | Middle | 68,000 | 60,000 | 29.0 | 75.3 |
| | | | | Bottom | 74,000 | 60,500 | 21.0 | 68.8 |
| 8 | E6012 | None | 1200°F | Top | 67,700 | 59,500 | 18.0 | 34.1 |
| | | | | Middle | 70,500 | 62,700 | 17.0 | 33.2 |
| | | | | Bottom | 74,500 | 67,500 | 10.0 | 29.2 |
| 10 | E6012 | 400°F | 1200°F | Top | 65,000 | 59,700 | 18.7 | 34.1 |
| | | | | Middle | 66,700 | 60,200 | 16.7 | 42.6 |
| | | | | Bottom | 66,500 | 61,700 | 13.7 | 31.3 |

electrodes. The authors concluded that "the selection of electrodes with low hydrogen and good slag removal characteristics become very important in welding heavy sections."

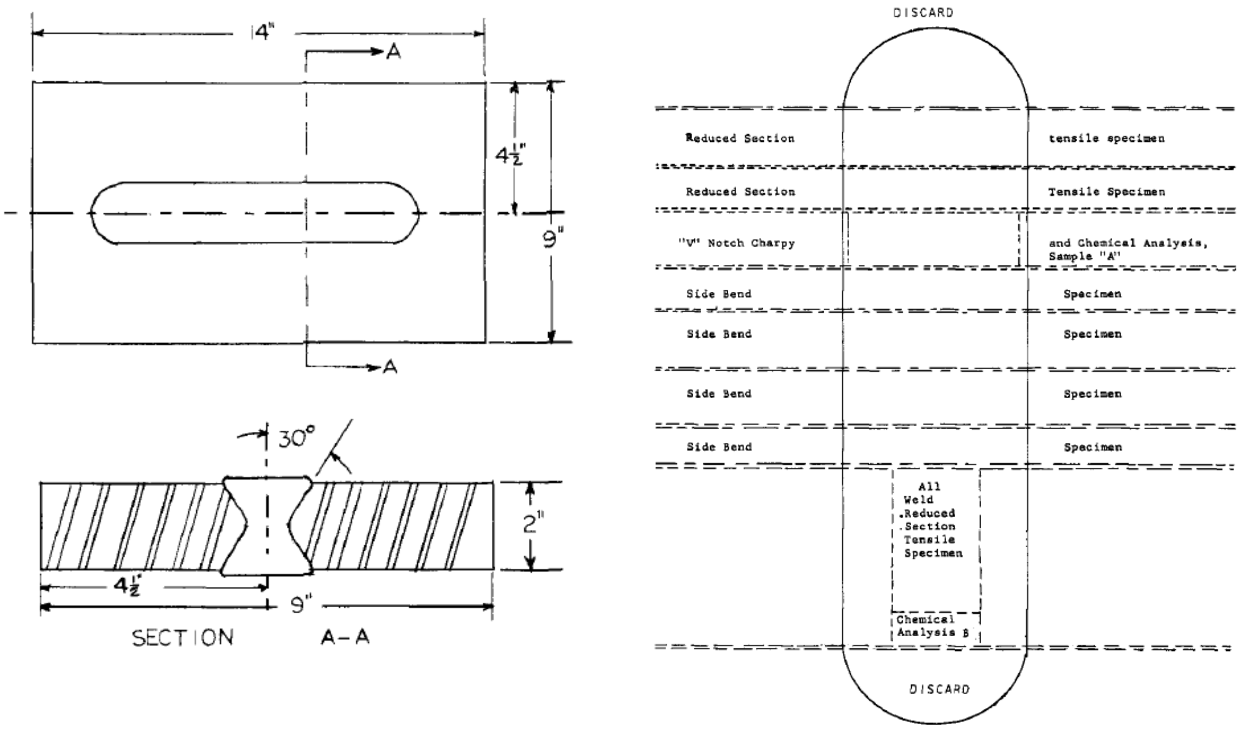



*Figure 3 Test plate schematic and location of removal of test specimens from the plate*

Steel Foundry Facts 277-03 Semi-automatic Repair Welding written in 1967 by E. Dobrec and M.R. McGregor [8] looked at qualifying the flux cored arc (FCA) welding process for steel foundry production welding. Both wrought and cast test plates were used (see Table 7 for chemistry). Test plate 5 was cast; test plates 2, 3, 4, & 6 were rolled; test plate 1 was not identified as cast or rolled. Each plate had two transverse tensiles, four side bends, three "v" notch Charpys, and one all weld metal tensile removed from them (see Figure 3) as well as

*Table 7 Chemical analysis of deposited metals*

**CHEMICAL ANALYSES OF TEST PLATES**

| Element | Plate 1 | Plate 2 | Plate 3 | Plate 4 | Plate 5 | Plate 6 |
|---|---|---|---|---|---|---|
| Carbon | .09 | A .12<br>B .14 | A .25<br>B .25 | A .11<br>B .11 | A .06<br>B .06 | A .09<br>B .10 |
| Manganese | 1.30 | A 1.80<br>B 1.83 | A .87<br>B .91 | A 1.88<br>B 1.85 | A 1.04<br>B .99 | A .82<br>B .83 |
| Silicon | .25 | A .97<br>B .97 | A .05<br>B .05 | A .99<br>B .96 | A .42<br>B .50 | A .38<br>B .32 |
| Chromium | | A .01<br>B .01 | A NEG<br>B NEG | A .03<br>B .03 | A 2.30<br>B 2.30 | A .03<br>B .03 |
| Nickel | | A .02<br>B .02 | A NEG<br>B NEG | A .02<br>B .02 | A .03<br>B .03 | A .01<br>B .01 |
| Molybdenum | .76 | A NEG<br>B NEG | A NEG<br>B NEG | A NEG<br>B NEG | A 1.24<br>B 1.25 | A NEG<br>B NEG |
| Vanadium | | A .004<br>B | A NEG<br>B NEG | A .004<br>B .004 | A .014<br>B .010 | A .017<br>B .017 |
| Copper | | A .06<br>B .06 | A NEG<br>B NEG | A .06<br>B .06 | A .02<br>B .04 | A NEG<br>B NEG |

hardness checks covering the parent metal, heat affected zone, and weld (see Figure 4 and Table 8). All the plates were radiographed after welding and shown to be sound except for Plate 3 (which was a wrought plate) which showed measurable amounts of slag inclusions. Table 9 shows the result of the transverse tensile tests (A and B) as well as the all-weld metal tensile (C). The transverse tensile properties are comparable to the all-weld longitudinal tensile properties. The yield strength in Plate 3 is low but, as mentioned earlier, that plate had significant slag seen on the radiograph, so the lower ductility is not surprising. Charpy impact results can be seen in Table 10. The conclusion of this paper was that "quality welds can be produced with the semi-automatic equipment using CO2 gas and flux cored wires."

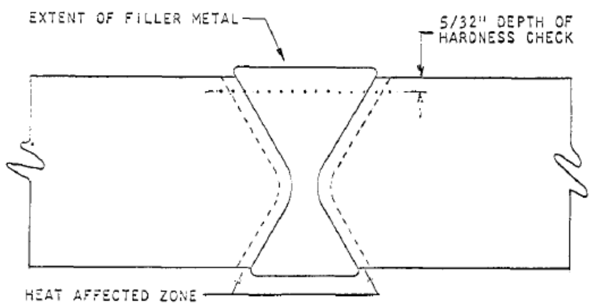



*Figure 4 Location of hardness survey through parent metal heat affected zone and weld metal.*

*Table 8 Tensile Results*

**PHYSICAL TEST PROPERTIES**

| Item | Plate 1* | Plate 2* | Plate 3* | Plate 4* | Plate 5* | Plate 6* |
|---|---|---|---|---|---|---|
| A | 78,000 | 81,500 | 73,500 | 70,500 | 90,000 | 69,000 |
| B | 80,500 | 77,500 | 74,000 | 71,000 | 88,500 | 67,500 |

* Tensile Strength, P.S.I.

| C | | | | | | |
|---|---|---|---|---|---|---|
| Yield | 68,500 | 69,500 | 45,000 | 71,000 | 74,000 | 54,500 |
| Tensile | 80,500 | 89,000 | 73,500 | 87,500 | 89,000 | 70,500 |
| Elong. | 29.0 | 24.0 | 21.1 | 26.0 | 10.0 | 35.0 |
| R. A. | 66.0 | 47.4 | 35.6 | 49.7 | 28.4 | 69.7 |

KEY:
- A: Machined Transversly Through Weld.
- B: Machined Transversly Through Weld.
- C: Machined from all Weld Material.

*Table 9 Hardness Survey of Weld Plate*

**HARDNESS - ROCKWELL B SCALE**

| Spot | Plate 1 | Plate 2 | Plate 3 | Plate 4 | Plate 5 | Plate 6 |
|---|---|---|---|---|---|---|
| 1 | | 43.5 | 71.5 | 67.0 | 93.0 | 72.0 |
| 2 | | 44.0 | 72.5 | 70.0 | 92.0 | 72.0 |
| 3 | | 49.5 | 74.0 | 70.0 | 92.0 | 71.5 |
| 4 | | 57.0 | 74.0 | 71.0 | 90.5 | 71.0 |
| 5 | | 56.5 | 76.0 | 72.0 | 95.0 | 73.0 |
| 6 | | 58.0 | 80.0 | 76.0 | 93.5 | 78.0 |
| 7 | | 57.0 | 82.0 | 77.0 | 93.0 | 79.5 |
| 8 | | 56.0 | 82.0 | 80.0 | 93.0 | 80.0 |
| 9 | | 54.0 | 80.0 | 84.0 | 90.0 | 80.0 |
| 10 | | 50.0 | 81.5 | 90.5 | 92.5 | 81.0 |
| 11 | | 42.5 | 80.0 | 89.0 | 90.0 | 81.0 |
| 12 | | | 81.0 | 88.5 | 91.0 | 77.0 |
| 13 | | | 82.0 | 89.0 | 93.0 | 80.0 |
| 14 | | | 82.0 | 87.0 | 95.0 | 78.5 |
| 15 | | | 78.0 | 80.0 | 95.0 | 81.0 |
| 16 | | | 74.0 | 76.0 | 94.0 | 80.5 |
| 17 | | | 74.0 | 74.0 | 88.5 | 80.0 |
| 18 | | | 74.0 | 70.0 | 93.0 | 75.5 |
| 19 | | | 72.0 | 71.0 | 93.0 | 72.0 |
| 20 | | | 71.0 | 70.0 | 93.5 | 71.5 |

*Table 10 Charpy Results*

**CHARPY IMPACT TEST**

| Mark | Plate 1* | Plate 2* | Plate 3* | Plate 4* | Plate 5* | Plate 6* |
|---|---|---|---|---|---|---|
| 1 | | 41 | 9 | 25 | 12 | 43 |
| 2 | | 35.5 | 9 | 32 | 41 | 97 |
| 3 | | 41 | 4 | 36 | 16.5 | 94 |

* - Ft/Lbs.
Size. 10 MM × 10 MM × 55 MM
Type: "V" Notch
Temp.: Room

Steel Founders Research Journal 8-1 Preparation for Welding by the Air-Carbon Arc Process published by E.J. Ridal and W.J. Jackson [9] was concerned with whether surfaces prepared by air-carbon arc gouging could be satisfactorily welded without grinding. To ascertain this, a step wedge test block (see Figure 5) was cast with dimensions having a total length of 380 mm (~15") and 100mm (~4") wide. Twelve test blocks were poured for each of three steel grades (see Table 12 for grade chemistries). This was enough to do the planned testing plus leave 3-4 test blocks for spares. Table 11 shows the combination of gouging and heat treatment cycles. Figure 6 shows the location on the test block where the Charpy and tensile specimens were taken. Table

13 to Table 23 show the result of the Charpy, tensile, and hardness profiles. Since this data comes from a step block casting that has multiple section sizes and was set up to simulate production welding of castings by first arc air gouging a section (as if to remove an unacceptable quality detail) and then the resulting gouge was filled in with weld metal, this data is especially useful for determining the effect of production welding on steel castings. The conclusion of this paper was that air-carbon arc gouging and welding can be successfully carried out on the three cast steels examined.

*Table 12 Gouging and Heat Treatment Cycles (with 20mm dia. electrodes and air pressure 90 psi)*

| PH As Cast, Gouge | | Anneal, PH Gouge | | Anneal, PH Gouge, PH, Weld | | Anneal, PH Gouge, PH, Weld Heat-Treat | |
|---|---|---|---|---|---|---|---|
| SP | MP | SP | MP | SP | MP | SP | MP |
| A | A | A | A | A | A | A | A |
| B | B | B | B | B | B | B | B |
| D | D | D | D | T | T | T | T |
| | | | | C | C | C | C |
| | | | | D | D | D | D |

PH = Preheat
SP = Single Pass
MP = Multi Pass
A = Section Examined for Cracks in HAZ
B = Hardness Traverses
T = Tensile
C = Charpy
D = Macro and Micro-Examination

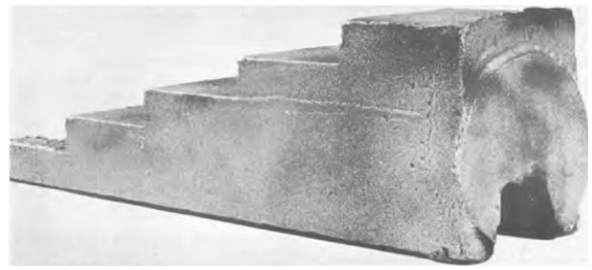


*Figure 6 Step Block Casting*

*Table 12 Chemistry for the three grades cast*

| Steel | C% | Si% | Mn% | P% |
|---|---|---|---|---|
| 1¼% Cr-Mo | 0.18 | 0.46 | 0.75 | .025 |
| 5% Cr-Mo | 0.17 | 0.42 | 0.66 | .025 |
| 1½% Ni-Cr-Mo | 0.30 | 0.36 | 0.42 | .020 |

| Steel | S% | Mo% | Ni% | Cr% |
|---|---|---|---|---|
| 1¼% Cr-Mo | .019 | 0.46 | 0.17 | 1.11 |
| 5% Cr-Mo | .018 | 0.53 | 0.19 | 4.13 |
| 1½% Ni-Cr-Mo | .010 | 0.36 | 1.66 | 0.61 |

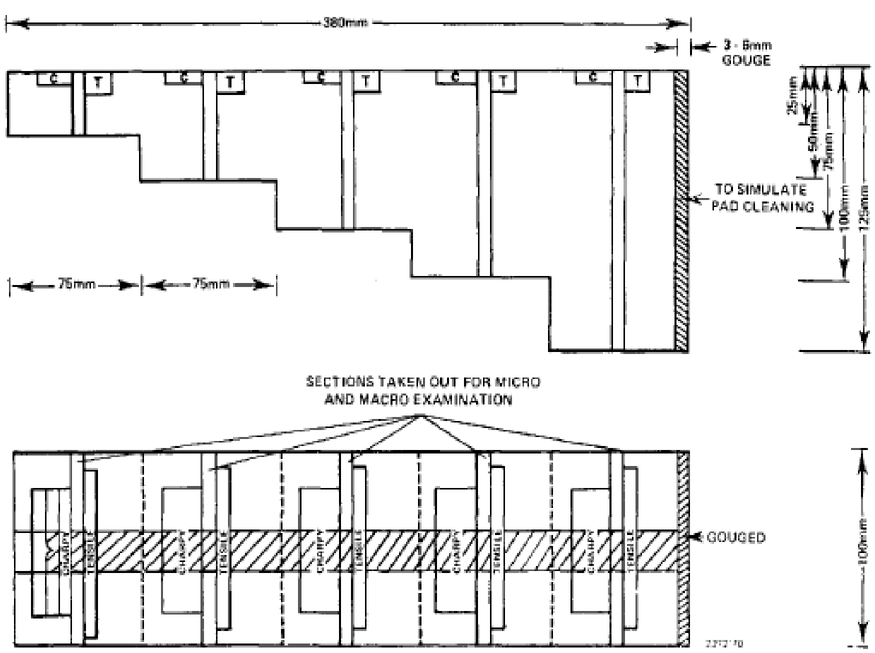



*Figure 5 The size and shape of the test block and position of test pieces to be taken.*

*Table 13 Tensile and Impact Properties of 1 ¼% Cr-Mo Steel Welded Single Pass and Multi Pass Gouges, Welded with Chromotrode 76.12*

| Type of Gouge | Section Thickness mm | Gouging and Welding Sequence | UTS MPa | YS MPa | El % | R of A % | Charpy V-Notch Impact at +22°C J |
|---|---|---|---|---|---|---|---|
| Single Pass | 25 | Anneal-PH 250°C Gouge-PH 200°C-Weld-Temper | 599 | 420 | 14.4 | 30.0 | 41, 38, 35 |
| | 50 | | 592 | 406 | 23.8 | 58.5 | 35, 35, 46 |
| | 75 | | 582 | 420 | 22.2 | 58.5 | 54, 61, 49 |
| | 100 | | 582 | 420 | 22.2 | 62.5 | 49, 43, 49 |
| | 125 | | 599 | 434 | 25.0 | 61.8 | 62, 60, 62 |
| | 25 | Anneal-PH 250°C Gouge-PH 200°C-Weld-Harden-Temper | 609 | 462 | 16.0 | 59.0 | 46, 47, 43 |
| | 50 | | 579 | 434 | 16.0 | 28.0 | 83, 85, 71 |
| | 75 | | 595 | 442 | 22.0 | 59.5 | 53, 56, 62 |
| | 100 | | 588 | 449 | 22.0 | 60.0 | 62, 43 |
| | 125 | | 579 | 434 | 22.0 | 57.0 | 54, 46 |
| Multi Pass | 25 | Anneal-PH 250°C Gouge-PH 200°C-Weld-Temper | 666 | 606 | 12.5 | 28.4 | 96, 90, 90 |
| | 50 | | 628 | 410 | 10 | 23 | 78, 88, 74 |
| | 75 | | 600 | 560 | 8 | 18.5 | 84, 86, 76 |
| | 100 | | 684 | 618 | 20 | 56 | 64, 72, 70 |
| | 125 | | 688 | 580 | 16 | 41 | 49, 64, 62 |
| | 25 | Anneal-PH 250°C Gouge-PH 200°C-Weld-Harden-Temper | 490 | 398 | —— | —— | 32, 48, 74 |
| | 50 | | 518 | 398 | 22 | 51.6 | 80, 32, 56 |
| | 75 | | 512 | 388 | 20 | 43 | 79, 54, 116 |
| | 100 | | 510 | 390 | 25 | 65 | 82, 132, 116 |
| | 125 | | 520 | 402 | 15 | 27.3 | 96, 123, 85 |

*Table 14 Tensile and Impact Results on 5% Cr-Mo Steel Welded Single Pass and Multi Pass Gouges, Welded with Surprex C*

| Type of Gouge | Section Thickness mm | Gouging and Welding Sequence | UTS MPa | YS MPa | El % | R of A % | Charpy V-Notch Impact at +22°C J |
|---|---|---|---|---|---|---|---|
| Single Pass | 25 | Anneal-PH 300°C Gouge-PH 250°C-Weld-Temper | 659 | 468 | 22.5 | 60.5 | 130, 115, 119 |
| | 50 | | 675 | 497 | 22.2 | 64.0 | 126, 113, 111 |
| | 75 | | 673 | 497 | 20.5 | 66.5 | 114, 102, 100 |
| | 100 | | 663 | 488 | 21.0 | 65.0 | 130, 100, 108 |
| | 125 | | 647 | 466 | 23.8 | 67.0 | 122, 122, 133 |
| | 25 | Anneal-PH 300°C Gouge-PH 250°C-Weld-Harden-Temper | 647 | 462 | 22.2 | 52.9 | 117, 103, 113 |
| | 50 | | 647 | 468 | 22.2 | 61.8 | 113, 119 |
| | 75 | | 655 | 476 | 22.7 | 58.5 | 106, 107, 117 |
| | 100 | | 661 | 476 | 25.0 | 58.5 | 111, 117, 110 |
| | 125 | | 655 | 454 | 22.0 | 56.0 | 119, 115, 108 |
| Multi Pass | 25 | Anneal-PH 300°C Gouge-PH 250°C-Weld-Temper | 668 | 388 | 20 | 74.8 | 154, 150, 138 |
| | 50 | | —— | —— | —— | —— | ——, 155, 156 |
| | 75 | | 774 | 612 | 20 | 68.1 | 165, 152, 154 |
| | 100 | | 700 | 590 | 18 | 71 | ——, 132, 123 |
| | 125 | | 700 | 560 | 19 | 67.4 | 136, 56, 149 |
| | 25 | Anneal-PH 300°C Gouge-PH 250°C-Weld-Harden-Temper | 564 | 436 | 23 | 74.8 | 200, 204, —— |
| | 50 | | 560 | —— | 21.3 | 72.2 | 164, 174, 176 |
| | 75 | | 558 | 540 | 21.3 | 69 | 168, 212, 201 |
| | 100 | | 534 | —— | 21.3 | 75 | 180, 176, 172 |
| | 125 | | 544 | —— | 21.3 | 72.2 | 86, 160, 192 |

*Table 15 Tensile and Impact Properties of 1 ½% Ni-Cr-Mo Steel on Welded Single Pass and Multi Pass Gouges, Welded with Tensitrode 75.55*

| Type of Gouge | Section Thickness mm | Gouging and Welding Sequence | UTS MPa | YS MPa | El % | R of A % | Charpy V-Notch Impact at +22°C J |
|---|---|---|---|---|---|---|---|
| Single Pass | 25 | Anneal-PH 200°C Gouge-PH 150°C-Weld-Temper | 709 | 579 | 16.0 | 45.0 | 68, 55, 126 |
| | 50 | | 703 | 530 | 16.3 | 38.5 | 71, 68, 72 |
| | 75 | | 695 | 544 | 13.8 | 32.0 | 102, 77, 102 |
| | 100 | | 703 | 530 | 18.3 | 46.0 | 53, 61, 68 |
| | 125 | | 720 | 565 | 16 | 48.0 | 107, 84, 107 |
| | 25 | Anneal-PH 200°C Gouge-PH 150°C-Weld-Harden-Temper | 731 | 609 | 16.1 | 55.0 | 69, 66, 80 |
| | 50 | | 717 | 565 | 16.1 | 52.5 | 95, 88, 122 |
| | 75 | | 717 | 544 | 16.1 | 39.0 | 68, 49, 56 |
| | 100 | | 704 | 558 | 16.0 | 54.5 | 136, 130, 92 |
| | 125 | | 732 | 585 | 15 | 46.5 | 128, 91, 91 |
| Multi Pass | 25 | Anneal-PH 200°C Gouge-PH 150°C-Weld-Temper | 780 | 712 | 16.3 | 61.5 | 72, 58, 58 |
| | 50 | | 768 | 720 | 17.5 | 61.5 | 60, 45, 50 |
| | 75 | | 786 | 630 | 18.7 | 66.7 | 38, 44, 40 |
| | 100 | | 770 | 750 | 12.5 | 66.0 | 42, 28, 41 |
| | 125 | | 820 | 762 | 17.5 | 60.7 | 30, 30, 33 |
| | 25 | Anneal-PH 200°C Gouge-PH 150°C-Weld-Harden-Temper | 486 | —— | 2 | 6 | 66, 22, 123 |
| | 50 | | 704 | 506 | 17.5 | 65 | 25, 81, 52 |
| | 75 | | 622 | 440 | 5 | —— | 17.5, 13, 76 |
| | 100 | | 676 | 468 | 9 | 35.6 | 37, 13, 88 |
| | 125 | | 710 | 636 | 16.2 | 47.1 | 108, 102, —— |

*Table 16 Hardness Traverses of 1 ¼% Cr-Mo Steel, Single Pass Gouges*

| Section Thickness mm | PH 250°C Gouge As Cast | | | Anneal-PH 250°C Gouge | | | Anneal-PH 250°C Gouge-PH 200°C-Weld-Temper | | |
|---|---|---|---|---|---|---|---|---|---|
| | Max. HAZ Hardness HV | Depth HAZ mm | Hardness of Parent HV | Max. HAZ Hardness HV | Depth HAZ mm | Hardness of Parent HV | Max. HAZ Hardness HV | Hardness of Parent HV | Hardness of Weld Metal HV |
| 25 1 | 285 | 1.5 | 238-254 | 373 | 2.0 | 166-192 | 233 | 197-225 | 234 |
| 2 | | Gouged Out | | 327 | 1.0 | 162-179 | 241 | 196-206 | 238 |
| 3 | | Gouged Out | | 274 | 0.6 | 162-166 | 237 | 195-216 | 230 |
| 50 1 | | | | 274 | 1.0 | 172-178 | 235 | 216-226 | 232 |
| 2 | | | | 409 | 1.0 | 159-202 | 287 | —— | —— |
| 3 | | | | 304 | 1.0 | 159-216 | 272 | 190 | 267 |
| 75 1 | | | | 290 | 1.0 | 172-182 | 256 | 169-220 | 234 |
| 2 | | | | 413 | 1.0 | 164-176 | 268 | 197-216 | 266 |
| 3 | | | | 363 | 1.0 | 165-186 | 280 | 199-211 | 260 |
| 100 1 | | | | 339 | 1.0 | 162-199 | 235 | 216-228 | —— |
| 2 | | | | 348 | 1.0 | 193-205 | 287 | —— | —— |
| 3 | | | | 370 | 0.8 | 167-213 | 262 | 192-195 | —— |
| 125 1 | 333 | 2.0 | 245-264 | 360 | 1.3 | 162-210 | 240 | 211-227 | 230 |
| 2 | 311 | 2.0 | 232-283 | 363 | 1.3 | 174-193 | 245 | 196-225 | 230 |
| 3 | 338 | 2.0 | 236-265 | 441 | 1.3 | 162-207 | 230 | 189-225 | 229 |

*Table 17 Hardness Traverse on 1 ¼% Cr-Mo Steel, Multipass Gouges*

| Section Thickness mm | Anneal-PH 250°C Gouge-PH 200°C-Weld-Temper | | | Anneal-PH 250°C Gouge-PH 200°C-Weld-Harden-Temper | | |
|---|---|---|---|---|---|---|
| | Max. HAZ Hardness HV | Hardness Weld Metal HV | Hardness of Parent Material HV | Max. HAZ Hardness HV | Hardness Weld Metal HV | Hardness of Parent Material HV |
| 25 1 | 237 | 167 | 154-157 | 174 | — — | 159 |
| 2 | 233 | 150 | — — | 203 | 168 | 159-178 |
| 3 | 233 | 150 | 154-157 | — — | — — | — — |
| 50 1 | 229 | 163 | 165-161 | 170 | 164 | 164-172 |
| 2 | 237 | 163 | 155-161 | 189 | 166 | 167-172 |
| 3 | 240 | 210 | 150-157 | 176 | 165 | 172 |
| 75 1 | 233 | 228 | 154-157 | 181 | 153 | 148-163 |
| 2 | 241 | 222 | 150-157 | 219 | 158 | 148-158 |
| 3 | 240 | 229 | 154-161 | 194 | 158 | 146-160 |
| 100 1 | 235 | 220 | 148-161 | 196 | 159 | 158-163 |
| 2 | 239 | 225 | 157-162 | 207 | 157 | 156-163 |
| 3 | 240 | 221 | 155-158 | 205 | 159 | 158-164 |
| 125 1 | 240 | 227 | 154-158 | 198 | 167 | 161-175 |
| 2 | 252 | 231 | 157-160 | 210 | 165 | 160-175 |
| 3 | 255 | 231 | 156-161 | 211 | 167 | 161-175 |

*Table 18 Hardness Traverses on 5% Cr-Mo Steel, Single Pass Gouges*

| Section Thickness mm | Anneal-PH 300°C Gouge | | | Anneal-PH 300°C Gouge-PH 250°C-Weld-Temper | | | Anneal-PH 300°C Gouge-PH 250°C-Weld-Harden-Temper | | |
|---|---|---|---|---|---|---|---|---|---|
| | Max. HAZ Hardness HV | Depth HAZ mm | Hardness of Parent Material HV | Max. HAZ Hardness HV | Hardness of Parent Material HV | Hardness of Weld Metal HV | Max. HAZ Hardness HV | Hardness of Parent Material HV | Hardness of Weld Metal HV |
| 25 1 | 437 | 5.9 | 159-167 | 217 | 214-219 | 218 | 229 | 216-219 | 230 |
| 2 | | Gouged Out | | 215 | 216-220 | 222 | 235 | 215-221 | 239 |
| 3 | | Gouged Out | | 217 | 223 | 221 | 223 | 212-217 | 230 |
| 50 1 | 268 | 0.76 | 164-183 | 217 | 222-228 | 235 | —— | —— | —— |
| 2 | 464 | 0.30 | 163-188 | 237 | 218-225 | 239 | —— | —— | —— |
| 3 | 433 | 1.0 | —— | 230 | 215-220 | 231 | —— | —— | —— |
| 75 1 | 354 | 1.0 | 178-190 | 228 | 224-229 | 223 | 230 | 211-216 | 233 |
| 2 | 348 | 1.0 | 174-202 | 233 | 225-237 | 230 | 235 | 207-216 | 242 |
| 3 | 450 | 1.0 | 171-185 | 230 | 230-227 | 230 | 237 | 212-220 | 235 |
| 100 1 | 376 | 1.3 | 193-209 | 223 | 214-220 | 224 | 222 | 212-219 | 221 |
| 2 | 299 | 1.0 | 167-195 | 227 | 218-229 | 234 | 233 | 215-224 | 231 |
| 3 | 405 | 1.3 | 168-185 | 223 | 223 | 232 | 229 | 212-227 | 226 |
| 125 1 | 394 | 1.0 | 180-201 | 203 | 197-206 | 198 | 234 | 222 | 234 |
| 2 | 387 | 1.3 | 179-190 | 219 | 212-216 | 207 | 239 | 215-228 | 230 |
| 3 | 441 | 2.5 | 166-198 | 210 | 213-230 | 203 | 239 | 221-229 | 228 |

*Table 19 Hardness Traverses on 5% Cr-Mo Steel, Multipass Gouges*

| Section Thickness mm | Anneal-PH 250°C Gouge - PH - Weld-Temper | | | Anneal-PH Gouge 250°C-Weld-Harden-Temper | | |
|---|---|---|---|---|---|---|
| | Max. Hardness HAZ HV | Hardness Weld Metal HV | Hardness of Parent Material HV | Max. Hardness HAZ HV | Hardness Weld Metal HV | Hardness of Parent Material HV |
| 25 1 | 190 | 230 | 184 | 190 | 188 | 184 |
| 2 | 234 | 230 | 158-182 | —— | —— | —— |
| 3 | —— | —— | —— | —— | —— | —— |
| 50 1 | 231 | 228 | 216-222 | 231 | 186 | 216 |
| 2 | 223 | 222 | 218-224 | 223 | 187 | 224 |
| 3 | 224 | 225 | 221 | 224 | 187 | 221-224 |
| 75 1 | 219 | 156 | 220-225 | 219 | 182 | 220-225 |
| 2 | 236 | 224 | 216-220 | 236 | 182 | 220-216 |
| 3 | 227 | 223 | 216 | 227 | 180 | 218 |
| 100 1 | 244 | 228 | 160 | 232 | 295 | 215-223 |
| 2 | 265 | 230 | 158 | 242 | 184 | 219 |
| 3 | 245 | 230 | 174 | 227 | 175 | 218 |
| 125 1 | 328 | 270 | 186-201 | 228 | 185 | 226 |
| 2 | 336 | 280 | 196-202 | 246 | 188 | 234 |
| 3 | 304 | 275 | 182-192 | —— | —— | —— |

*Table 20 Hardness Traverses on 1 ½% Ni-Cr-Mo Steel, Single Pass Gouges*

| Section Thickness mm | PH 200°C As Cast-Gouge | | | Anneal-PH 200°C Gouge | | |
|---|---|---|---|---|---|---|
| | Max. HAZ Hardness HV | Depth HAZ mm | Hardness of Parent Material HV | Max. HAZ Hardness HV | Depth HAZ mm | Hardness of Parent Material HV |
| 25 1 | 276 | 10.0 | —— | 254 | 0.8 | 213-237 |
| 2 | —— | —— | —— | —— | —— | —— |
| 3 | —— | —— | —— | —— | —— | —— |
| 50 1 | 283 | 1.5 | 240-266 | 262 | 0.8 | 189-206 |
| 2 | 351 | 1.5 | 245-270 | 258 | 1.0 | 181-206 |
| 3 | 309 | 2.5 | 233-270 | 317 | 1.3 | 165-203 |
| 75 1 | 322 | 2.0 | 228-270 | 265 | 1.5 | 176-213 |
| 2 | 333 | 2.0 | 222-285 | 247 | 1.5 | 177-203 |
| 3 | 304 | 2.0 | 224-260 | 325 | 1.0 | 176-216 |
| 100 1 | 348 | 1.0 | 254-266 | 254 | 1.0 | 181-212 |
| 2 | 322 | 1.5 | 238-265 | 306 | 1.0 | 172-201 |
| 3 | 290 | 2.3 | 237-272 | 290 | 0.6 | 186-237 |
| 125 1 | 366 | 2.0 | 235-270 | 314 | 2.3 | 180-201 |
| 2 | 264 | —— | —— | 209 | 1.5 | 179-197 |
| 3 | 368 | 2.0 | 230-287 | 314 | 0.8 | 168-198 |

*Table 21 Hardness Traverses on 1 ½% Ni-Cr-Mo Steel, Single Pass Gouges, continued*

| Section Thickness mm | | Anneal-PH 200°C Gouge-PH 150°C-Weld-Temper | | | Anneal-PH 200°C Gouge-PH 150°C-Weld-Harden-Temper | | |
|---|---|---|---|---|---|---|---|
| | | Max. HAZ Hardness HV | Hardness of Parent Material HV | Weld Metal Hardness HV | Max. HAZ Hardness HV | Hardness of Parent Material HV | Weld Metal Hardness HV |
| 25 | 1 | —— | —— | —— | 262 | 271-258 | 245 |
| | 2 | —— | —— | —— | 256 | 254-262 | 248 |
| | 3 | —— | —— | —— | 255 | 252-250 | 240 |
| 50 | 1 | 238 | 254-235 | 240 | 252 | 257-268 | 245 |
| | 2 | 239 | 241-240 | 237 | 257 | 250-252 | 242 |
| | 3 | 236 | 226-237 | 235 | 246 | 247-238 | 242 |
| 75 | 1 | 232 | 243-252 | 237 | 256 | 266-254 | 244 |
| | 2 | 339 | 237-243 | 240 | 236 | 252-233 | 246 |
| | 3 | 241 | 229-237 | 235 | 256 | 255-265 | 242 |
| 100 | 1 | 237 | 235-237 | 236 | 247 | 255-242 | 243 |
| | 2 | 249 | 243-248 | 242 | 237 | 246-241 | 243 |
| | 3 | 245 | 237-241 | 237 | 248 | 241-252 | 248 |
| 125 | 1 | 247 | 244-231 | 238 | 258 | 257-263 | 245 |
| | 2 | 227 | 226 | 240 | 241 | 246-241 | 239 |
| | 3 | 233 | 242-225 | 244 | 242 | 239-246 | 246 |

*Table 22 Hardness Traverses on 1 1/2% Ni-Cr-Mo Steel, Multipass Gouges*

| Section Thickness mm | | PH 200°C As Cast-Gouge | | | Anneal-PH 200°C Gouge | | |
|---|---|---|---|---|---|---|---|
| | | Max. HAZ Hardness HV | Depth HAZ mm | Hardness of Parent Material HV | Max. HAZ Hardness HV | Depth HAZ mm | Hardness of Parent Material HV |
| 25 | 1 | 339 | 3.0 | 256-288 | 322 | 1.5 | 182-198 |
| | 2 | 306 | 2.0 | 245-270 | 294 | 1.0 | 169-201 |
| | 3 | 309 | 2.0 | 247-283 | 304 | 1.0 | 194-180 |
| 50 | 1 | 279 | 2.0 | 235-276 | 360 | 1.5 | 195-227 |
| | 2 | 317 | 2.0 | 252-294 | 266 | 1.0 | 181-206 |
| | 3 | 227 | 2.0 | 227-292 | 304 | 1.0 | 186-207 |
| 75 | 1 | 317 | 3.0 | 245-272 | 274 | 0.8 | 182-219 |
| | 2 | 309 | 2.0 | 240-270 | 294 | 0.8 | 183-207 |
| | 3 | 342 | 2.0 | 227-264 | 339 | 0.8 | 188-209 |
| 100 | 1 | 342 | 2.5 | 230-258 | 330 | 2.0 | 206-210 |
| | 2 | 354 | 1.5 | 249-262 | 470 | 1.0 | 195-235 |
| | 3 | 370 | 1.5 | 245-292 | 354 | 1.0 | 192-220 |
| 125 | 1 | 354 | 2.0 | 235-319 | 322 | 1.0 | 181-212 |
| | 2 | 351 | 2.0 | 227-268 | 294 | 1.0 | 190-206 |
| | 3 | 366 | 2.0 | 242-283 | 342 | 1.0 | 182-205 |

*Table 23 Hardness Traverses on 1 1/2 % Ni-Cr-Mo Steel, Multipass Gouges, continued*

| Section Thickness mm | | Anneal-PH 200°C Gouge-PH 150°C-Weld-Temper | | | Anneal-PH 200°C Gouge-PH 150°C-Weld-Harden-Temper | | |
|---|---|---|---|---|---|---|---|
| | | Max. HAZ Hardness HV | Hardness of Weld Metal HV | Hardness of Parent Material HV | Max. HAZ Hardness HV | Hardness of Weld Metal HV | Hardness of of Parent Material HV |
| 25 | 1 | 275 | 192 | —— | 251 | 230 | —— |
| | 2 | 280 | 264 | 163 | 264 | 242 | 263-260 |
| | 3 | —— | —— | —— | —— | —— | —— |
| 50 | 1 | 295 | 265 | 183 | 262 | 237 | 245-212 |
| | 2 | 308 | 262 | 181-187 | 265 | 240 | 233-249 |
| | 3 | 294 | 273 | 184-189 | 253 | 241 | 250-258 |
| 75 | 1 | 308 | 271 | 179-185 | 263 | 245 | 232-236 |
| | 2 | 323 | 268 | 183-188 | 280 | 242 | 240 |
| | 3 | 305 | 271 | 183-189 | 251 | 241 | 248-253 |
| 100 | 1 | 325 | 277 | 174-180 | 275 | 235 | 235-238 |
| | 2 | 331 | 275 | 177-183 | 265 | 245 | 226 |
| | 3 | 307 | 279 | 184-186 | 247 | 242 | 244-252 |
| 125 | 1 | 264 | 235 | 168-172 | 258 | 248 | 250 |
| | 2 | 261 | 242 | 160-163 | 274 | 233 | 230-248 |
| | 3 | 264 | 226 | 158-161 | 271 | 239 | 229-246 |

SFSA Special Report 21 Literature Review: Weldability of Cast Steels published by the Carbon and Low Alloy Technical Research Committee in 1982 under the guidance of Dr. John M. Svoboda [10] has a chart showing the relationship between preheat temperature and single/multi pass welding on the maximum hardness (see Figure 7) of manganese- molybdenum steel castings. Steel hardness is directly related to steel tensile strength. Special Report 21 also has Charpy impact data for cast steels used in the fabrication of dragline and dipper buckets. Figure 9 and Figure 8 show Charpy impact variations at -30°C (-22 °F) and -50 °C (-58 °F) across butt welds between 12M alloy to austenitic Mn-Ni steel and between 12M alloy to low alloy quenched and tempered plate steel. The authors concluded that “the 12M alloy showed a high level of notch toughness in HAZ when welded using correct procedures and precautions.”

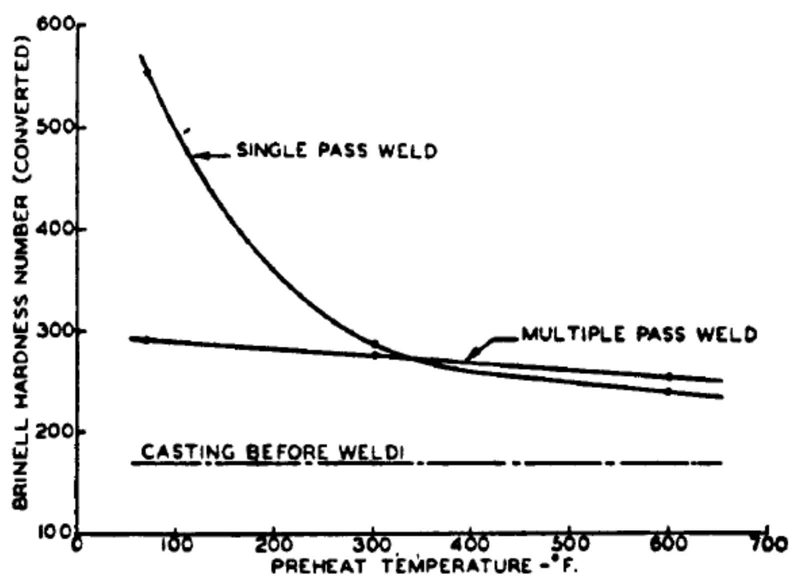



*Figure 7 Effect of preheat on the maximum hardness obtained in the heat-affected zone of manganese-molybdenum steel castings.*

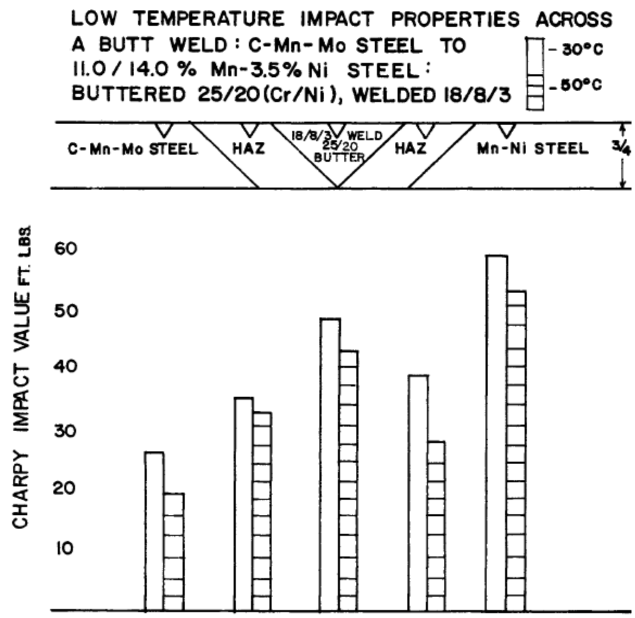



*Figure 8 Charpy impact variations at -30°C and -50°C across a butt weld between 12M alloy steel and austenitic manganese steel.*

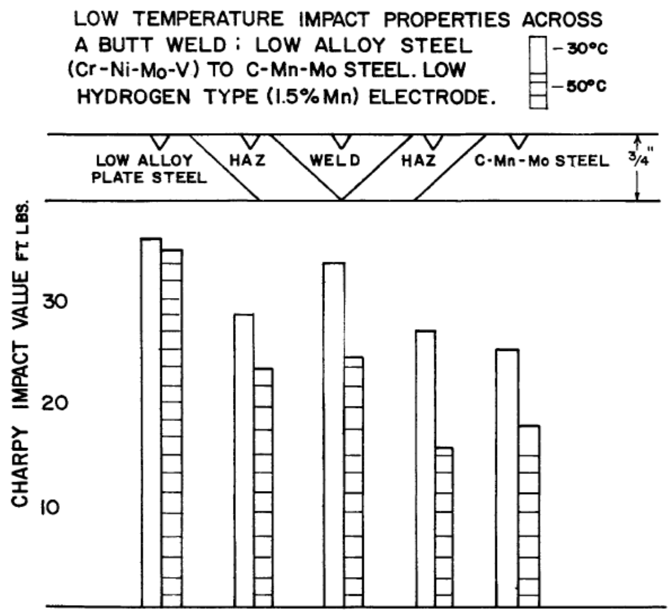
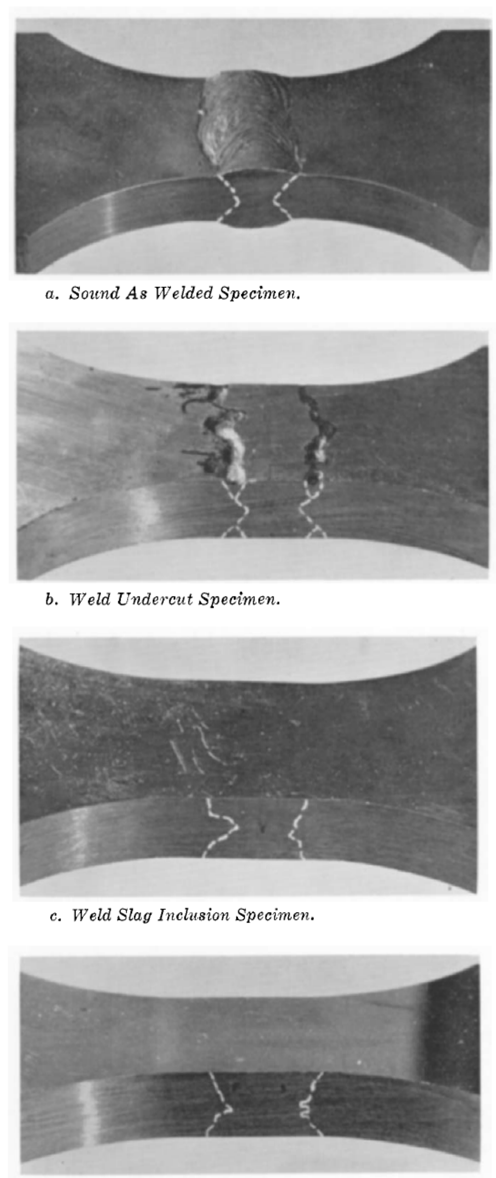



*Figure 9 Charpy impact variations at -30°C and -50°C across a butt weld between 12M alloy steel and a low alloy quenched and tempered plate steel.*

SFSA Research Foundation Report B Correlation of Destructive Testing of Steel Castings with Stress Analysis and Mechanical Properties [11] and SFSA Research Foundation Report E The Evaluation of Discontinuities in Commercial Steel Castings by Dynamic Loading to Failure in Fatigue [12] both performed destructive testing on a number of commercial castings to see how real castings with quality details compared with their simulated service failures. While there is no mention of welding on these castings, the reports reiterate that these were commercial castings and so it is safe to assume production welding did occur on these castings prior to destructive testing. In Foundation Report B, 12 castings were tested with static loading to failure. Of the 12 tested, 9 failed by applying loads from 4 to over 20 times the maximum service load. The other three castings were not able to be tested to failure because the accompanying service components failed before the castings failed or the strength of the casting exceeded the capacity of the testing facilities. The positions of the highest stress concentration were the positions of casting failure upon destructive testing. Nine of the castings tested contained quality details of various types and severity, and yet all 12 castings withstood loads simulating service conditions and did not fail until loads were in considerable excess of service requirements. Despite having quality details of considerable magnitude, castings will perform satisfactorily in highly stressed applications. For the castings tested, the location of failure was always dictated by the stress concentration of the design and not by the presence or location of quality details. The safety factors used in the design of most steel castings are so high that they make insignificant the variations in strength properties between the test bar and casting. This would also be true of small variations of properties due to production welding a casting when correct welding procedures are followed.

Foundation Report E looked at 7 commercially produced steel castings and performed both dynamic and static loading to failure to investigate the effect of discontinuities and the location of stress concentrations on fatigue failure and the reduction of the endurance limit. Again, even though welding was not mentioned, these were commercially prepared steel castings so they were likely production welded. The conclusions were that the fatigue and static failures always occurred at locations of maximum stress regardless of the presence of quality details in other sections. The static load failure always occurred in excess of the maximum designed service loads. It was influenced by the part design and not by the quality details. The safety factors for the steel castings in fatigue varied from 1.4 to 3.0. The tensile and fatigue properties determined for these cast steels were typical for the types of steel utilized. "The research proved conclusively that steel castings with discontinuities of considerable magnitude will perform satisfactorily in fatigue loading. Accordingly, the presence of quality details may not require casting rejection." In both reports, the conclusion was that quality details "of considerable magnitude" were not problematic for service. It would not be unreasonable to apply the results of this study to production welding of steel castings. If a weld is performed by a certified welder, using a qualified welding process, and meets the material and NDT requirements for the casting, it should not cause any reduction in service life of the casting and would have even less impact on the performance of the part than the quality detail that was removed by the weld.



a. Sound As Welded Specimen.

b. Weld Undercut Specimen.

c. Weld Slag Inclusion Specimen.

d. Weld Incomplete Penetration Specimen.

*Figure 10 Bending Fatigue Specimens of Cast Ni-Cr-Mo Steel.*

SFSA Research Foundation Report C The Effects of Surface Discontinuities on the Fatigue Properties of Cast Steel Sections [13] looked at the effect of severe surface quality details on the fatigue strength of low alloy cast steel. The surface quality details were more severe than permitted by ASTM E125 Reference Photographs for Magnetic Particle Indications on Commercial Steel Castings because previous research had shown that shrinkage porosity must be severe (Classes 5 and 6 ASTM E71 Reference Radiographs) before a decrease of 8 percent was observed in the strength of the cast steel sections. The goal of this research was to see the effect of various types of surface quality details on fatigue properties of cast steels. The conclusions of the study were that "the fatigue strength in bending and torsion of low alloy cast steel is lowered by the presence of severe surface quality details. However, the severe quality details lowered the endurance strength and ratio to the same or less extent as the presence of notches in the standard fatigue tests."

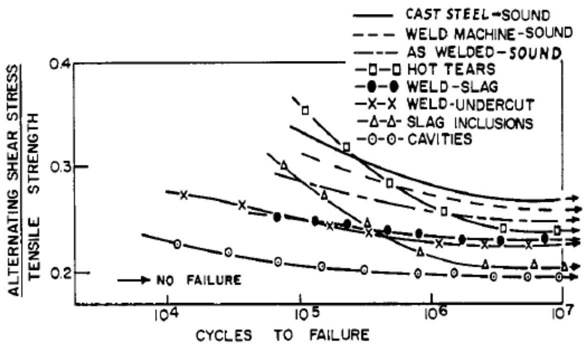



*Figure 14 Relation Between Alternating Shear Stress/Tensile Strength and Number of Cycles to Failure for Torsion Fatigue Specimens and Tempered Conditions*

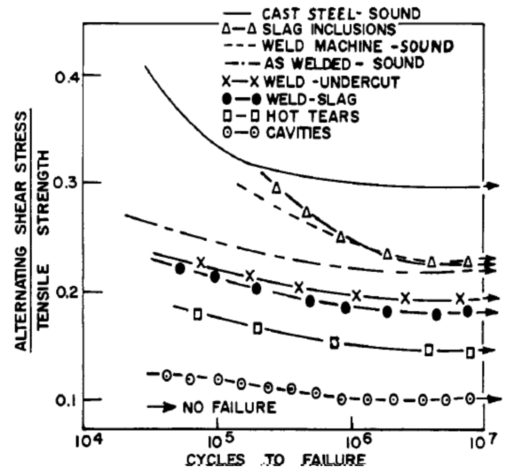



*Figure 14 Relation Between Alternating Shear Stress/Tensile Strength and Number of Cycles to Failure for Torsion Fatigue Specimens Quenched and Tempered Condition.*

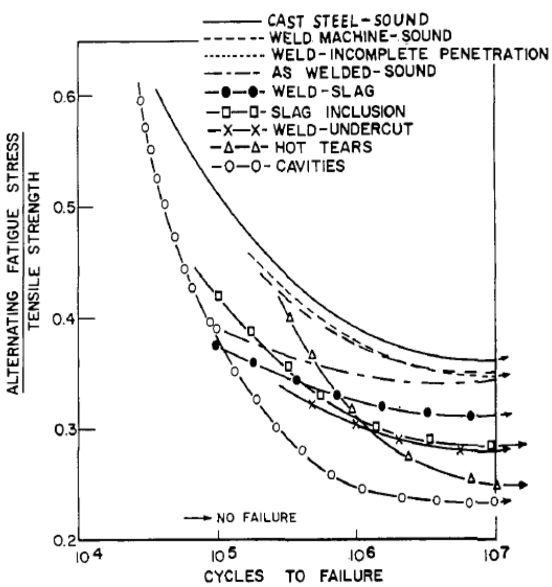



*Figure 12 Relation Between Alternating Fatigue Stress/Tensile Strength and Number of Cycles to Failure for Bending Fatigue Specimens Normalized and Tempered Condition.*

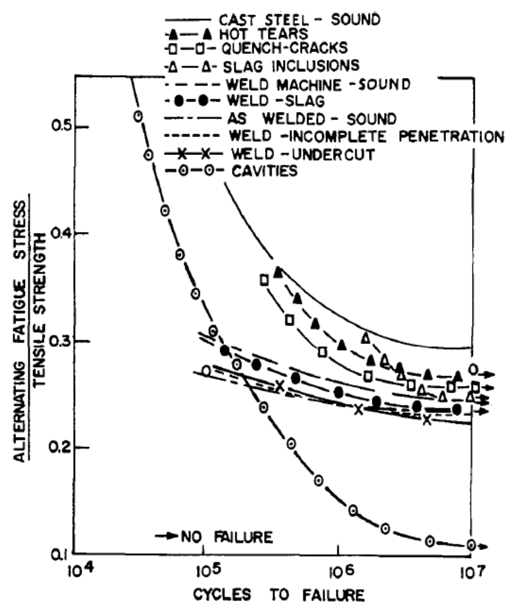



*Figure 12 Relation Between Alternating Fatigue Stress/Tensile Strength and Number of Cycles to Failure for Bending Fatigue Specimens Quenched and Tempered Conditions*

Figure 10 shows examples of the fatigue test specimens with weld quality details. Figure 12 through Figure 13 show the effect of these severe cast and weld quality details on the bending and torsion fatigue strength. Comparing “As Welded Sound” and “As Welded Machined” to “Cast Steel Sound”, welding does result in a slight decrease in cycles to failure transition temperatures and diminished fracture energies. Given that the welded and machined impact energies performed like the sound cast steel, production welding of steel castings to remove unacceptable quality details increases part performance and lowers cost by lowering the scrap rate.

SFSA Research Foundation Report H A Review of Welding Cast Steels and Its Effects on Fatigue and Toughness Properties [15] is a summary of the findings of all the SFSA Research Foundation Reports A thru G. The conclusions of this report state "Fatigue properties of welded steel castings are improved by removing weld reinforcements, the use of low hydrogen shielding, automatic compared to manual welding, full heat treatments and peening. The toughness of welds is optimized by low carbon, oxygen, nitrogen, sulfur, and phosphorous contents with a minimum alloy content for the required strength level; low heat inputs and multipass welds; low hydrogen arc shielding and basic fluxes; and flat welding positions and automatic welding processes."

SFSA Special Report 11 A Review of Welding Cast Steels and Its Effects on Fatigue and Toughness [16] deals with the effect of welding cast steels on fatigue and toughness properties. The presence of weld quality details can lower both the fatigue and toughness properties. The effect of these quality details varies with size and location relative to the areas of highest stress concentration. Generally, the most damaging weld quality details in order of decreasing severity are cracks, undercuts, slag inclusions, porosity, and the presence of weld reinforcements. These quality details should be found during non-destructive testing (NDT) of the weld, so if there is an issue it can be corrected. With regards to weld configuration the report notes that "the weld geometry or configuration is a major consideration in weldments joining wrought sections and shapes, but these considerations do not apply for the most part to welds in steel castings. When repair or fabrication welds are made on steel castings and ground flush to the smooth contour of the part, the effect of weld geometry is removed unless undercuts have occurred during welding. Severe quality details in welds in cast steel lower the endurance strength of the weld from 3 to 20 percent, depending on heat treatment condition and type of fatigue testing." Table 24 and Table 25 give a summary of fatigue results for bending and torsion fatigue specimens. Table 26 shows the approximate loss in endurance limit for bending fatigue and torsion fatigue based on weld quality detail. "The loss in fatigue properties from the sound weld occurs because of the different compositions and the geometric effect of the weld reinforcement previously discussed. The sound-machined specimen loses fatigue strength only because of the difference in weld and base casting properties and composition. These specimens were heat treated after welding so any heat effects would be removed." "Peening of the surface with an air hammer is a technique that is adaptable to the repair and fabricated welds in castings. The improvements in the fatigue behavior obtained by peening are illustrated in Figure 15 and Figure 16. At $2 \times 10^6$ cycles, the fatigue strengths are 15.68 ksi and 26.88 ksi for the as-welded and peened specimens, so hammer peening increased the fatigue strength 70%. Stress relieving after peening removes most of the beneficial effects of peening. Other work shows similar improvements in fatigue strength."

The effect of welds for production or fabrication on steel castings is like the effect of welds on the performance of any welded or weld fabricated steel product.

*Table 24 Summary of Fatigue Results for Bending Fatigue Specimens*

| Heat Treatment | Tensile Strength (psi) | Discontinuity | Endurance Limit (psi) | Endurance Ratio |
|---|---|---|---|---|
| QT | 145,000 | Cast Steel - Sound | 45,000 | 0.310 |
| QT | 122,000 | Weld-Machined - Sound | 30,600 | 0.251 |
| QT | 122,000 | Weld - Slag | 29,700 | 0.243 |
| QT | 122,000 | As Welded - Sound | 29,450 | 0.241 |
| QT | 121,200 | Weld - Incomplete Penetration | 29,100 | 0.240 |
| QT | 121,200 | Weld - Undercut | 28,300 | 0.233 |
| NT | 83,100 | Cast Steel - Sound | 30,000 | 0.361 |
| NT | 89,800 | Weld - Machined - Sound | 31,500 | 0.352 |
| NT | 88,300 | Weld - Incomplete Penetration | 31,100 | 0.350 |
| NT | 89,800 | As Welded - Sound | 30,900 | 0.345 |
| NT | 89,900 | Weld - Slag | 28,200 | 0.314 |

QT = Quenched and Tempered

NT = Normalized and Tempered.

*Table 25 Summary of Fatigue Results for Torsion Fatigue Specimens*

| Heat Treatment | Tensile Strength (psi) | Discontinuity | Endurance Limit (psi) | Endurance Ratio * |
|---|---|---|---|---|
| QT | 126,000 | Cast Steel - Sound | 27,600 | 0.298 |
| QT | 124,100 | Weld - Machined | 28,500 | 0.230 |
| QT | 124,100 | As Welded - Sound | 27,400 | 0.221 |
| QT | 121,200 | Weld - Undercut | 23,600 | 0.195 |
| QT | 124,100 | Weld - Slag Inclusions | 22,700 | 0.184 |
| NT | 83,100 | Cast Steel - Sound | 23,600 | 0.270 |
| NT | 90,200 | Weld - Machined | 23,600 | 0.261 |
| NT | 90,200 | As Welded - Sound | 22,600 | 0.250 |
| NT | 90,200 | Weld - Slag | 21,200 | 0.234 |
| NT | 88,300 | Weld - Undercut | 20,300 | 0.230 |

$^{*}\frac{\text{Endurance Limit}}{\text{Tensile Strength}}$ = Endurance Ratio

*Table 26 Approximate % Loss in Endurance Limit Due to Weld Quality details in Bending Fatigue and Torsion Fatigue at Two Tensile Strength Levels.*

For Bending Fatigue - At Two Tensile Strength Levels

| DISCONTINUITY | APPROX, % LOSS IN ENDURANCE LIMIT Q & T-122 ksi | N & T-88 ksi |
|---|---|---|
| Weld - Undercut | 31 | 22 |
| Weld - Incomplete Penetration | 22 | 6 |
| Weld - Slag Inclusions | 21 | 13 |
| Weld - Sound - Not Machined | 20 | 5 |
| Weld - Sound Machined | 19 | 2 |

For Torsion Fatigue - At Two Tensile Strength Levels

| DISCONTINUITY | APPROX. % LOSS IN ENDURANCE LIMIT Q & T-122 ksi | N & T-88 ksi |
|---|---|---|
| Weld - Undercut | 36 | 15 |
| Weld - Slag Inclusions, Severe | 30 | 13 |
| Weld - Sound - Not Machined | 20 | 8 |
| Weld - Lack of Penetration | 15 | 10 |
| Weld - Sound Machined | 15 | 3 |

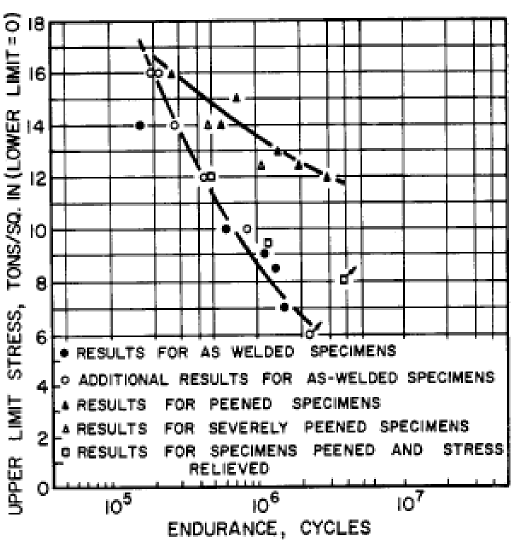



*Figure 15 Fatigue behavior of as-welded, peened and peened and stress relieved transverse gusset welds tested in pulsating tension.*

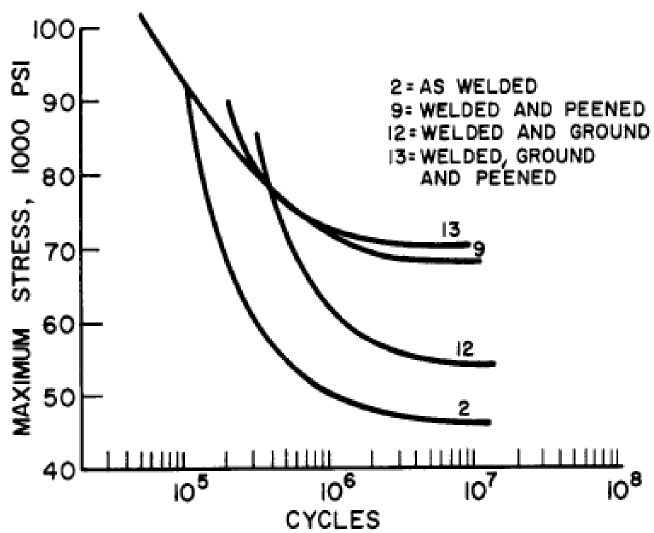



*Figure 16 Effect of grinding and peening on the S-N curves of transverse butt welds.*

In the 2020 SFSA T&O paper [Weld Qualification of Cast Steels] by Kant, Dupont, and David, [17] the weldability of two cast grades (A216 WCB and A958 SC8630) were compared to their wrought counterparts. Welds were performed between cast to cast, cast to wrought, and wrought to wrought plates, and appropriate mechanical tests were conducted to evaluate the welds. The mechanical tests were done per AWS D1.1 Structural Welding Code and included bend tests, tensile tests, Charpy v-notch tests, and hardness tests. Table 27 gives the base metal chemical composition for the two steel compositions tested. Table 28 shows the combination of cast and wrought plates that were welded for testing. Tests performed are shown in Table 29; these included tests required in AWS D1.1, ASME BPVC Section IX, and ASTM A488 for qualifying a base material as well as additional testing for informational purposes.

*Table 27 Base Metal Chemical Composition (Maximum Weight Percent Unless Range is Given)*

| Elements | A216 WCB (Cast carbon steel) | A516 Grade 70 (Wrought carbon steel) | 8630 (Cast and wrought low alloy steel) |
|---|---|---|---|
| C | 0.30 | 0.1 – 0.22 | 0.28 – 0.33 |
| Mn | 1.0 | 1.0 – 1.7 | 0.60 – 1.0 |
| P | 0.035 | 0.03 | 0.035 |
| S | 0.035 | 0.03 | 0.04 |
| Si | 0.60 | 0.6 | 0.30 – 0.60 |
| Cu | 0.3 | 0.3 | --- |
| Ni | 0.5 | 0.3 | 0.40 – 0.70 |
| Cr | 0.5 | 0.3 | 0.40 – 0.60 |
| Mo | 0,2 | 0.08 | 0.15 – 0.25 |
| V | 0.03 | 0.02 | |
| Nb | - | 0.01 | |

*Table 28 Weld Combinations for Base Metals in Scope of the Study*

| Weld Combinations | Cast to Cast | Cast to Wrought | Wrought to Wrought |
|---|---|---|---|
| Base Metal 1 | A216 WCB to A216 WCB | A216 WCB to A516 Grade 70 | A516 Grade 70 to A516 Grade 70 |
| Base Metal 2 | SC8630 to SC8630 | SC8630 to Mill 8630 | Mill 8630 to Mill 8630 |

*Table 29 Test Plan as per AWS D1.1, ASME BPVC Section IX, ASTM A488, and Additional Tests*

| ASME BPVC Section IX (for ¾” ≤ test coupon T < 1.5”)[1] | AWS D1.1 (for test coupon T ≥ 1”)[2] | Additional [Lehigh] Tests | ASTM A488 [Procedure] (3/4” to 1-1/2” thickness) |
|---|---|---|---|
| 4 transverse side bend<br>2 reduced section tensile | 4 transverse side bend<br>2 reduced section tensile | 2 longitudinal root bend[3]<br>2 longitudinal face bend[3]<br>2 transverse root bend[4]<br>2 transverse face bend[4]<br>1 weld metal tensile[5]<br>1 macroetch[6]<br>1 macrohardness[7]<br>CVN[8] | 4 transverse side bend<br>2 reduced section tensile |

*[1] Qualifies 3/16” to 2T base metal thickness*

*[2] Qualifies 3/16” and thicker*

*[3] Required in ASME BPVC Section IX and AWS D1.1 only if bending properties between base metals or base metal and weld metal are markedly different (e.g. welding Grade 115 to Grade 60)*

*[4] Required in ASME BPVC Section IX for test coupon T <3/4” and in AWS D1.1 for test coupon T ≤ 3/8”*

*[5] Required in AWS D1.1 to qualify ESW and EGW or to qualify filler metal (consumable)*

*[6] Required in AWS D1.1 for PJP and fillet welds*

*[7] For informational purposes only*

*[8] CVN is not required by the material specification A148 115/95 so CVN test will be done only for informational purposes. CVN test will be @ lower shelf temperature (to be determined from DBTT testing of cast base metal). Lower shelf T is typically used because it is the worst case scenario (provides most conservative value). Test at 2 locations (3 samples each location): weld metal and HAZ (on cast-to-mill, HAZ in both sides will be tested)*

Table 30 shows the results of the bend and tensile tests for the cast A216 WCB and wrought A516 Grade 70 materials. Some of the bend tests failed at first but then per the ASME BPVC Section IX two more bars were tested and both passed. So ultimately all the bend tests were a pass. Examination of the bend tests that failed showed cracking was inter-dendritic and in the base metal away from the weld indicating a possible hot tear in the casting that opened during the bend test. The failed bend tests were not related to the weld and the subsequent retests passed.

*Table 30 Summary of Test Results for A216 WCB and A516 Grade 70 Welds as per AWS D1.1*

| Test Type | Direction | Number of Tests | Cast to Cast (A216 WCB to A216 WCB) | Cast to Wrought (A216 WCB to A516 Grade 70) | Wrought to Wrought (A516 Grade 70 to A516 Grade 70) |
|---|---|---|---|---|---|
| Bend Test | Transverse Root | 2 | Acceptable | Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable) | Acceptable |
| | Transverse Face | 2 | Acceptable | Acceptable | Acceptable |
| | Longitudinal Face | 2 | Acceptable | Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable) | Acceptable |
| | Longitudinal Root | 2 | Acceptable | Acceptable | Acceptable |
| | Transverse Side | 4 | Acceptable | Acceptable | Acceptable |
| Tensile Test | Transverse | 2 | Avg. UTS: 73.8 ksi<br>Failure Location: Base Metal | Avg. UTS: 75 ksi<br>Failure Location: Base Metal | Avg. UTS: 79.3 ksi<br>Failure Location: Base Metal |
| | All Weld | 1 | YS: 90.5 ksi<br>UTS: 97.6 ksi<br>%Elongation: 24 | YS: 87 ksi<br>UTS: 94.8 ksi<br>%Elongation: 24 | YS: 75.5 ksi<br>UTS: 86.3 ksi<br>%Elongation: 27 |
| | Base Metal | 2 | YS: 38.4 ksi<br>UTS: 72.8 ksi<br>%Elongation: 29 | none | YS: 47.5 ksi<br>UTS: 78.1 ksi<br>%Elongation: 34 |

Table 31 is a summary of the test results for the 8630 steel grade. A few of the tests failed initially but when retested all the retests passed. So, all the weld conditions passed per the ASME BPVC Section IX for both the A216 WCB/A516 Grade 70 and the 8630 steel.

*Table 31 Summary of the Test Results for the Cast and Wrought 8630 Welds as per AWS D1.1*

| Test Type | Direction | Number of Tests | Cast to Cast 8630 | Cast to Wrought 8630 | Wrought to Wrought 8630 |
|---|---|---|---|---|---|
| Bend Test | Transverse Root | 2 | Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable) | Acceptable | Acceptable |
| | Transverse Face | 2 | Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable) | Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable) | Acceptable |
| | Longitudinal Face | 2 | Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable) | Acceptable | Acceptable |
| | Longitudinal Root | 2 | Acceptable (note: 2-retests) (Initial 2 of 2 unacceptable) | Acceptable (note: 2-retests) (Initial 2 of 2 unacceptable) | Acceptable |
| | Transverse Side | 4 | Acceptable | Acceptable | Acceptable |
| Tensile Test | Transverse | 2 | Avg. UTS: 129.3 ksi<br>Failure Location: HAZ | Retest: Avg. UTS: 98 ksi<br>Failure Location: Base Metal<br>Previous Test: Avg. UTS: 86.1 ksi<br>Failure Location: Base Metal | Avg. UTS: 74.3 ksi<br>Failure Location: Base Metal |
| | All Weld | 1 | UTS: 135.8 ksi<br>YS: 117 ksi<br>%Elongation: 15 | UTS: 146.5 ksi<br>YS: 126.6 ksi<br>%Elongation: 17 | UTS: 134.2 ksi<br>YS: 90.1 ksi<br>%Elongation: 12 |
| | Base Metal | 2 | UTS: 139.55 ksi<br>YS: 119.8 ksi<br>%Elongation: 12 | none | TBD |

Figure 17 shows the results of the Charpy impact testing for the base metals for A216 WCB and A516 Grade 70. In accordance with AWS D1.1, CVN testing was done in the weld, at the fusion line + 1mm, and at the fusion line + 5mm. Figure 18 shows the results of the impact testing in the weld and at 1mm and 5mm from the fusion line. The authors concluded that "The impact toughness in all welds and locations were similar/better as compared to the cast base metal. The similar impact toughness in all locations showed that welding cast steels is not detrimental to the impact toughness at/near the weld." Figure 19 is the microhardness profile across the weld for the cast-to-cast plate weld. Figure 20 is the microhardness profile across the weld for the cast-to-wrought welds. It is interesting to see how symmetrical this trace is around the weld center indicating that the cast plate responded in the same way as the wrought plate to the weld.

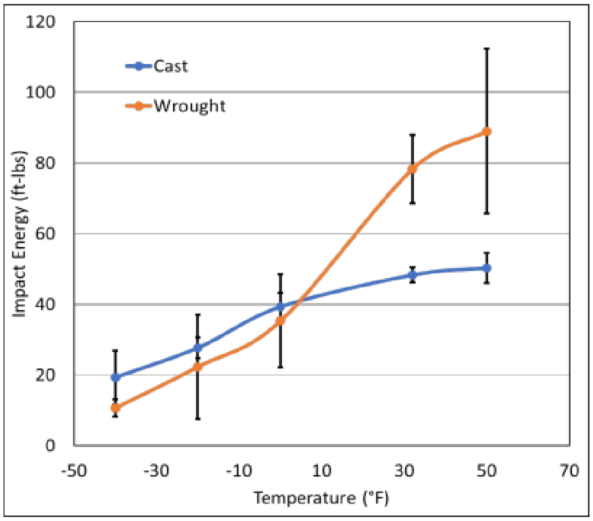



*Figure 17 Base metal impact toughness for A216 WCB and A516 Grade 70 as a function of test temperature*

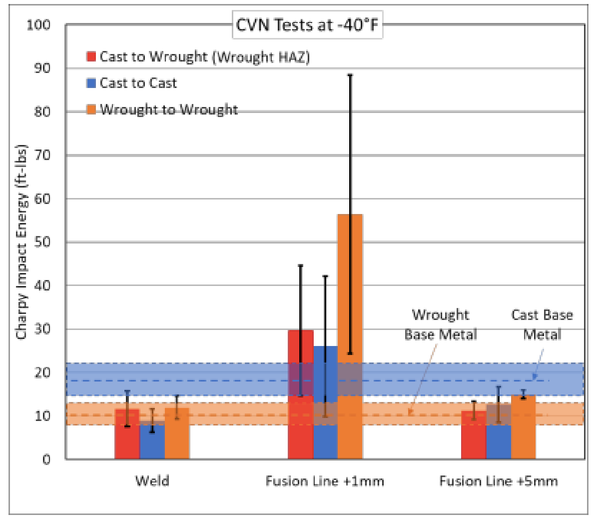



*Figure 18 Weld impact toughness for the A216 WCB (cast) and A516 Grade 70 (wrought) as per AWS D1.1 at -40°F test temperature*

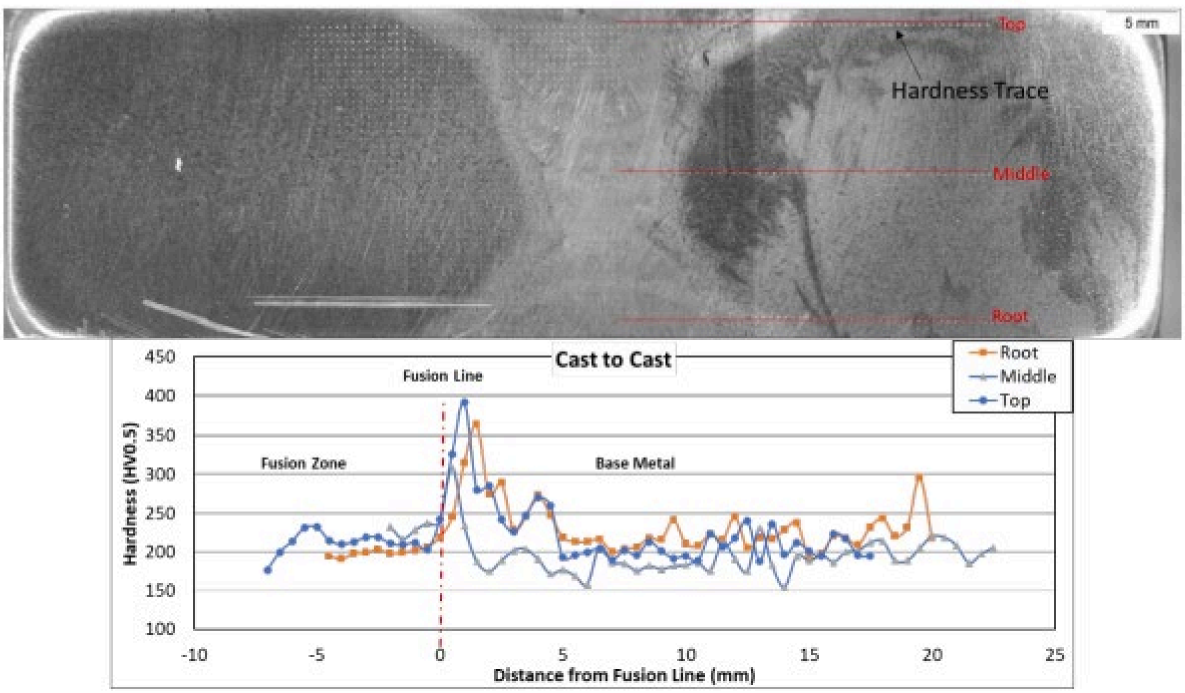



*Figure 19 (1) Stereo microscope image shows the etched weld cross-section of the A216 WCB to WCB weld. Lines on the image highlight the location of the microhardness trace. (b) Shows the microhardness trace as a function of distance from the fusion line.*

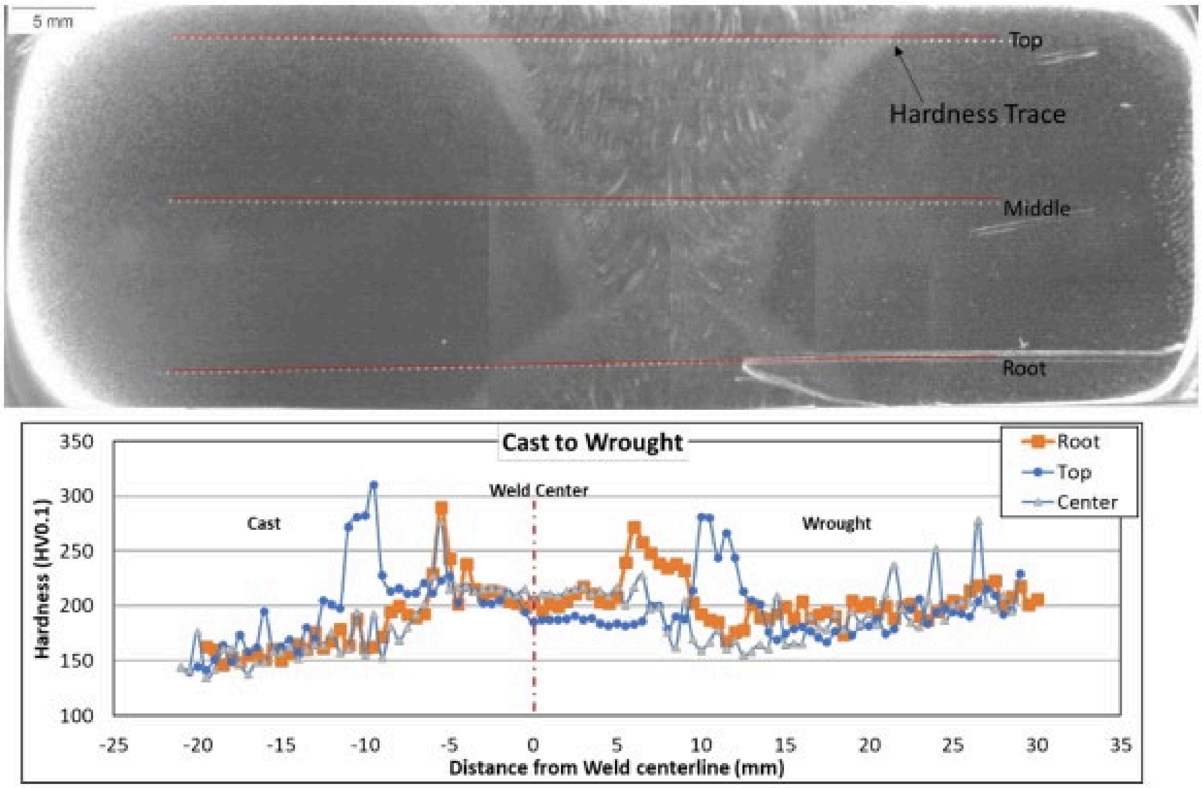



*Figure 20 (a) Stereo microscope image shows the etched weld cross-section of the A16 WCB to A516 Grade 70 weld. Lines on the image highlight the location of the microhardness trace. (b) Shows the microhardness trace as a function of distance from the fusion line.*

Figure 21 shows the impact test results for the base metal for the 8630 cast and wrought plates. The wrought plate was Charpy impact tested both transverse and longitudinal to the rolling direction. Figure 22 shows the impact test results at 32°F (0°C) and Figure 23 shows the impact test results at 0°F (-18°C) in the weld region for the 8630 steels. "The impact toughness in the cast to wrought and cast to cast 8630 welds was similar/better than the respective base metals at 0°F." At 32°F "the toughness in all the three regions for all weld combinations was similar/better than the respective base metals. No degradation in weld toughness as compared to the base metal suggests that welding of the cast/wrought 8630 plates did not have a detrimental effect on the impact toughness in/around the weld." Figure 24 shows the microhardness traces across the weld for the cast-to-cast weld and the hardness profile.

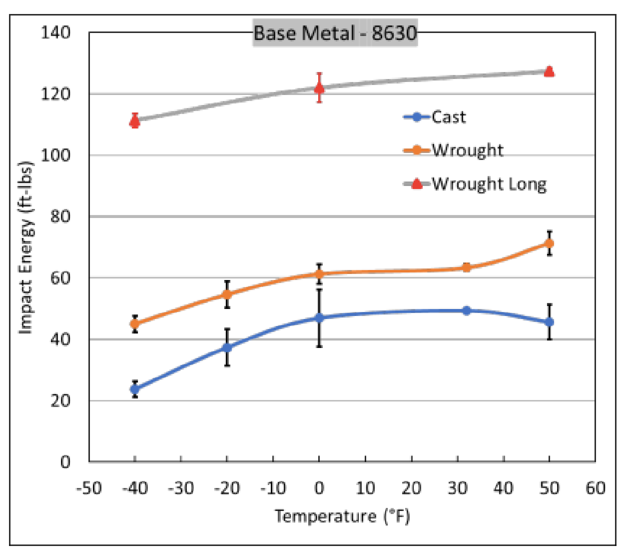



*Figure 21 Base metal impact toughness for cast and wrought 8630 as a function of test temperature. The wrought base metal was tested in transverse and longitudinal orientation with respect to the weld.*

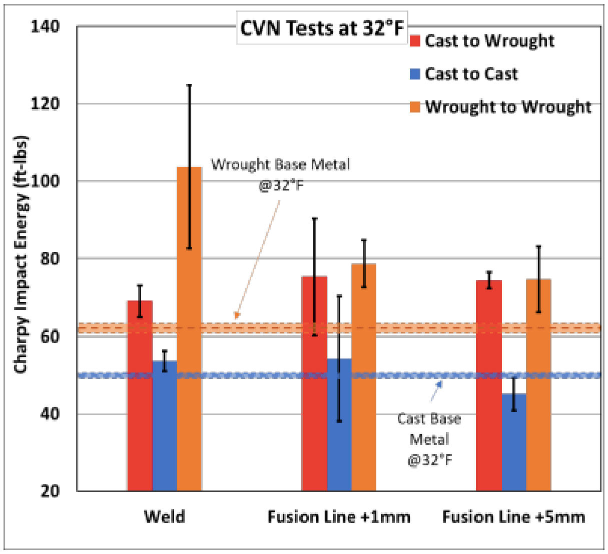



*Figure 22 Weld impact toughness for cast and wrought 8630 as per AWS D1.1 at 32°F test temperature. The cast and wrought base metal toughness at 32°F are plotted as horizontal bands.*

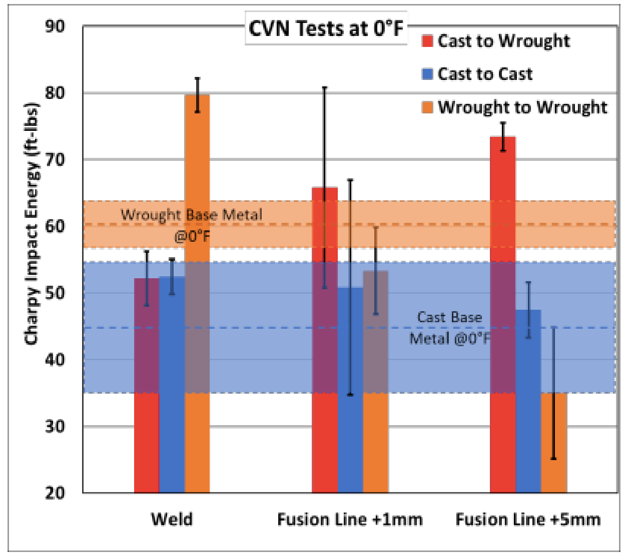



*Figure 23 Weld impact toughness for cast and wrought 8630 as per AWS D1.1 at 0°F test temperature. The cast and wrought base metal toughness at 0°F are plotted as horizontal bands.*

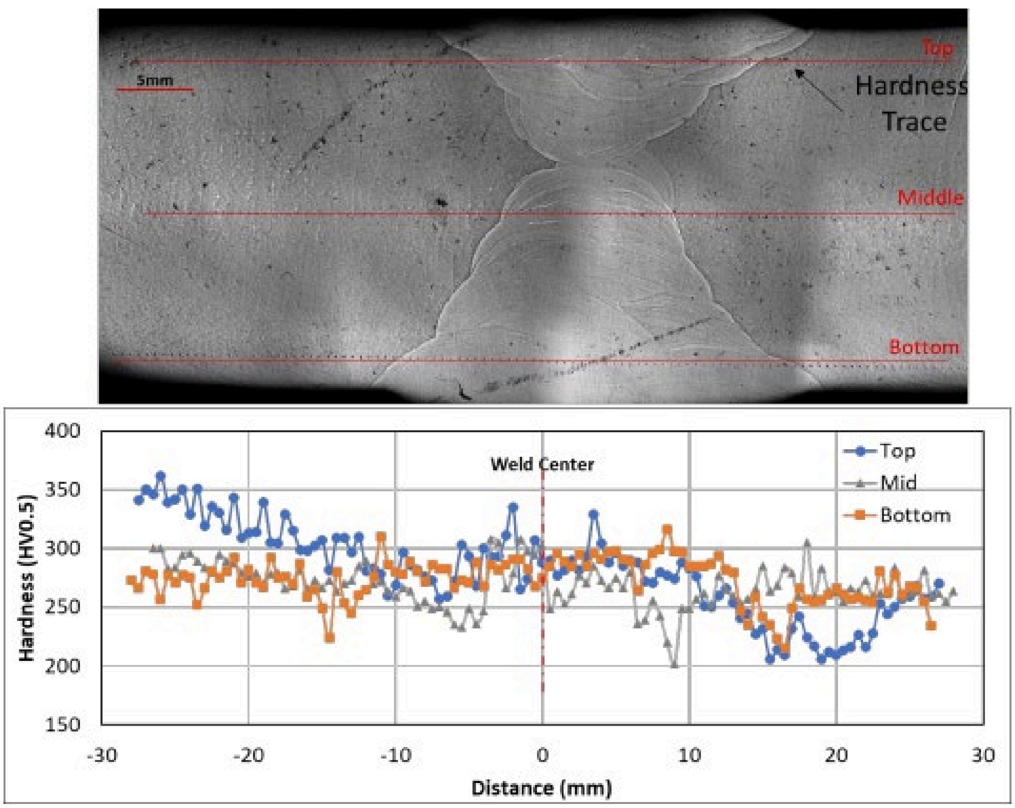
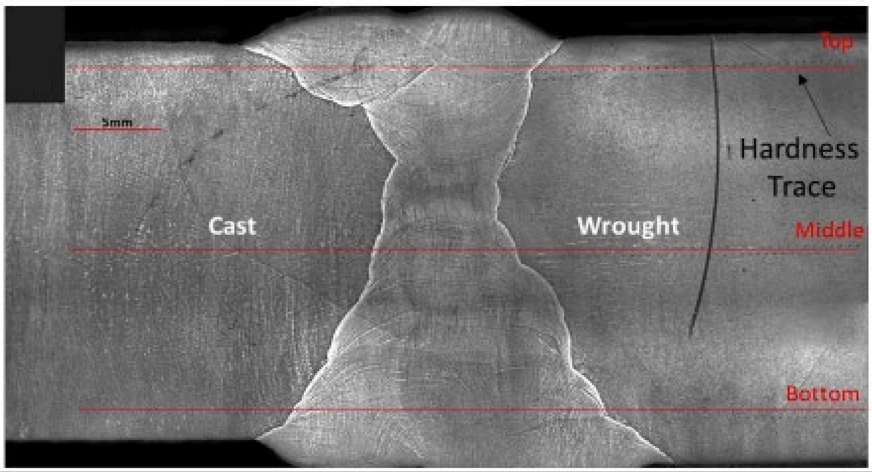



*Figure 24 (a) Stereo microscope image shows the etched weld cross-section of the cast to cast 8630 weld. Lines on the image highlight the location of the microhardness trace. (b) Shows the microhardness trace as a function of distance from the fusion line.*

The authors noted that, "The hardness across the weld was relatively uniform between the FZ, HAZ, and base metal. Unlike WCB welds, no hardening was observed in the HAZ. The uniform hardness across the weld correlated well with the uniform toughness between the FZ, FZ +1mm, FZ +5mm regions of the cast-to-cast weld." Figure 25 is the microhardness trace and hardness values for the cast-to-wrought welded plate. The wrought plate had a lower hardness than the cast plate, and the fusion zone had a higher hardness than either base material. "This could be due to the variation in the chemical composition of the fusion zone as compared with the base metals."



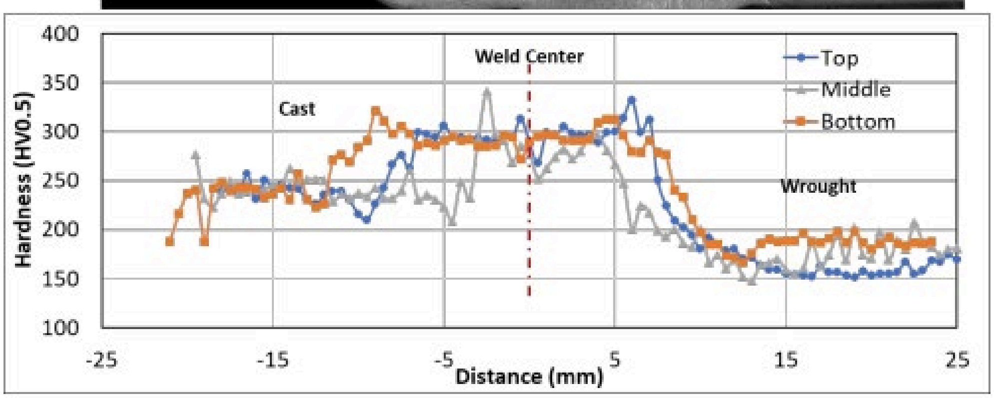




*Figure 25 (a) Stereo microscope image shows the etched weld cross-section of the cast to wrought 8630 weld. Lines on the image highlight the location of the microhardness trace. (b) Shows the microhardness trace as a function of distance from the fusion line.*

The conclusions of this paper were that:

1. "Weld mechanical tests as per AWS D1.1 performed satisfactorily for all the weld combinations between the cast and wrought grades of A216 WCB and SC8630 welds."
2. "No degradation in impact toughness was observed in the weld region compared to the base metals for both WCB and SC8630 steels."
3. "Tensile testing revealed that failure under tensile load occurred away from the weld in the base metal for A216 WCB to A216 WCB and A516 Grade 70 to A516 Grade 70 welds. This suggests no localized region for strain localization/weak areas due to welding."

In the 2021 SFSA T&O paper Experimental Evaluation of Welded Interfaces Between Steel Castings and Round HSS [18], cast steel components were welded to round hollow structural sections(HSS) under various welding conditions (different root gaps, groove angles, joint geometry, backing bar treatment, etc.) and then full PQR qualification tests were performed including radiography (RT), ultrasonic (UT), tension and side bend tests. Test results obtained included strength and ductility. Fatigue life testing is currently underway. The authors summarized the results obtained so far saying, "good performance of several cast to weld interface details was observed."

To summarize all these various studies regarding the properties of welded steel castings, steel castings can be welded and still meet the mechanical properties, toughness and fatigue life required. To ensure that welds on steel castings meet the part requirements, it is important to use a casting supplier with integrity who follows best practice in qualifying their welders and welding procedures. The foundry's welding program should be audited regularly, including checking and auditing the quality system, traceability, and NDT qualifications for the plant. Poor in process welding will result in surface or subsurface indications that will not pass NDT. Levels of NDT sampling are used to verify compliance.

## Nondestructive Testing

Nondestructive testing (NDT), also known as nondestructive inspection (NDI) or nondestructive evaluation (NDE), are test methods that find areas of non-conformance without destroying the part. Depending on the severity, location, and customer requirements, non-conformances may be removed and production welded to correct these non-conformances or, if they are too severe, the part may need to be scrapped.

The five NDT methods used on steel castings are Visual Inspection, Liquid or Dye-Penetrant (LP or PT), Magnetic Particle (MPI or MT), Radiography (RT), and Ultrasonic (UT). Some of these examination techniques are for identifying surface quality details, some for near surface quality details, and some for deep subsurface quality details. Table 32 gives a summary of the advantages and disadvantages of each method along with relevant specifications.

### Visual Inspection

Visual inspection is the easiest NDT and should be done on every part both before and after production welding. It is required for steel castings ordered to ASTM requirements by the General Technical Delivery Requirements. The advantages are it is low in cost, requires virtually no tools, and can be done in process. Visual inspection is for identifying surface quality details. SFSA Research Report 120 Surface/Near Surface Indications: Characterization of Surface Anomalies from Magnetic Particle and Liquid Penetrant Indications [19] investigated the depth of surface and near-surface linear and non-linear indications as well as the measurement variance in visual inspection methods and how that applies to levels called out in ASTM A903 Standard Specification for Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection. [20] Castings will always have various degrees of surface roughness. It is important to have some objective standard agreed upon between the foundry and the customer regarding what is acceptable and what is unacceptable regarding surface roughness and quality details.

*Table 32 Comparison of nondestructive testing methods (NDT)*

| NDT/NDE: | Visual Inspection | Liquid Penetrant | Magnetic Particle | Radiography | Ultrasonic |
|---|---|---|---|---|---|
| Advantages: | Low cost<br>Applicable to magnetic and nonmagnetic materials<br>Can be done while work is in process | Easy to use<br>Applicable to magnetic, and nonmagnetic materials<br>Low cost | Permits controlled sensitivity<br>Relatively low cost method | When the indications are recorded on film, gives a permanent record<br>Applicable to magnetic and nonmagnetic materials<br>Allows for subsurface inspection | Very Sensitive<br>Applicable to magnetic and non-magnetic materials<br>Permits probing of joints inaccessible to radiography |
| Limitations: | Applicable to surface discontinuities only | Only discontinuities open to the surface are detectable | Applicable to ferromagnetic materials only<br>Requires skill in interpretation of indications and recognition of irrelevant patterns<br>Difficult to use on rough surfaces | Requires skill in choosing angles of exposure, operating equipment, and interpreting indications<br>Requires safety precautions<br>Cracks difficult to detect | Requires high degree of skill in interpreting pulse-echo patterns<br>Permanent record is not readily obtained |
| Equipment Required: | Surface comparator<br>Pocket rule<br>Straight edge<br>Workmanship standards | Commercial kits, containing fluorescent or dye penetrants and developers<br>Application equipment for the developer<br>A source of ultraviolet light - if fluorescent method is used | Special commercial equipment<br>Magnetic powders – dry or wet form; may be fluorescent for viewing under ultraviolet light | Commercial x-ray or gamma units, made especially for inspecting welds, castings, and forgings<br>Film and processing facilities | Special commercial equipment, either of the pulse-echo or transmission type |
| Enables Detection of: | Surface discontinuities – cracks, porosity, slag inclusions, adhering sand, scale, etc. | Surface discontinuities not readily visible to the unaided eye | Excellent for detecting surface and subsurface discontinuities to approximately ¼" below the surface – especially cracks | Internal macroscopic flaws – cracks, porosity, blow holes, non-metallic inclusions, shrinkage, etc. | Sub-surface discontinuities, including those too small to be detected by other methods<br>Especially for detecting subsurface, planar discontinuities |
| Remarks: | | | Elongated discontinuities parallel to the magnetic field may not show; for this reason the field should be applied from two directions at or near right angles to each other | Radiographic inspection is required by many codes and specifications<br>Useful in process qualification<br>Because of cost, its use should be limited to those areas where other methods will not provide the assurance required | |
| Important Specs/Documents: | ASTM A802 Standard Practice for Steel Castings, Surface Acceptance Standards, Visual Examination<br>SCRATA Comparator Plates - for establishing mutually agreeable acceptance criteria for a specific part<br>ISO 11971 Steel and Iron Castings – Visual Examination of Surface Quality<br>MSS SP-55 Quality Standard for Steel Castings for Valves, Flanges, and Fittings, and Other Piping Components (Visual Method for Evaluation of Surface Irregularities) | ASTM E165 Standard Practice for Liquid Penetrant Testing for General Industry<br>ASTM E433 Standard Reference Photographs for Liquid Penetrant Examination<br>ASTM A903 Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection<br>ISO 3452-1 Non-Destructive Testing – Penetrant Testing – General Principles<br>ISO 4987 Steel Castings – Liquid Penetrant Inspection<br>MSS SP-93 Quality Standard for Steel Castings and Forgings for Valves, Flanges, Fittings, and Other Piping Components – Liquid Penetrant Examination Method | ASTM E125 Standard Reference Photographs for Magnetic Particle Indications on Ferrous Castings<br>ASTM E709 Standard Guide for Magnetic Particle Examination<br>ASTM A903 Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection<br>ASTM E1444 Standard Practice for Magnetic Particle Testing for Aerospace<br>ASTM E3024 Standard Practice for Magnetic Particle Testing for General Industry<br>ISO 4986 Steel Castings – Magnetic Particle Inspection<br>MSS SP-53 Quality Standard for Steel Castings and Forgings for Valves, Flanges, Fittings, and Other Piping Components – Magnetic Particle Examination Method | ASTM E94 Standard Guide for Radiographic Examination Using Industrial Radiographic Film<br>ASTM E186 Standard Reference Radiographs for Heavy-Walled (2 to 4-1/2 in. (50.8-114mm)) Steel Castings<br>ASTM E192 Standard Reference Radiographs of Investment Steel Castings for Aerospace Applications<br>ASTM E280 Standard Reference Radiographs for Heavy-walled (4-1/2 to 12 in. (114-305mm)) Steel Castings<br>ASTM E446 Standard Reference Radiographs for Steel Castings up to 2 in. (50.8mm) in Thickness<br>ASTM E1742 Standard Practice for Radiographic Examination<br>ASTM E2007 Standard Guide for Computed Radiography<br>ASTM E2033 Standard Practice for Radiographic Examination Using Computed Radiography (Photostimulable Luminescence Method)<br>ASTM E2660 Standard Digital Reference Images for Steel Castings for Aerospace Applications<br>ASTM E2868 Standard Digital Reference Images for Steel Castings up to 2 in. (50.8 mm) in Thickness<br>ASTM E3030 Standard Digital Reference Images for Heavy-Walled (2 to 4-1/2 in. (50.8-114mm)) Steel Castings<br>ASTM -In Progress: Standard Digital Reference Images for Heavy-walled (4.5 to 12 in.) Steel Castings<br>ISO 4993 Steel and Iron Castings – Radiographic Testing<br>ISO 5579 Non-Destructive Testing – Radiographic Testing of Metallic Materials Using Film and X- or Gamma Rays – Basic Rules<br>MSS SP-54 Quality Standard for Steel Castings for Valves, Flanges, Fittings, and Other Piping Components – Radiographic Examination Method | ASTM A609 Standard Practice for Castings, Carbon, Low-alloy, and Martensitic Stainless Steel, Ultrasonic Examination Thereof<br>ISO 4992 Steel Castings – Ultrasonic Testing - Part 1: Steel Castings for General Purpose<br>MSS SP-94 Quality Standard for Ferritic and Martensitic Steel Castings and Forgings for Valves, Flanges, Fittings, and Other Piping Components – Ultrasonic Examination Method |

### Liquid or Dye Penetrant

In liquid or dye penetrant inspection (LP or PT), a dye is applied to the surface of a clean casting where it can penetrate cracks and other surface quality details. A developer is then applied which draws the dye out of the cracks, making them visible to the inspector. LP does not work well on as-cast or machine blasted surfaces because of the high likelihood of false indications. It does work well on machined, ground, or very smooth as-cast surfaces. LP works well for checking for cracking especially in austenitic stainless steel, which is not magnetic so MPI is not an option.

### Magnetic Particle Inspection

With magnetic particle inspection (MPI or MT), a magnetic field is either induced in the part or the part is magnetized through direct magnetization. The magnetized part is coated with fine iron particles either using the wet method, where the particles are suspended in an oil-based fluid, or the dry method. If there is a surface or near surface quality detail it will create localized changes in flux density in the casting which will attract the magnetic particles making the quality detail visible to the inspector. Unlike visual inspection or liquid penetrant, magnetic particle inspection can also find quality details near the surface but not open to the surface of the casting. SFSA Special Report 34 Best Practices for Magnetic Particle Inspection on Cast Steel is a valuable resource for more information about mag particle inspection [21] as well as the 2018 T&O Paper on the same subject by David Eisenmann [22].

### Radiography

Radiographic testing (RT), or X-ray examination, can detect internal quality details such as cracks, porosity, blow holes, nonmetallic inclusions, and shrinkage. RT is performed by x-raying a part in front of a special film. The more material the x-ray needs to penetrate, the fewer x-rays will hit the film on the other side. So, if an indication such as a blow hole creates a large empty space inside the casting, more x-rays will make it through the casting to hit the film recording a darker spot. Because of how it works, quality details such as cracks which don't leave much of a void inside the casting won't show up darkly on the film and can be challenging to detect using RT. To perform RT, a commercial x-ray or gamma unit is required along with special film, a processing facility, and a qualified operator. None of this is cheap so, while x-ray is required in many specifications, it should be reserved for inspection only in those areas where other inspection methods will not work.

### Ultrasonic Testing

Ultrasonic Testing (UT) works in a similar manner as radar. A sound wave is sent, and the detector "hears" the wave or an echo. It can be performed in two different ways: (1) an ultrasonic pulse is sent through the material and observed when the pulse returns to the transmitter/receiver (pulse/echo technique) or (2) by sending a continuous transmission through the part with a receiver on the other side (through-transmission technique). UT is used to look for internal quality details in steel castings. Because of how ultrasonic testing works it does a better job at finding internal cracks (as long as they are not parallel to the testing direction) than radiography. Special commercial equipment is needed along with a couplant gel for ultrasonic testing. Ultrasonic Testing of Steel Castings by J.D. Lavender published by SFSA in 1976 gives an overview of ultrasonic testing. [23] The results of ultrasonic testing can be challenging to interpret. More recently phased array ultrasonic testing (PAUT) has been used and allows the beam to sweep over a range of angles instead of the fixed angle in conventional UT. Phased array is the same technology used in medical ultrasounds. It can create a 2D image similar to radiography that can be saved in the permanent record of the casting and gives a more detailed picture of what is going on inside a casting than traditional UT. [24]

## 2. Welder and Process Qualification

Welding on castings is a normal part of the casting production and fabrication process. To ensure the quality of these welds the welders as well as the welding process must be qualified.

### Specifications Employed

The ASTM Specification A488 or the ASME Boiler and Pressure Code (ASME BPVC) Section IX provide a proven basis for a qualified welding procedure. These specifications are generally recognized and contain the essential elements for welder qualification. Even in cases where casting specifications do not require such qualification, it is advantageous to follow such procedures. Welding is a necessary part of the steel casting business. It is used for:

- adding features to a casting,
- filling in cavities in castings created when unacceptable features are removed,
- cast-weld fabrication to simplify the casting procedure,
- or to meet stringent soundness levels by welding the casting rather than using extensive padding and chills.

Since welding is required for steel castings to meet a variety of specifications, the welding process should be controlled as the casting process is controlled.

### Welding Procedure

A welding procedure comprises three separate parts – a written welding procedure, a qualification of that procedure, and a performance test or qualification of the welder or operator indicating his ability to use that procedure [25]. The written welding procedure consists of instructions to the welder. The weld quality depends on setting and controlling the variables which are in the written instructions. For this reason, the written procedure must be tested under actual shop conditions to determine that it can produce sound welds that meet the material property requirements with the given preheat, postheat, current, and voltage ranges. Test results showing that this has been accomplished are recorded in the qualification document. After the written procedure has been tested and approved, a determination is made that each welder can follow that procedure. For this reason, the code requires that every welder be qualified by his current employer even though he may have been qualified to weld the same material at another employer. Constant auditing to determine that procedures are being followed is an essential part of the process [25]. Welder qualifications can be performed on rolled steel plate, but actual qualification of a procedure shall be on cast steel plate.

The written welding procedure must provide limits on all the significant variables involved in welding a material. As a basis for developing a procedure, ASTM A488 or Section IX of the ASME Boiler and Pressure Vessel Code is suitable for any casting production or fabrication welding and is required by ASTM and ASME specifications. These specifications provide a form which covers all the needed variables. While it is not necessary to use this form, it will eliminate the possibility of overlooking some important detail. A written procedure in narrative form is frequently employed because it is easier for the welders to understand [25].

## Process Qualification

Once the welding procedure has been prepared, it must be tested or qualified. This is done by simply making a weld using the procedure and performing the required tests. Again, it is suggested that ASME BPVC Section IX or ASTM A488 be used as a guide. Completion of the forms completes the qualification. The welding procedure qualification test establishes the ability of the welding procedure to deposit sound metal. While welder ability is a factor, the technique used is important. This is a test of the weld procedure not of the welder. The qualification indicates whether the preheat is high enough to prevent underbead cracking and establishes the ability of the combination of electrode, interpass temperature, and post-weld heat treatment to meet minimum tensile and impact requirements as specified in the basic specification. The bend bars required by the qualification verify the absence of a metallurgical notch due to hardness differentials between the weld, HAZ, and parent metal.

The qualification test of the procedure should set ranges for the factors specified so that difficulties are not encountered during production welding. A procedure which is qualified with the variables held on the safe side of the limits may not assure good welds if production welding is performed with the variables on the unsafe side. In the welding of hardenable grades which require preheating, the qualification of the procedure should be performed with the plates whose chemical analysis is on the high side of the range using a preheat temperature on the low side of the range. Similarly, for those grades where the HAZ tends to be very hard, the post-weld heat treatment temperature should be held near the low side of the stress relief or tempering range when heat treating the plate from which the bend bars are to be taken. If the ability of the electrode to respond to higher post-weld treatments is doubtful, a section of the weld may be given an additional heat treatment on the high side of the stress relief or tempering range and checked for hardness to assure that the weld will always meet the tensile requirements [25]. Rapid solidification and cooling of the weld will increase the hardness of the deposited weld metal. Harder weld deposits result from these conditions and result in a higher hardness after the post-weld heat treatments. A rapid solidification or effective quench of the weld metal can be obtained using external heat sinks when depositing the weld.

## Welder Qualification

Besides having a qualified welding procedure, each welder should be qualified to the procedure, demonstrating their ability to produce a sound weld. The qualifications are shown by a qualification certificate of the welder stating the procedures and materials for which they are qualified.

Procedures and requirements for welder qualification or certification are set forth in detail in ASME BPVC Section IX, ASTM A488, and MIL-STD-00248 (Ships). If the requirements of Section IX of the ASME BPVC are met, the qualification is automatically accepted by ASTM A488 and MIL-STD-00248.

Most agencies require proof of continuing proficiency of individuals to weld with a process. This requirement is met by use of a written record that a welder has satisfactorily welded with the qualified process at least once in a stated period (usually 90 days). The record is signed and dated by a welding supervisor to assure its validity.

It is noteworthy that if an individual's qualifications are not maintained, they can be renewed by the successful welding of only one of the test joints (plate or pipe) previously welded. The essential elements used on the initial qualification must be used for the requalification test joint.

### Other Considerations for Quality Welds

As added safeguards for welding procedure, voltmeters and ammeters that are checked regularly for accuracy should be located on the machine. A written control for electrodes is also required, including the handling or drying treatments (drying of electrodes is discussed in further detail in Section 4). Issuing only limited quantities of one type of electrode for each manual welding station will assist in preventing the use of incorrect electrodes and reduce the opportunity for moisture pickup. Frequent checks of weld quality by x-ray examination and magnetic particle inspection, even when the specifications do not require this, ensure that the welds are sound and free of cracks. Some code requirements specify the chemical compositions of the weld deposit. In these cases, it may well be desirable to check the deposited composition of each lot of electrodes before their use.

In addition to following the specification for each casting, it is necessary to review the service and processing requirements of the casting that is being production welded or fabricated. These requirements are usually part of the purchase order. However, special considerations such as surface hardening of the casting, low temperature service and corrosive environments including possible stress corrosion cracking conditions could well alter the welding process. These factors must be evaluated before that process is established to ensure an acceptably welded casting [25].

## 3. Welding Processes and Parameters

The primary welding methods used for production and fabrication welding of steel castings are described below. These welding processes include shielded metal-arc (SMAW), flux-cored arc (FCAW), gas metal-arc (GMAW), gas tungsten-arc (GTAW), submerged-arc (SAW), and electroslag welding (ESW).

### Shielded Metal Arc Welding, (SMAW)

Shielded metal-arc welding, called stick welding, is a manual welding process. Flux-covered consumable electrodes are used with the SMAW process. Combustion and decomposition of the flux provides a gaseous shielding for the weld puddle, electrode tip, and surrounding area. The shielding prevents air from reacting with the molten weld metal, reducing oxide and nitride formation and hydrogen absorption. Impurities in the molten weld metal, such as oxides and salts, react with the flux and form a slag. Additional shielding is provided by the slag. The SMAW process is shown schematically in Figure 26.

A variety of covered electrodes are used with the SMAW processes. These electrodes are classified by tensile strength of the deposited weld metal, allowable welding positions, and depth of penetration. A detailed list of electrode classifications and commercially available electrodes complying with these classifications are contained in Section 4 of this report.

Either alternating current, AC, or direct current, DC, can be used with the SMAW process. DC current can be either straight or reverse polarity. The choice usually depends on availability of equipment and the type of electrode used. AC and DC equipment can be combined also. Some factors affecting the choice of the power supply include [26]:

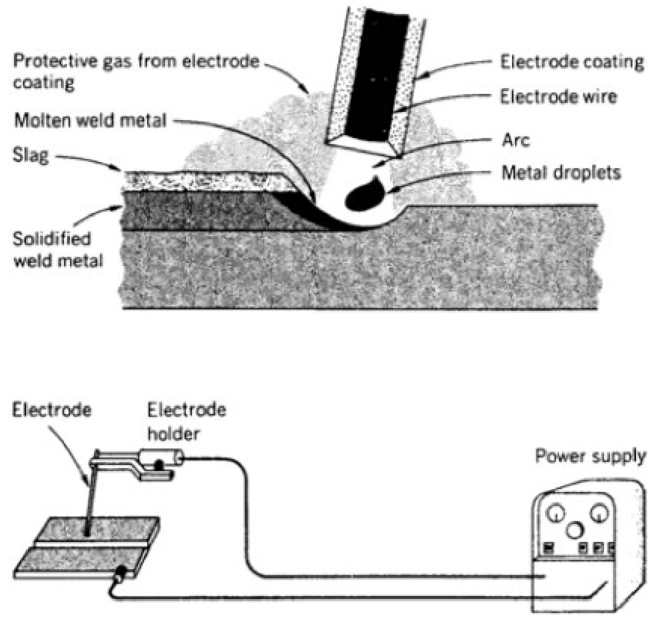


*Figure 26 Shielded Metal-Arc Welding, SMAW [26]*

- Cable length - For AC welding the cable length is more critical than for DC welding because the voltage drop in long cables added to that at the arc can overload the power source or prevent its developing sufficient voltage for a proper arc.
- Current type - DC surpasses AC when low current values are used with small-diameter welding wires.
- Electrode type - All classes of covered electrodes are satisfactory for DC welding; only AC/DC-rated electrodes with coverings specifically formulated for alternating current should be used with AC welding.
- Arc starting - When small-diameter electrodes are used the arc is more difficult to start with AC than with DC current. When the arc is struck at a low current setting, the electrodes may stick or “freeze”, unless designed specifically for AC operation.
- Thickness to be welded - Because of the steady, easily started arc, DC current is preferable for welding sheet metal.
- Arc length - Maintaining a short arc, when the arc must be crowded into a molten puddle, is easier with DC than with AC.
- Arc blow - AC current is well-suited for welding thick sections using large-diameter electrodes and maximum current levels because arc blow is rarely a problem with AC current.
- Weld spatter - Somewhat more weld spatter is produced with AC welding, partly because of the pulsating nature of the current.
- Weld position - DC current is somewhat easier to use for out-of-position welding on thicker sections, because lower currents can be used.

The SMAW process is very versatile. The equipment is simple, portable, and less expensive than equipment used for other processes. All that is needed is an adequate power supply, a simple electrode holder, and cables. Furthermore, SMAW welding can be performed in any position. The SMAW process is suitable for casting production welding because of its versatility, wide selection of available electrodes, and simplicity.

Several limitations of the SMAW process should be recognized. The deposition rate and deposition efficiency, which is defined as the ratio of the weight of deposited weld metal to the net weight of filler metal used (excluding stub), are low compared to other welding processes.

Welding must be stopped after each stick is used, and the remaining stub is wasted. Slag must be removed after each pass. The SMAW process cannot be automated since the flux covering would be damaged from coiling the electrode and automatic feeding. An adaption of the SMAW process has been developed which permits automatic use. This process, flux-cored arc welding, is discussed below.

## Flux-Cored Arc Welding, FCAW

The FCAW process overcomes major limitations of the SMAW process. Besides being suitable for automatic welding, FCAW provides higher deposition rates, less time lost to changing electrodes, and less wasted material. The FCAW process is shown schematically in Figure 27.

In flux-cored arc welding a tubular electrode with a flux core replaces the covered stick electrodes used in SMAW. This allows coiling and mechanical feeding of the electrodes. Higher deposition rates are possible compared to those of the SMAW process since less electrode heating occurs which damages the flux covering of stick electrodes and limits the maximum current used in the SMAW process.

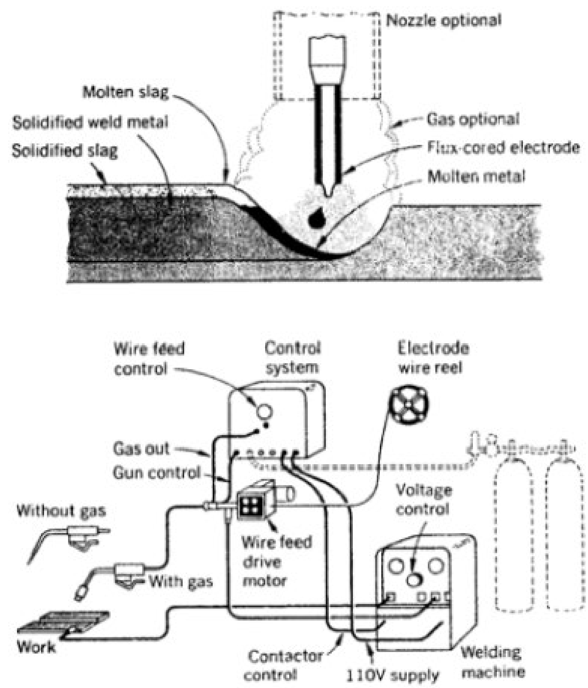



*Figure 27 Flux-Cored Arc Welding, FCAW [26]*

Two general processes are utilized: self-shielding, which is identical in principle to the SMAW process, and auxiliary gas shielding. In the latter process an auxiliary shielding gas provides shielding to the molten weld metal in addition to the flux gases and the slag.

A DC reverse polarity hook-up is normally used with either constant current or constant voltage control. Arc voltage, current, travel speed, and electrical stickout (the length of the electrode extending between the point of electrical contact within the gun and the work) are the principal operating variables to be controlled. Arc voltage variations will have the following effects [26]:

- Excessive arc voltage results in heavy splatter and a porous weld.
- Increasing the arc voltage flattens and widens the weld bead.
- Decreasing the voltage may cause a convex bead with a rope-like appearance.
- Extremely low voltage causes the electrode to “stub” on the workpiece. The electrode dives through the molten weld puddle and strikes the unmelted base metal at the bottom of the puddle.
- With higher current, higher voltage can be used without causing porosity. Using the highest voltage possible (without causing porosity) will result in a weld-bead shape which is satisfactory for most applications.

With all other variables held constant, current variations will have the following effects [26]:

- Excessive current produces convex weld beads, which results in wasted weld material and poor appearance.
- Melting rate, deposition rate, and penetration are increased by increasing the current.
- Large-droplet transfer occurs when the current is too low and causes difficulty in maintaining a uniform weld bead.
- Increasing the current increases the maximum voltage that can be used without causing porosity.

With all other variables held constant, travel-speed variations will have the following effects [26]:

- An excessive travel speed results in a convex weld bead with uneven edges and shallow penetration.
- Too slow a travel speed results in slag interference, slag inclusions, and a rough, uneven weld bead.

With all other variables held constant, electrical stickout will have the following effects [26]:

- Increasing the stickout decreases the welding current; decreasing stickout increases the current.
- When stickout is increased the actual voltage is lowered. A lower arc voltage increases weld-bead convexity and reduces the likelihood of porosity.
- When stickout is excessive, spatter and irregular arc action will result.
- Short stickout produces greater weld penetration than long stickout.
- When stickout is too short, spatter will build up on the nozzle and the contact tube.

Besides the advantages of the FCAW process already discussed, the self-shielding and auxiliary gas methods each have their own advantages. While both methods are suitable for out-of-position welding, the self-shielding method is less penetrating than the auxiliary gas method. The self-shielding method is therefore suitable for poor joint fit-up. The auxiliary gas shielding method can be used for a wider range of thicknesses and produces better joint penetration.

## Gas Metal-Arc Welding, GMAW

The GMAW process, also known as Metal-Inert Gas Welding, MIG, can be used as an automatic, or a semi-automatic welding process. The GMAW process uses a continuously fed bare consumable electrode wire. Shielding is supplied by gas. The shielding gas is either helium, argon, carbon dioxide, or mixtures of these gases. The GMAW process is shown schematically in Figure 28. The power source used with GMAW is basically direct current, constant voltage, and usually reverse polarity.

The GMAW process can produce top quality welds. It is suitable for welding in all position. Since flux is not used, slag removal is not required and slag entrapment in the weld is not of concern.

Electrodes are produced from high purity material. The electrode composition depends on the composition of the metal being production welded or fabricated, shielding gas, metal transfer technique, and welding position. Composite wires are available for welding alloy steels.

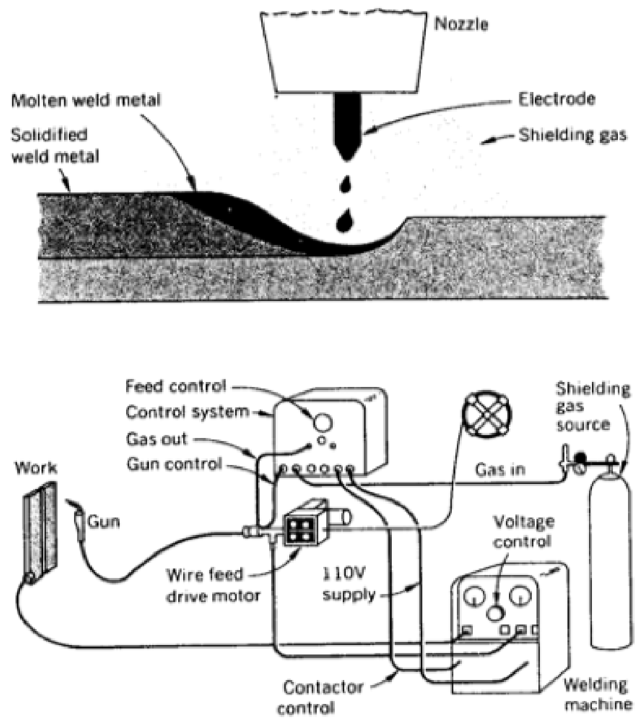



*Figure 28 Gas Metal-Arc Welding, GMAW [26]*

Generally, carbon dioxide shielding gas is used for welding steels. Good welding speed and penetration are attained with carbon dioxide. Carbon dioxide is also less expensive than the other gases which could be used. Mixtures of carbon dioxide with argon, and sometimes helium are also common for welding steels. Argon, being relatively heavy, is used for down hand welding and horizontal fillet welds. Helium is used for thick sections.

Metal transfer is accomplished by either a short circuit or spray transfer technique. The short circuit method is a low heat input technique, which is suitable for welding thin sections. However, the metal transfer occurs by globular drops which fall downward regardless of the welding position. This limitation can be overcome by combining the short circuit and spray transfer techniques. Spray transfer is a high heat input technique which produces maximum penetration and higher deposition rates. Spray transfer is particularly suited for thicker sections. Unlike short circuit transfer, the weld metal is propelled from the electrode to the work piece; hence, spray transfer is suitable for out-of-position welding. With spray transfer, weld splatter is minimized, high deposition efficiency is attainable, and weld control is enhanced. The combination of the short circuit and spray transfer techniques lowers the heat input- thus, improving the GMAW process for welding thin sections. Sections with a thickness of about 3/8" are considered thin sections. Sections measuring 2" and heavier are thick sections.

## Gas Tungsten-Arc Welding, GTAW

The GTAW process, also known as Tungsten-Inert Gas, TIG, can be used as an automatic or as a semi-automatic welding process. A non-consumable tungsten electrode is used to produce the arc and generate heat at the welding surface. Shielding is commonly provided by argon gas. Helium is also used at times. A filler metal may or may not be used, but it is usually for joining thick sections. The GTAW process is like the GMAW process, except that the work piece is joined by coalescence of the base metal, unless filler metal is added. The GTAW process is shown schematically in Figure 29.

The end profile of the tungsten electrode determines the current density at the welding surface. Profiles range from pointed to a bulbous mass which has a greater diameter than the electrode. DC straight polarity is normally used but pulsed current power supplies are also available.

Features of the GTAW process include top quality welds, no weld spatter, no slag removal, and all position welding. The GTAW process is suitable for welding a wide range of metal thicknesses. However, the GTAW process is slow, and the shielding gas is expensive. Because of these limitations, the GTAW process may not be advantageous over other welding processes for welding steel castings.

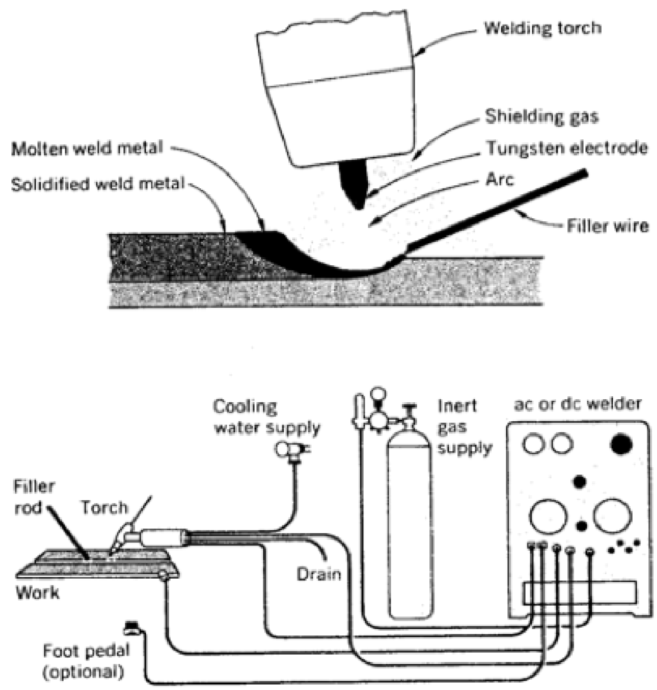



*Figure 29: Gas Tungsten-Arc Welding, GTAW [26]*

## Submerged-Arc Welding, SAW

The SAW process is used more frequently as a fully automatic process, although it is adaptable for semi-automatic welding. The SAW process utilizes a bare, continuously fed, consumable electrode wire. A granular fusible flux shields the weld metal and the electrode. Either DC or AC current is used with the SAW process. This process is shown schematically in Figure 30.

The SAW process is most suitable for casting production welding of unalloyed low carbon steels containing less than 0.3% C, 0.05% P, and 0.05% S. [26] Medium carbon steels and low alloy steels can be welded by this process, although preheat, post heat, and special electrodes are often required.

High welding currents can be used. This is possible with the bare electrode wire of the SAW process, since excessive resistance heating of the flux, which causes the flux to break down, is not a problem. High welding current produces high heat input, and therefore permits high welding speeds and deposition rates. Other advantages are less filler metal is consumed since shallow V-groove weld end preps can be used, wires for welding unalloyed low carbon steel are inexpensive, the insulating effect of the flux results in deeper penetration, and heat distortion is minimized.

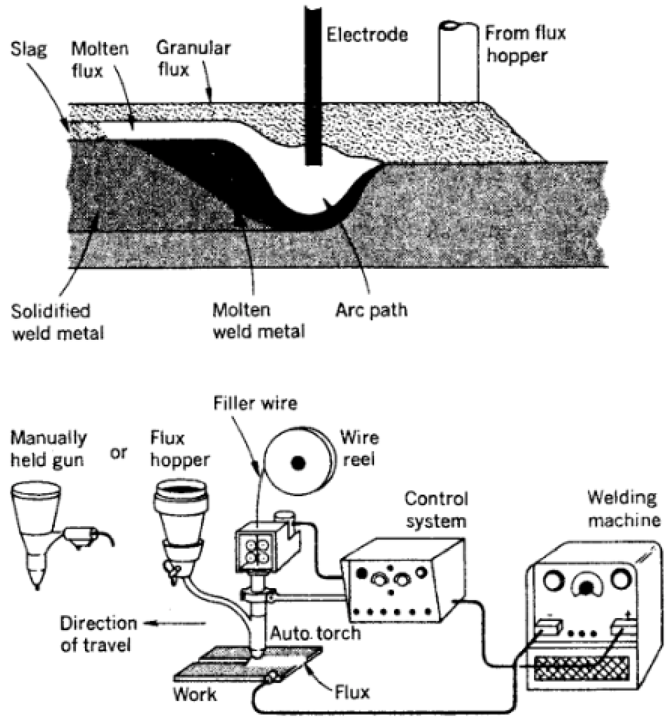



*Figure 30: Submerged-Arc Welding, SAW [26]*

Limitations of the SAW process are largely those common to other flux-type welding processes. In particular, the SAW process is limited to flat position welding of groove welds, and flat and horizontal fillet welds with thicknesses of 3/16” [26] or greater, to prevent burn-through.

## Electroslag Welding, ESW

The ESW process has some characteristics of submerged-arc welding; it is used for welding in the vertical position. One method utilizes bare electrode wires which are fed continuously into a molten slag pool contained between water-cooled dams. The ESW process begins with an arc to melt the flux and create a pool of molten slag. The arc is then extinguished, and a molten pool of weld metal and base metal is maintained by the heat generated from the resistance of the flux to the passage of current from the electrode to the base metal. The metal solidifies as the water-cooled dams are moved upward. The ESW process is shown schematically in Figure 31.

The ESW process has not been widely used in casting production welding. It is used though for cast weld assemblies with heavy sections [27] [2] and is well adapted to joining thick sections over 2” [27]. Some features of the ESW process are [26] the extremely high deposition rates which can be attained, the thickness which can be welded in one pass, the minimal requirements for joint preparation and fit-up, little or no distortion, and low flux consumption.

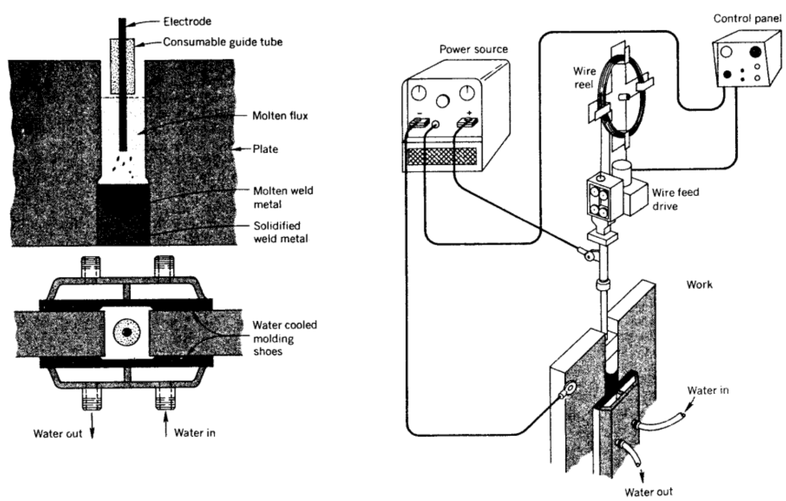



*Figure 31 Electroslag Welding. ESW [26]*

## Selection of the Welding Process

Many factors are considered when selecting a welding process for a particular application. The type of welding to be performed, the types of steel to be welded, the size and quality of the weld are but a few of the factors which must be evaluated.

The type of welding which will be performed i.e., casting production vs fabrication welding is one practical consideration. Manual or semi-automatic welding processes are most adaptable for casting production welding, except for very large production welds when automatic welding processes could be feasible. Fabrication welding may allow application of high-speed automatic processes. The amount of welding to be performed is another factor to consider. Sophisticated, complex, and expensive equipment may not be justified for a small operation or if welding is limited to casting production welding. Location can be a factor. If welding must be performed in areas that are difficult to keep clean and free from drafts, weld quality could be impaired when welding with shielding gas. If the gas is blown away, it will not be effective in preventing contamination of the weld metal. The necessity for high production rates may be an overriding factor. High deposition rates can be attained with automatic equipment. Figure 32 through Figure 35 show approximate deposition rates for the various welding processes. Economics have already been mentioned, but capital costs and operating costs will also become a factor when comparing the alternatives.

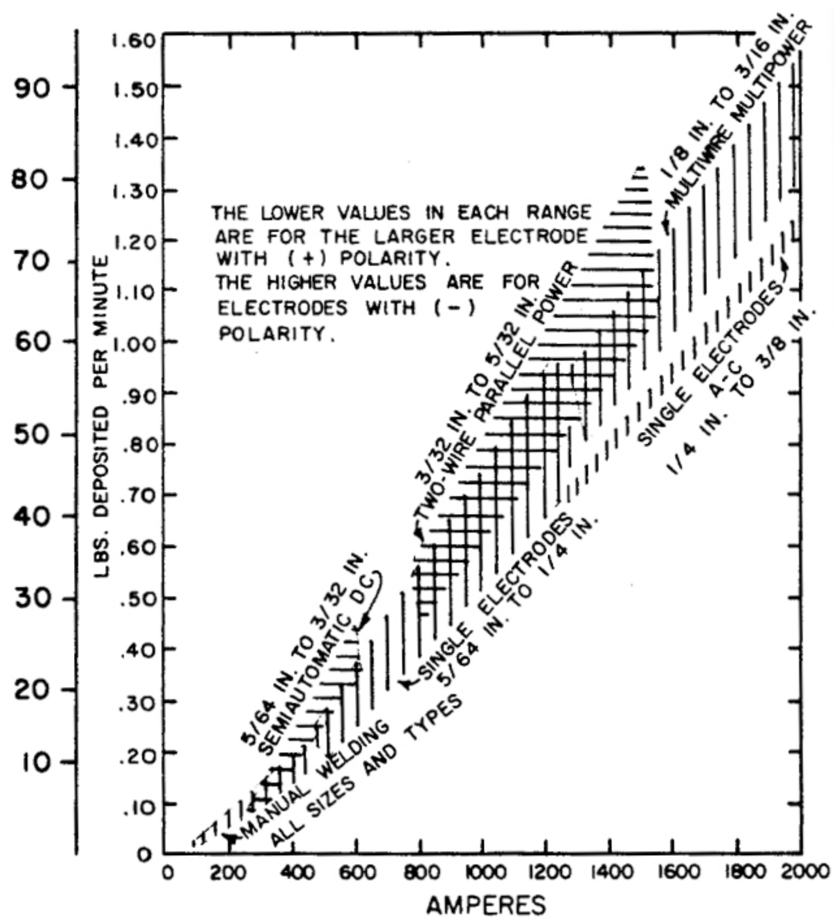



*Figure 32 Approximate deposition rate of shielded metal-arc and submerged-arc processes on mild steel [28]*

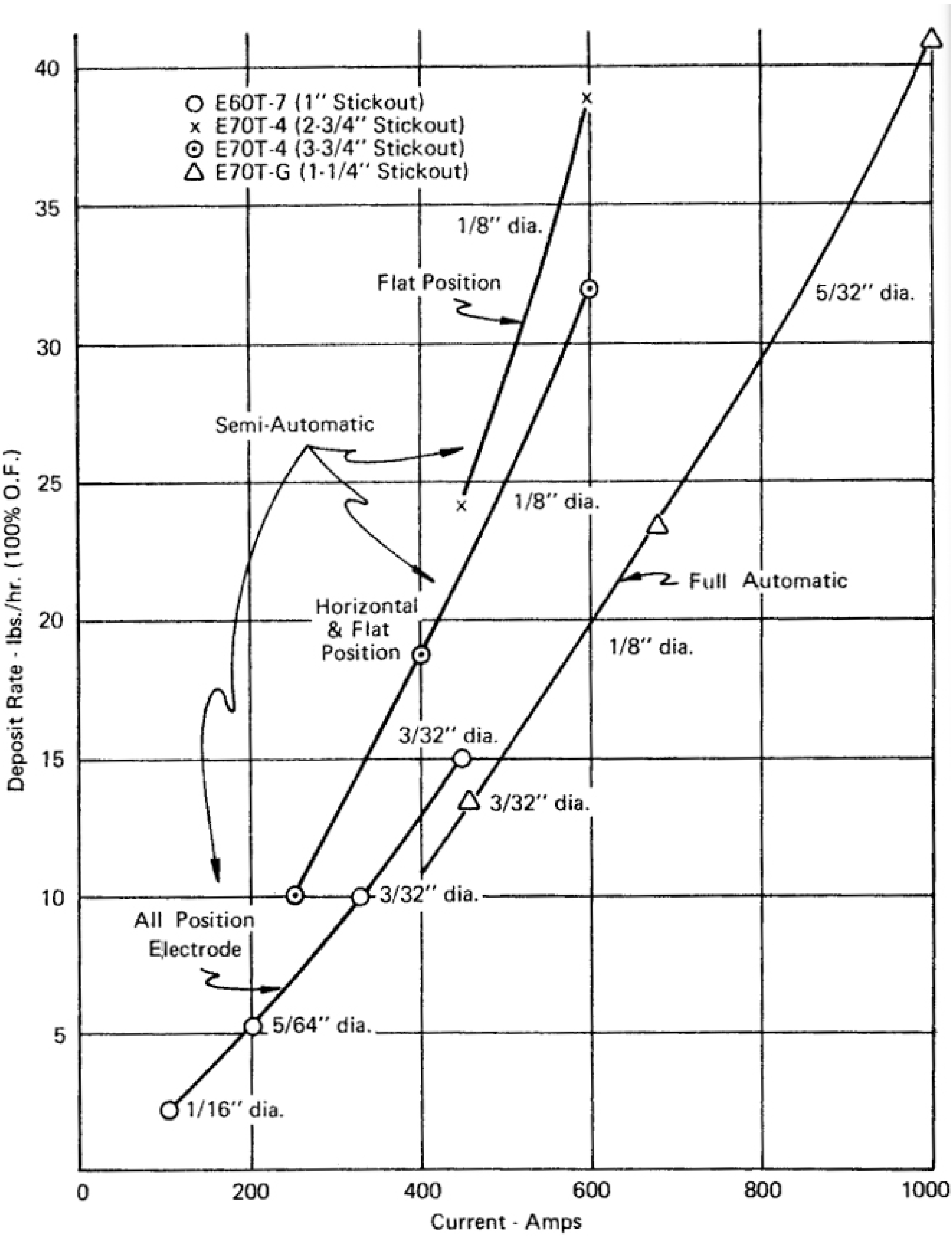



*Figure 33 Approximate deposition rate of flux-cored arc welding processes for self-shielded electrodes [29]*

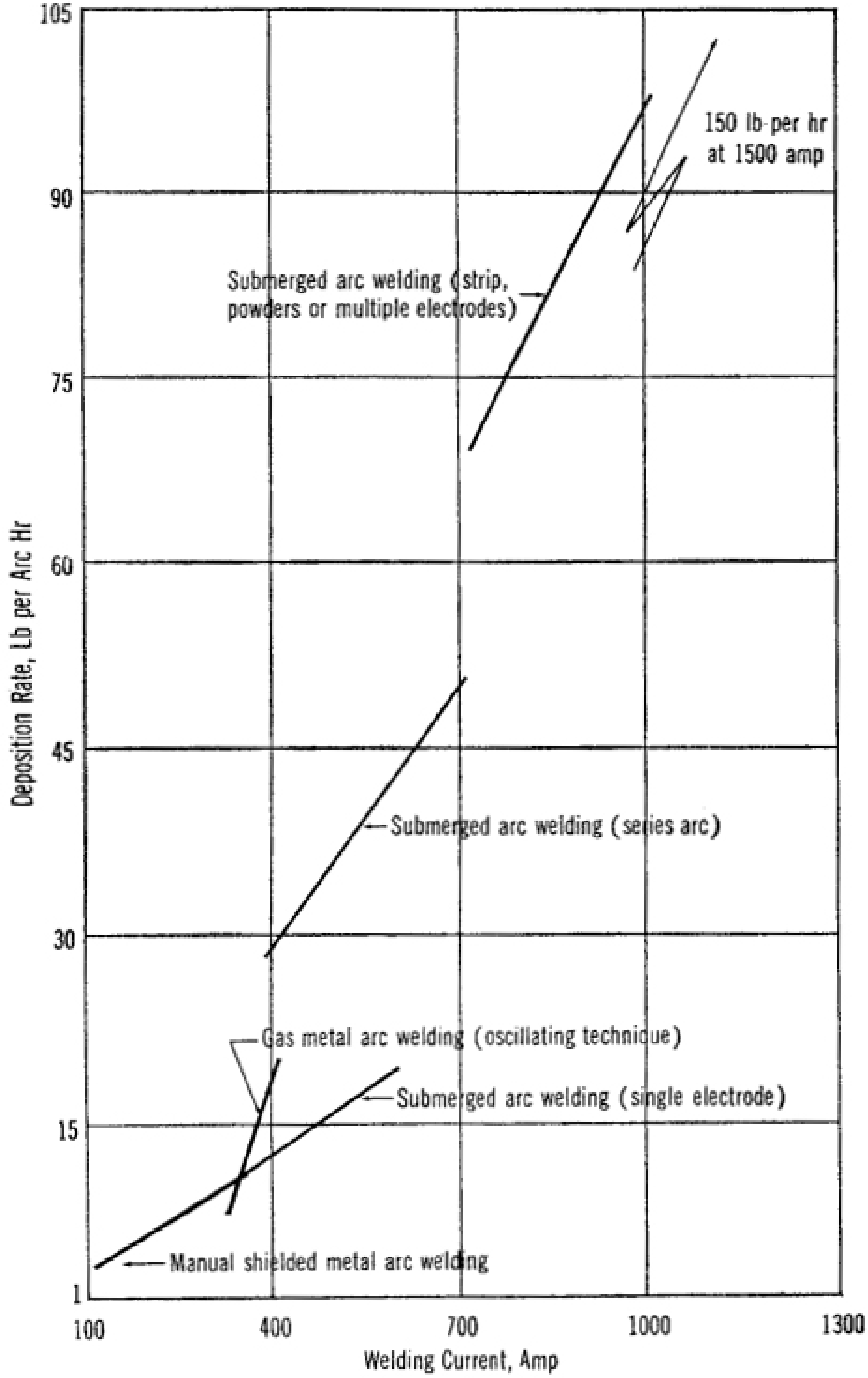



*Figure 34 Approximate deposition rate of Gas Metal-Arc Welding [30]*

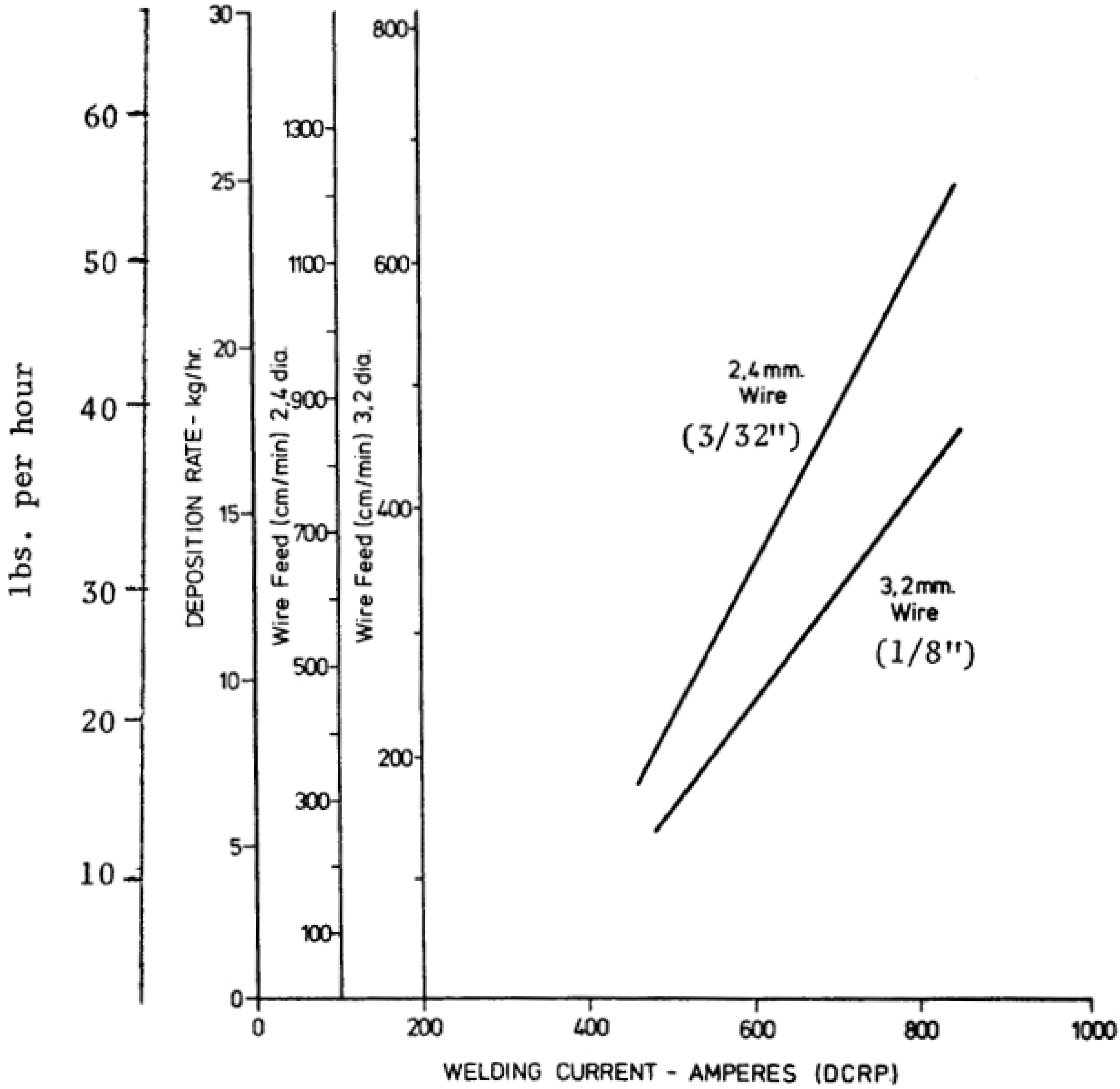



*Figure 35 Approximate deposition rate of Electroslag Welding for a single electrode. [31]*

The features of the various welding methods discussed previously in this section must be considered with the advantages and limitations of each when deciding on the best process. Each situation must be considered based on the various circumstances and availability of welding equipment. The following individual comparison of the various welding processes highlights their differences.

- The shielded metal arc welding, SMAW, is versatile and a widely used process for casting production and fabrication welding. Electrodes are available for a range of steel alloys, welding positions and shielding atmospheres. The low hydrogen type of coating is employed for carbon and low alloy steel castings because of the reduced problems with cold cracking without preheating. However, the SMAW process has disadvantages including low deposition rates, low deposition efficiency of the electrode metal in the weld deposit (about 70%), high electrode stub losses, high losses in welding time to replace electrodes, and fairly difficult slag removal [32]. The manual arc welding SMAW process also does not generally produce as high a weld quality as the semi-automatic processes. It is also more difficult to operate than processes that feed the electrode into the weld puddle and welding fume collection is more difficult [32].

- The semi-automatic flux-cored arc welding FCAW, and $CO_2$ shielded, gas metal arc welding, GMAW, processes have higher deposition rates, higher efficiency of electrode usage and welder time. These processes generally make higher quality welds and are easier to control and operate than the SMAW process [32] [33]. For these reasons, many steel foundries have replaced the SMAW process with FCAW and GMAW processes for casting production and fabrication welding. [32] [33] [34] [35] Advantages of these processes also include easier slag removal for the FCAW process and little slag problems with the GMAW process compared to the SMAW process. The shielding gas for carbon and low alloy steels should be $CO_2$ to minimize costs [34] [35]. The FCAW process can be used together with $CO_2$ gas shielding if the quality of the weld requires this [26]. However, electrode types are limited as will be shown by the lists in Section 4. Electrodes and Fluxes of this report; in addition the semi-automatic equipment cannot be moved into difficult to reach locations with the ease of the manual SMAW process [26] [32] [34]. While the equipment available for the FCAW and GMAW process is relatively trouble free, it does require more maintenance than manual equipment. Other limitations of the FCAW and GMAW processes are that they are not readily adaptable to welding overhead except with special weld preparation, and to welding small castings or sections under ¼" thickness [34]. The GMAW process is susceptible to difficulties from drafts or air movement [26] [33].

- The gas tungsten arc welding, GTAW, produces a high-quality weld with an automatic or semi-automatic process. While it is adaptable to a wide variety of metals and thicknesses, the rate is slow compared to the FCAW and GMAW processes and the argon or helium shielding gas is expensive. For these reasons, it is not widely used for carbon and low alloy cast steel production or fabrication welding.

- Submerged arc welding, SAW, can be adapted to semi-automatic steel casting production welding with some advantages in selected applications [36]. The automatic process is directly applicable to many types of fabrication welds [2]. The deposition rates are high and under many conditions significantly higher than the FCAW and GMAW processes. Welder fatigue is reduced by the shielding effect of the flux, thus allowing higher heat inputs. The welds are of high quality and relatively free from spatter, reducing post weld finishing. The unfused flux can be recovered, and different fluxes can be used to control the composition of the weld deposit. The process is limited to the flat or horizontal positions with flux retainers because of the loose granular flux. Steel thicknesses should be 3/16" or greater to prevent burn-through from the high heat [26] [36].

- The electroslag welding, ESW, is primarily useful for cast weld assemblies of heavy sections because of the very high deposition rates. Because of this high deposition rate and minimal joint preparation, the process could have limited applicability to very large production welds in carbon and low alloy steel [26] [2]. The process is limited to use in the vertical position.

The cost of welding also deserves attention in the design stage. With cast fabrications, manual, semiautomatic, or automatic procedures are selected, depending on number of parts and contour of welds. Large production runs involving assemblies which combine centrifugally and statically cast parts are automated to as great an extent as permitted by the location, orientation, and accessibility of the weld grooves.

The primary factor in selecting a welding process is weld quality. The quality of the weld should meet, if not exceed, the requirements in effect for the base material. All the welding processes discussed will produce welds of good quality and acceptability, but this depends largely on welder performance and on the soundness of the welding procedures. However, some processes inherently result in better quality welds by the nature of the process e.g., GTAW. The mechanical properties and nondestructive tests of the weld will ultimately be the judge of weld quality and acceptability. The effect of welding processes on fatigue and toughness was discussed in Section 1 of this report under Properties of Welded Steel Castings [27].

The types of steel being welded must be considered when choosing a welding process since availability of some electrodes may be limited. Electrode selection and availability are discussed in detail next in Section 4. Electrodes and Fluxes.

# 4. Electrodes and Fluxes

## American Welding Society Classification

Specifications for welding electrodes and flux are published by the American Welding Society, AWS. The AWS specifications are issued according to welding process and type of metal, e.g., flux-cored arc welding of mild and low alloy steels.

The following are specifications on various electrode classifications:

- AWS 5.1/A5.1M:2012 Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding [37] This specification contains requirements for covered mild steel electrodes for shielded metal-arc welding of carbon and low alloy steels. The electrodes are classified based on the mechanical properties of the as-welded deposited weld metal, type of covering, welding position of the electrode, and type of current.
- AWS A5.5/A5.5M:2014 Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding [38] - This specification contains requirements for covered low alloy steel electrodes for shielded metal-arc welding of carbon and low alloy steels. Electrodes are classified based on the mechanical properties of the deposited weld metal, type of covering, welding position of the electrode, type of current and the chemical composition of the deposited weld metal.
- AWS A5.17/A5.17M:2019 Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding [39] - This specification contains requirements for carbon steel electrodes and fluxes for submerged arc-welding of carbon and low alloy steel. Electrodes are classified based on their as-manufactured chemical composition. Fluxes

are classified based on the mechanical properties of a weld deposit made in combination with a particular electrode.

- AWS A5.18/A5.18M:2005 Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding [40] - This specification contains requirements for mild steel, solid electrodes for gas metal-arc welding of mild and low alloy steel. Electrodes are classified based on their mechanical properties of deposited weld metal.
- AWS A5.20/A5.20M:2005 Specification for Carbon Steel Electrodes for Flux Cored Arc Welding [41] - This specification contains requirements for mild steel composite electrodes for flux-cored arc welding of mild and low alloy steels. Electrodes are classified based on whether carbon dioxide is required as a separate shielding gas, the type of current, their usability for either single or multiple pass applications, and the chemical composition and as-welded mechanical properties of deposited weld metal.
- AWS A5.23/A5.23M:2011 Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding [42] - This specification contains requirements for bare solid and composite electrodes and fluxes producing low alloy steel weld metal for submerged arc welding of carbon and low alloy steels. Electrodes are classified based on their as-manufactured composition. Fluxes are classified based on the mechanical properties and the chemical composition of a weld deposit made by using the flux in combination with a particular electrode.
- ANSI/AWS A5.25/A5.25M-97 (R2009) Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding [43] - This specification contains requirements for solid and metal cored electrodes and fluxes for the electroslag welding of carbon and high strength low alloy steels. Solid electrodes are classified based on their chemical composition. Metal cored electrodes are classified based on the chemical analysis of undiluted weld metal. Flux is classified based on the mechanical properties of the weld deposit made with a particular electrode.

Copies of these specifications can be found at https://pubs.aws.org/. Table 33 summarizes AWS electrode specifications based on welding procedure and steel alloy. These specifications include pertinent information on mechanical properties and compositions as obtained from deposited weld metal without any significant admixture of base metal. In cases of welds where such mixing does occur, the mechanical properties and chemical analyses will probably be affected. The mechanical properties of welds are also influenced by the section size of the weld to some extent.

*Table 33 Common AWS Electrode Specifications*

| | SMAW | GMAW/GTAW | FCAW | SAW | Electroslag |
|---|---|---|---|---|---|
| **Carbon Steel** | A5.1 | A5.18 | A5.20 | A5.17 | A5.25 |
| **Stainless Steel** | A5.4 | A5.9 | A5.22 | A5.9 | |
| **Low Alloy Steel** | A5.5 | A5.28 | A5.29 | A5.23 | A5.25 |

Each specification identifies the classification system used for the type of electrode covered, and flux, if applicable. For example, covered electrodes for shielded metal-arc welding, SMAW, are designated by the letter prefix "E" followed by a set of four or five numbers (see Table 34). From left to right, the first two (or three) digits indicate the approximate tensile strength of the as-deposited weld metal in ksi. The next-to-last digit indicates the welding position in which the electrode can be used: "1" indicates an electrode that can be used for flat, horizontal, vertical, and overhead welding; "2" indicates an electrode that can be used for welds in the flat position and for horizontal fillet welds. The last digit indicates the current to be used and the type of covering on the electrode. In addition, a letter suffix used for low alloy steel covered electrodes designates the chemical composition of the deposited weld metal. Details of the electrode classification system for electrodes used with the other types of welding processes are described in the appropriate AWS specifications.

*Table 34 Example of Electrode Specification Breakdown*

| | | |
|---|---|---|
| **E8018-B1** | **E** | Indicates that this is an electrode |
| | **80** | Minimum tensile strength required in ksi (stress relieved) |
| | **1** | Welding Position |
| | **8** | Current |
| | **B1** | Chemical Composition |

## Selection

The selection of electrodes for the metal-arc welding of steel castings is not always simple. One reason for this is that electrode deposits are usually lower in carbon than the castings being welded. The weld metal, which is a mixture of the electrode metal and the fused base metal (manual metal-arc welds contain more electrode metal than base metal), is consequently also lower in carbon than the castings. To compensate for the lower carbon, alloying elements are frequently added. Most wrought steel welds are either left as deposited or are simply stress relieved, and the electrode compositions are designed to give adequate strength in these conditions. This simplifies the problem of selection when the castings are merely stress relieved after welding.

When the weld is intended to remain in the as-welded or stress relieved condition, the selection of an electrode should be based on the mechanical properties of the as-deposited weld metal. Generally, the mechanical properties of the weld are selected to match the base metal mechanical properties. However, some cases do occur where a specific chemical analysis range of the weld is a requirement. If possible, welding should be performed with a low carbon content electrode that produces a weld yielding the required mechanical properties since the lower carbon content improves weldability. The hardenability, the brittleness of the weldment, and susceptibility to cracking increase with carbon content.

Castings that are fully heat treated after welding may result in the weld being softer than in the as-deposited or stress-relieved condition. To ensure that welds in castings will have strengths equal to the base metal, weld deposits should be of such a composition that they will have those strengths after heat treatment. Where such properties are listed, the choice of electrodes is obvious – use those whose heat-treated deposits match the heat-treated castings in properties, giving preference to the low-hydrogen types. Of course, it is not always necessary that welds match the strength of the casting. If this is the case then the lowering of weld strength by heat treatment is not important unless it affects some other step in the processing of the casting or the composite structure, such as machining.

## Special Composition Electrodes

An electrode of increased carbon content should be used when the casting is heat treated after welding. Carbon is the most potent element for raising the strength of the weld metal. Thus, to produce good matching of mechanical properties after heat treatment, the carbon content should be increased to match the base metal more closely. However, the carbon content of the electrode will still be less than the base metal. When a production or fabrication weld with close to homogeneous properties in the base metal and weld is required, some available shielded metal-arc welding electrodes that deposit heat treatable weld metal are listed in Table 35 [44].

*Table 35: Low Alloy Steel Covered Electrodes for Heat Treatable Weld Deposits (Not a recognized classification in current AWS-ASTM specifications) [44]*

| | C | Mn | S | Si | Cr | Ni | Mo |
|---|---|---|---|---|---|---|---|
| **Cr-Mo** | 0.10 | 0.55 | 0.02 | 0.45 | 0.50 | | 1.10 |
| **Cr-Ni-Mo** | 0.20 | 1.50 | 0.02 | 0.50 | 0.50 | 1.25 | 0.25 |
| **4130** | 0.25 | 1.00 | 0.02 | 0.50 | 1.00 | | 0.25 |
| **4140** | 0.40 | 1.00 | 0.02 | 0.50 | 1.00 | | 0.25 |
| **4340** | 0.40 | 1.00 | 0.02 | 0.50 | 1.00 | 2.00 | 0.25 |

This list of heat treatable electrodes is not comprehensive. There are many others which are available from various manufacturers. Other compositions of weld metal for high strength steels are also reported in references [44] and [45] for use in the SMAW, GMAW, GTAW and SAW processes. These electrodes are similar to those reported in Table 35 and are also not recognized classifications in current AWS-ASTM specifications but are available from various welding electrode suppliers. In general, these electrodes fall into the low carbon, medium carbon and matching carbon grades with the strength obtained from additional alloying elements added to the lower carbon weld deposits. Specific recommendations of the class of electrode for welding a high strength Mn-Ni-Cr-Mo steel for high strength levels are contained in [46]. The post weld heat treatment depends on the strength level and changes from tempering or stress relieving to water quenching and tempering as the strength level increases [46].

On heat treatable steels that are difficult to weld without cracking or where re-treatment of the casting after welding is not feasible, some welding is conducted with dissimilar filler metal. This welding on low alloy steel castings is conducted with austenitic stainless steel welding electrodes of the types listed in the specification AWS A5.9/A5.9M:2-17 (ISO 14343:2009 MOD) Welding Consumables-Wire Electrodes, Strip Electrodes, Wires, and Rods for Arc Welding of Stainless and Heat Resisting Steels – Classification [44] using the SMAW or GMAW processes. The types of electrodes used most widely for this welding are the 25Cr-12Ni (ER 309) and 25Cr-20Ni (ER 310). Austenitic stainless-steel welds minimize cracking in the base metal and HAZ. The welding is conducted with little or no preheat. The deposited weld metal is tough, although lower in strength than the base metal. The shielded metal arc electrodes employed utilize a mineral coating to provide low hydrogen conditions. A hardened zone is produced in the base metal, but this can be mitigated by multi-pass welding or a post-weld tempering treatment [44]. The use of austenitic weld deposits has been reduced recently by establishing low hydrogen conditions with low alloy electrodes, thereby minimizing cracking. These welds are then responsive to heat treatment.

The problem of dilution of the weld metal composition with the base metal exists in several instances. These include when: austenitic stainless steel weld deposits are used; carbon and high alloy steels are joined; and, to some extent, in welding higher carbon steels with the lower carbon electrodes described previously. Normally the weld beads are of a uniform composition and structure with only slight mixing at the weld edges because the lower alloy base metal is stirred into the weld melt by electromagnetic action [44]. However, high speed welding or excessive melting of the base metal can produce more heterogeneity. The gas-shielded metal-arc and the submerged-arc processes produce deeper penetration of deposited weld metal compared to manual welding with shielded electrodes. Thus, more dilution of the weld metal and base metal occurs. Dilution may cause some problems with the use of austenitic stainless-steel electrodes.

## Drying Electrodes

The weld coatings and fluxes employed should be kept dry. This is usually accomplished by not opening the sealed containers until just before use and then storing the electrodes or submerged arc fluxes near the stress relieving furnaces or other ovens. Redrying the electrodes, should these become damp during storage, should follow specific guidelines which depend on the type of coatings [47]. The moisture in low hydrogen coatings should be maintained below 0.3% to avoid under-bead cracking. One practice followed is to return all opened but unused low hydrogen electrodes to a redrying oven held at 250-300°F (121-149°C) after each shift. These are dried for eight hours before reuse. If the low hydrogen coatings have picked up moisture by long exposure to humid atmospheres, the coatings are restored to low moisture contents by redrying at temperatures such as 550°F (288°C) for one hour in a well-ventilated oven. The redrying temperature varies with the brand of electrode and the manufacturer's recommendations should be followed. Cellulose-type coatings however normally require moisture contents of from 2 to 5% for proper operation. Accordingly, drying practices that lower the moisture below these levels are not recommended. These types of electrode coatings are held in 100-120°F (38-49°C) ovens after opening and limited exposure; they are held in ovens at 275°F (135°C) if the desired moisture content of the coating is exceeded [47].

## Process Considerations

In addition to the factors relating to mechanical properties and chemical composition discussed above, the following additional items must be considered when selecting an electrode [48].

- **Welding Position -** Electrodes are designed to be used in specific positions. The third (or fourth) digit of the electrode classification indicates the welding position that can be used. Match the electrode to the welding position to be encountered.
- **Welding Current -** Some electrodes are designed to operate best with direct current (DC), others with alternating (AC). Some will operate on either. The last digit indicates welding current useability. Select the electrodes to match the type of power source to be used.
- **Joint Design and Fit-up –** Welding electrodes are designed with a digging, medium, or soft arc for deep, medium, or light penetration. The last digit of the classification also indicates this factor. Deep penetrating electrodes with a digging arc should be used when edges are not beveled or fit-up is tight. At the other extreme, light penetrating electrodes with a soft arc are required when welding on thin material or when root openings are too wide.

- **Thickness and Shape of Base Metal -** Weldments may include thick sections of complex shapes. The electrode selected should have maximum ductility to avoid weld cracking. Select the low-hydrogen types.
- **Production Efficiency and Job Conditions -** Some electrodes are designed for high deposition rates. The electrode selection should take this into consideration.

Once the proper electrode classification has been chosen, AWS FMC:2000 Filler Metal Comparison Charts [49] will aid in the selection of commercially available electrodes for steel and is highly recommended. These filler metal comparison charts list the manufacturers and brand names of the following types of electrodes: (1) covered mild steel electrodes, (2) covered low alloy steel electrodes, (3) bare carbon steel electrodes and fluxes for submerged-arc welding, (4) bare mild steel electrodes for gas metal-arc welding, (5) mild steel flux-cored arc welding electrodes, and (6) low alloy steel electrodes and fluxes for submerged-arc welding. Many of the classes of electrodes for electroslag welding are the same as those for submerged-arc welding and gas metal-arc welding. The comparison charts for these processes can be used to select electrodes for electroslag welding. Reference [49] also contains a description of the AWS classification system, an index of AWS classification designations, index of brand names, and names and addresses of electrode suppliers.

# 5. The Welding Operation

## Welding Methods and Materials

All conventional welding methods can be used for production welding and cast-weld fabrication. The choice depends on composition of the metals and the size and configuration of the structure. Cast carbon and low, medium, and high-alloy steels respond to welding processes the same as wrought steels of similar compositions. Likewise, preheat, post-heat, and joint preparation requirements and joint backup materials are similar.

Welding methods that have been successfully employed for cast-weld construction include manual arc welding with coated electrodes; and automatic and semiautomatic welding with gas-metal-arc, flux-cored wire, and submerged-arc and resistance welding. Fabrication of large, heavy-section castings is often done by the electroslag process.

Manual, coated electrode welding is generally the most economical process for welds in thin sections for overlays. Semiautomatic and automatic gas-metal-arc and flux-cored arc-welding methods are employed for more numerous or longer welds in thin and medium-thickness parts. The submerged-arc process deposits weld metal more rapidly but is limited to down-hand welding. The electroslag process is most useful for producing vertical joints in very heavy sections. Resistance welding is utilized to join simple shapes where sufficient quantities are involved to warrant the setup costs.

As in other material applications, statically cast, centrifugally cast, forged, and rolled forms are selected according to service requirements and economics for obtaining the needed shape. Carbon and low-alloy steels – the most widely used – are welded with E60XX to E120XX electrodes, depending on strength requirements of the application and strength of the base component. Heat and corrosion resistant parts can also be assembled by cast-weld fabrication.

The preheat and post-heating requirements will be described in further detail a little later in this report. Numerous examples of cast weld fabrication are described in [2] and [50].

## Production Welding to Meet Customer Specifications

Material specifications for steel castings govern the extent of inspection for indications, and the types and extent of indications that can be production welded. Nondestructive testing requirements relate to the quality details that are considered unacceptable indications. Quality details which are considered unacceptable must be removed, and the resultant cavity replaced with weld metal [51]. Non-destructive testing was covered in Section 1 of this report.

Indication removal is accomplished by mechanical metal removal methods including machining, chipping, and grinding. Rough machining when economically feasible eliminates many unnecessary welds and has much to recommend it as a procedure. Chipping and grinding are the more commonly used mechanical removal techniques with local machining in isolated areas. The mechanical metal removal methods can be performed without any preheat. Cavity size is usually kept at a minimum with chipping and, therefore, the volume of weld metal used in welding the cavity is usually minimized. However, chipping generally results in slower metal removal rates than achieved with grinding and the noise level is high [51]. Grinding, particularly with the high-speed grinders can be an efficient metal removal technique.

Unacceptable quality detail removal with flame cutting as a gouging operation is faster than chipping, but the resultant cavities are larger than those produced by chipping and grinding. Preheat should be applied when using flame cutting if the metal requires preheat when welding. Welding over flame gouged surfaces can be accomplished after removing adhering metal and slight grinding [51].

Air carbon-arc cutting, also referred to as the arc-air process, is widely used in the casting industry for removing unacceptable quality details as well as eliminating excess metal from gates, risers, and pads. Arc-air is the fastest of these gouging metal removal techniques and leaves the smallest cavity. The process is shown schematically in Figure 36. An arc is established between a carbon-graphite electrode and the work piece. The high temperatures produced at the arc melts the base metal. A high velocity air jet aimed at the arc, blows away the molten metal, leaving a cavity.

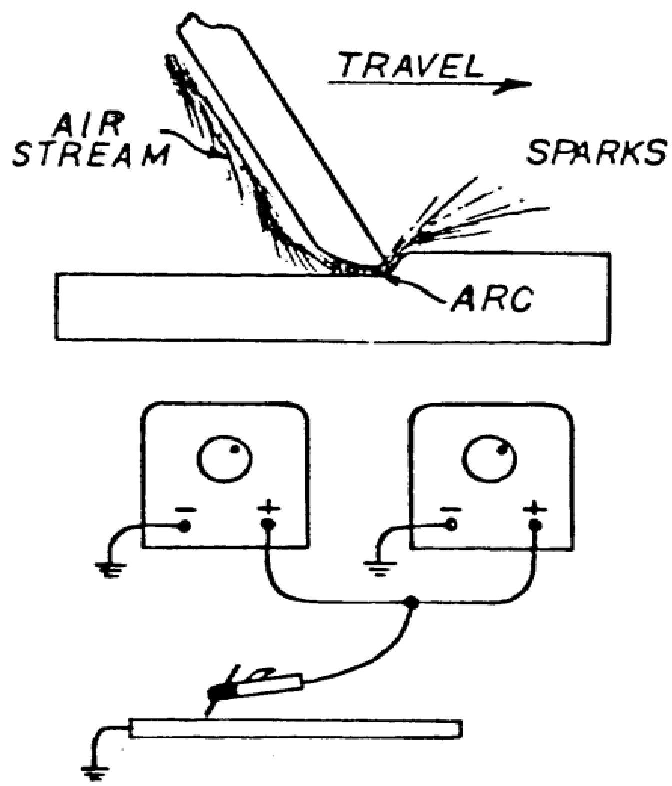



*Figure 36 Schematic illustration of air carbon-arc gouging. Two DC power supplies connected in parallel are shown. An AC power supply can be used also.*

The equipment required for air carbon-arc gouging includes an electrode holder, electrodes, power source, and an air supply. The electrode holder or cutting torch can be operated manually as well as in the semi-automatic or the automatic mode. The electrodes consist of a mixture of carbon and graphite. Three types of electrodes are normally used: DC copper coated electrodes, which are the most used electrodes; DC plain electrodes; and AC copper-coated electrodes. Electrodes are available in round sizes from 5/32" (4mm) to 3/4" (19mm) and flat half round shapes. Standard welding power units are used. Table 36 lists power sources recommended for arc gouging. Table 37 recommends current ranges for the various size electrodes. DC electrodes with direct current reverse polarity hook-up are recommended for arc gouging carbon and low alloy steels [52] [53] [54]. Compressed air, at pressures ranging from 80-100 psi, is normally required for arc-air gouging [52] . Compressed nitrogen or inert gas may be used in emergencies. The air stream must be of sufficient velocity and volume to remove the melted metal and slag. Table 38 contains recommended air pressures and consumption rates. It is important that the air pressure does not fall below the minimum specified for the torch. If this should happen, slag and carbon deposits could remain in the gouged cavity. Check out AWS C5.3:2000 (R2011) Recommended Practices for Air Carbon Arc Gouging and Cutting [53] for the most up to date information and practices for arc air gouging.

*Table 36 Power Sources for Arc Gouging [52] [53]*

| Type of Current | Type of Power Source | Remarks |
|---|---|---|
| DC | Variable voltage motor-generator, rectifier, or resistor-grid equipment | Recommended for all electrode sizes |
| DC | Constant-voltage motor-generator or rectifier | Recommended only for electrodes above 1/4" diameter |
| AC | Transformer | Should be used only with AC electrodes |
| AC-DC | Rectifier | DC supplied by three phase transformer rectifier is satisfactory. DC from single phase source not recommended. AC from AC-DC power source is satisfactory if AC electrodes are used. |

*Table 38 Recommended current ranges for Arc Gouging, Amperes [52] [53]*

| | **Electrode Size, in.** | | | | | |
|---|---|---|---|---|---|---|
| **Type of Electrode (and** | **5/32** | **3/16** | **1/4** | **5/16** | **3/8** | **1/2** |
| DC electrodes (DCRP) | 90-150 | 150-200 | 200-400 | 250-450 | 350-600 | 600-1000 |
| AC Electrodes | | 150-200 | 200-300 | | 300-500 | 400-600 |
| AC electrodes (DCSP) | | 150-180 | 200-250 | | 300-400 | 400-500 |

*Table 37 Air Consumption for Arc Gouging [52] [53]*

| Maximum electrode size in. | Application | Pressure, psi | Consumption, cfm |
|---|---|---|---|
| 1/4 | Intermittent-duty, manual electrode holder | 40 | 3 |
| 1/4 | Intermittent-duty, manual electrode holder | 80 | 9 |
| 3/8 | General purpose | 80 | 16 |
| 3/4 | Heavy-duty | 80 | 20 |
| 5/8 | Semiautomatic machanized electrode holder | 80 | 25 |

The arc-air process induces hardening on the gouged surface and in the heat affected zone (HAZ), which can result in subsequent cold cracking. Hardening is induced by carburization of the surface of the gouged area and from rapid thermal cycling that occurs during the gouging operation. The higher hardness in the heat affected zone is attributed more to the cooling cycle of the arc gouging rather than from the presence of additional carbon [51] [55]. Carbon pickup can occur from the electrode when the molten metal is allowed to dwell on the gouged surface. Carbon pickup from base metal at levels of about 0.20 to 0.35% have been measured for reverse polarity; this is reduced significantly by straight polarity DC [56]. Carbon pickup can be minimized by using an adequate supply of air to remove the molten metal from the gouged surface [57].

Experiments evaluating the effect of operating variables on the heat affected zone, HAZ, hardness have been performed on grades of carbon-manganese cast steel ranging from 0.20%C to 0.45%C using the arc-air process from removing metal. [58] Carbon electrode size, current, gouging techniques, and preheat were varied in the experiments. The hardness levels were measured after arc-air gouging and following subsequent welding of the gouged area.

In summary, the results of these experiments indicate that subsequent welding appears to remove the HAZ left by the arc-air process. However, it should be recognized that the hardened surface of the ground area is remelted during subsequent welding. This remelted layer forms the fusion zone between the base metal and weld metal. The hardness levels of the HAZ after welding approach levels that can be expected from welding alone. Preheat did not appear to affect the HAZ hardness after welding was performed for the casting sizes used in these experiments. However, preheat may be required to relieve the hardening effects of the arc-air process for thick casting sections, particularly in the high carbon range, and for hardenable low alloy steel castings. The conclusions from these experiments are listed below [57]:

1. The size of carbon electrode used at the optimum current has little effect on the hardness of the HAZ.
2. The gouging and application methods have a marked effect on the hardness values of the HAZ, and this appears to be associated with the amount of metal removed. In most instances the values were lower with the pad washing technique, where relatively small amounts of metal are removed.
3. The depth of the HAZ after gouging varied from 0.004” to 0.032”. The shallower depths were generally associated with the pad washing technique.
4. The hardness values obtained after gouging do not appear to have any detrimental effect on the surface of the gouge. There was no evidence of cracking or other unacceptable by-products.
5. Where subsequent machining is required, the HAZ may present some problems initially, although machining is usually carried out in the same areas as pad washing or shaping, where HAZ is shallowest.
6. Subsequent welding of a gouged surface removes the HAZ left by the arc-air process without detriment to the fusion zone and weld deposit.
7. The HAZ after welding is less well defined and much lower in hardness. The hardness values approach those considered to be generally acceptable for welded applications.
8. Preheating prior to arc-air gouging generally lowers the HAZ hardness, especially where a small electrode is used or where a pad washing technique is adopted.
9. Subsequent welding of the gouged surfaces using preheat appears to have little or no effect on the resultant hardness of the HAZ when compared with those obtained where no preheat was used. The values in each example are very similar.
10. Preheating appears to cause a slight rise in the hardness values obtained from the parent metal adjacent to the gouged and welded area.

11. The work carried out in this survey indicates that the arc-air process can be used without detriment to subsequent welding or machining operations on carbon-manganese steels up to 0.40-0.45% carbon content. It also indicates that the use of preheat prior to arc-air gouging is not always necessary. The decision whether to use preheat is governed by several factors including the shape, size, and analysis of the casting. Of necessity, the samples used in this survey have been limited in size and it would be expected that on larger castings, especially in the higher carbon range, higher HAZ hardnesses would occur, so that preheat may be required [57].

The high hardness surface and heat affected zone of an air carbon-arc gouged surface left in the as-gouged condition are potential sources of cracking. This layer can cause cracks to initiate unless removed by welding over this surface or by grinding. Because of the influence of the arc-air process on hardening, castings should be heat treated after arc-air metal removal. Preheating prior to arc airing can be employed to reduce the extent of hardening.

A qualification and testing program may be implemented to obtain control of parameters that will minimize hardness levels and minimize pick-up of carbon on the gouged surface. Such a program may use the type of specimen shown in Figure 37 that is gouged out by the operator using arc-air. This area is heat treated as specified in the welding procedure and tested with guided side bend specimens removed as shown in Figure 38 [51].

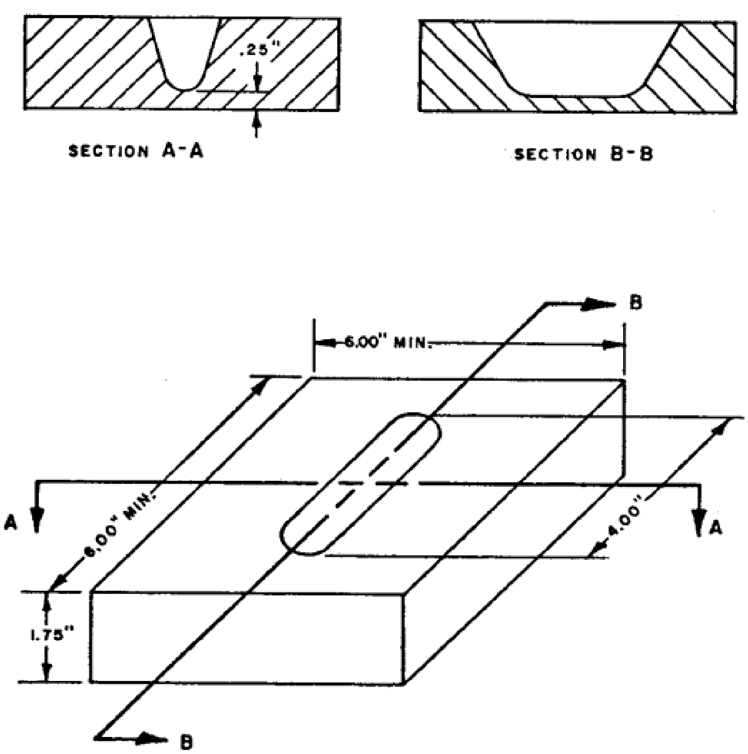



*Figure 37 Configuration for air carbon-arc cutting performance qualification specimen [51]*

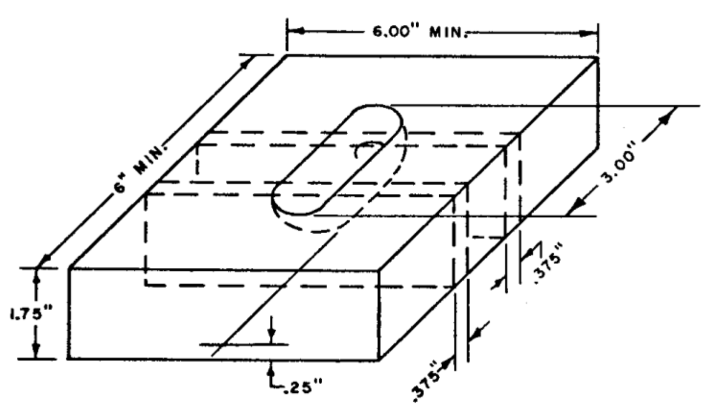



*Figure 38 Locations for removal of guided side bend samples after welding. [51]*

## Weld Preparation

Figure 39 and Figure 40 show suggested weld preparations for partial penetration and full penetration production welds. Typical weld preparations for weld joint design are shown in Figure 41 to Figure 46 [59]. In general, the weld preparation should have gradual contours and sufficient taper and root radii to avoid stress concentrations and to allow adequate access to the root of the cavity or weld joint with the welding electrode. Sharp inside corners serve as points of stress concentration which may start cracks during welding. Deep, narrow grooves hinder electrode manipulation and make it difficult to achieve full penetration.

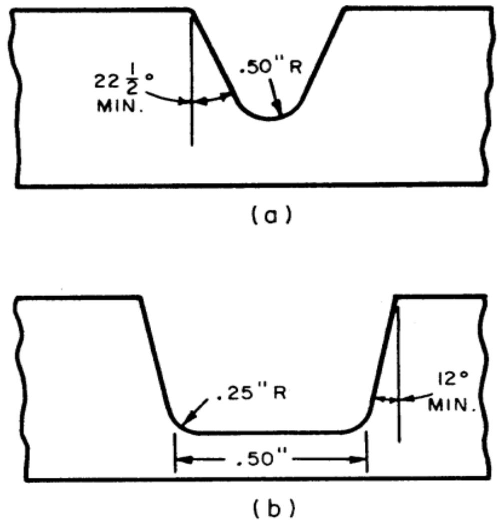



*Figure 39: Weld Preparations for partial penetration welds: (a) for minimum root width, (b) for bottom cavity greater than 1/2" [51].*

## Production Welding

When quality details extend entirely through a casting, it is best to turn it over and lay one or more sealing passes from the root side of the production weld. If this cannot be done, a backing should be used wherever possible. Backings can be made from refractory materials available in the foundry, such as firebrick, silica brick, mullite brick, magnesite, or carbon plates. These should be thoroughly dried, because water vapor produced during welding may cause cold cracking at the joint. Metals, such as copper, plain-carbon steel, or stainless steel may also be used as backing material. Ordinarily, the backup material merely acts as a dam and is not bonded to the weld metal. Such is the case with refractories and copper. Backings forming integral parts of the castings should generally have the same composition. Where pickup of backing metal is not wanted, it is possible to cover the backings with washes of refractory materials, but contamination should be avoided.

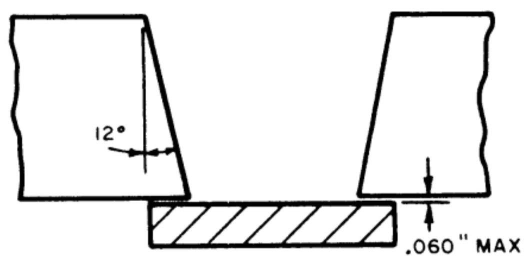



*Figure 40 Weld preparation for full penetration welds [51].*

To prepare a casting properly for production welding, the weld preparation must be inspected with a suitable nondestructive examination technique prior to welding. The inspection is intended to verify complete removal of unacceptable indications, although this may be difficult because the method of removing the indication may smear the metal across a crack. Normally, a visual inspection followed by a liquid penetrant or magnetic particle inspection are performed. ASTM steel casting specifications contain requirements concerning the weld preparation inspection and the degree of inspection required prior to welding.

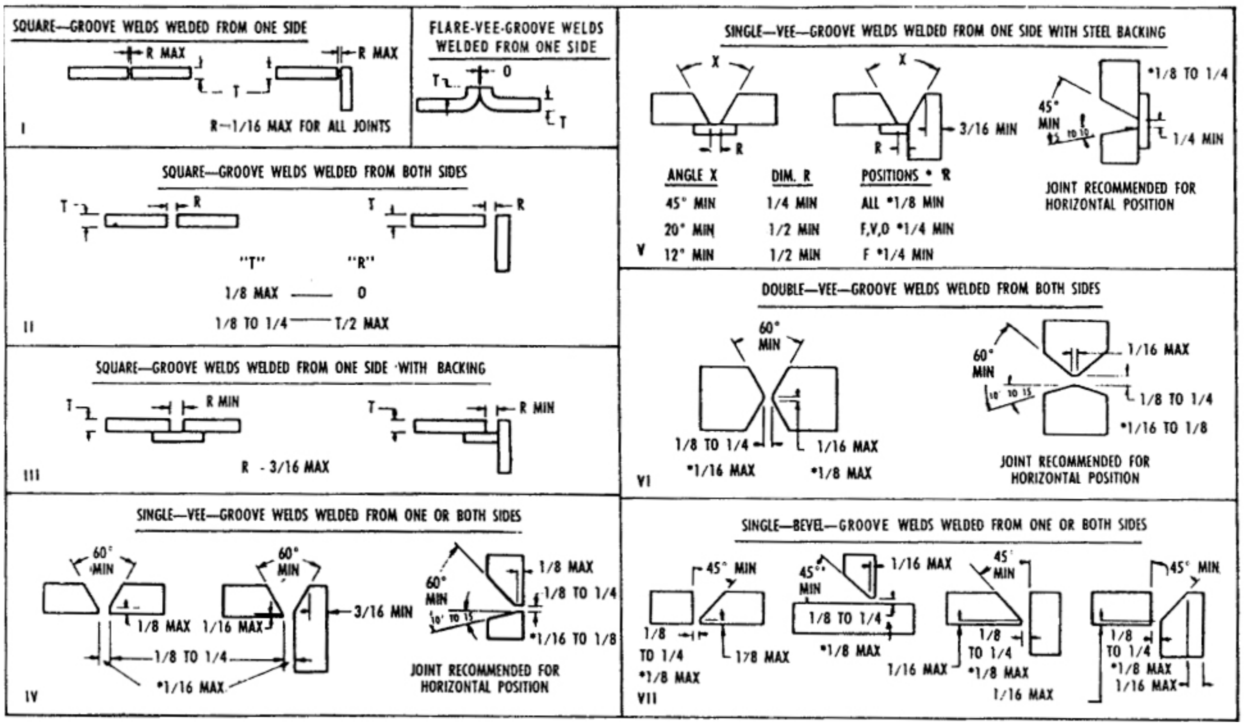



*Figure 41 Recommended proportions of grooves for shielded metal-arc, gas tungsten-arc, gas metal-arc, flux-cored arc, and gas welding (except pressure gas welding). Note: Dimensions marked * are exceptions that apply specifically to designs for gas metal-arc welding. [59]*

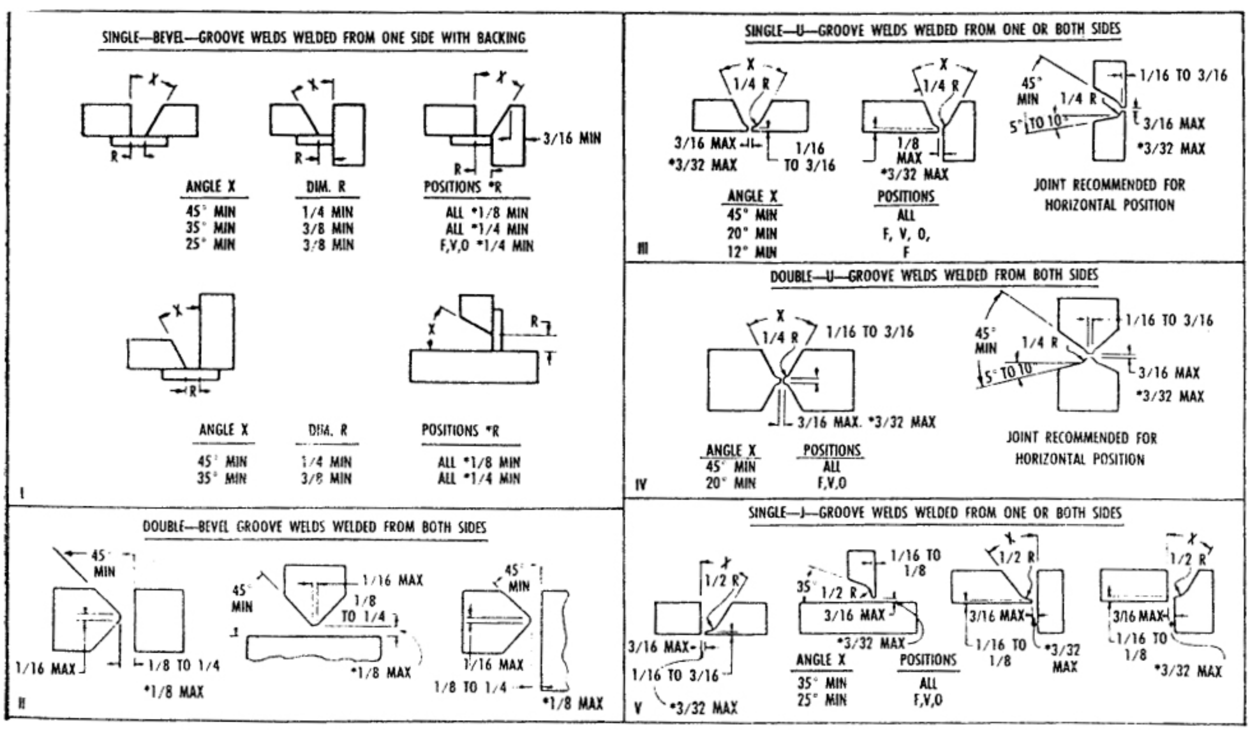



*Figure 42 Recommended proportions of grooves for shielded metal-arc, gas tungsten-arc, gas metal-arc, flux-cored arc, and gas welding (except pressure gas welding). Note Dimensions marked * are exceptions that apply specifically to designs for gas metal-arc welding. [59]*

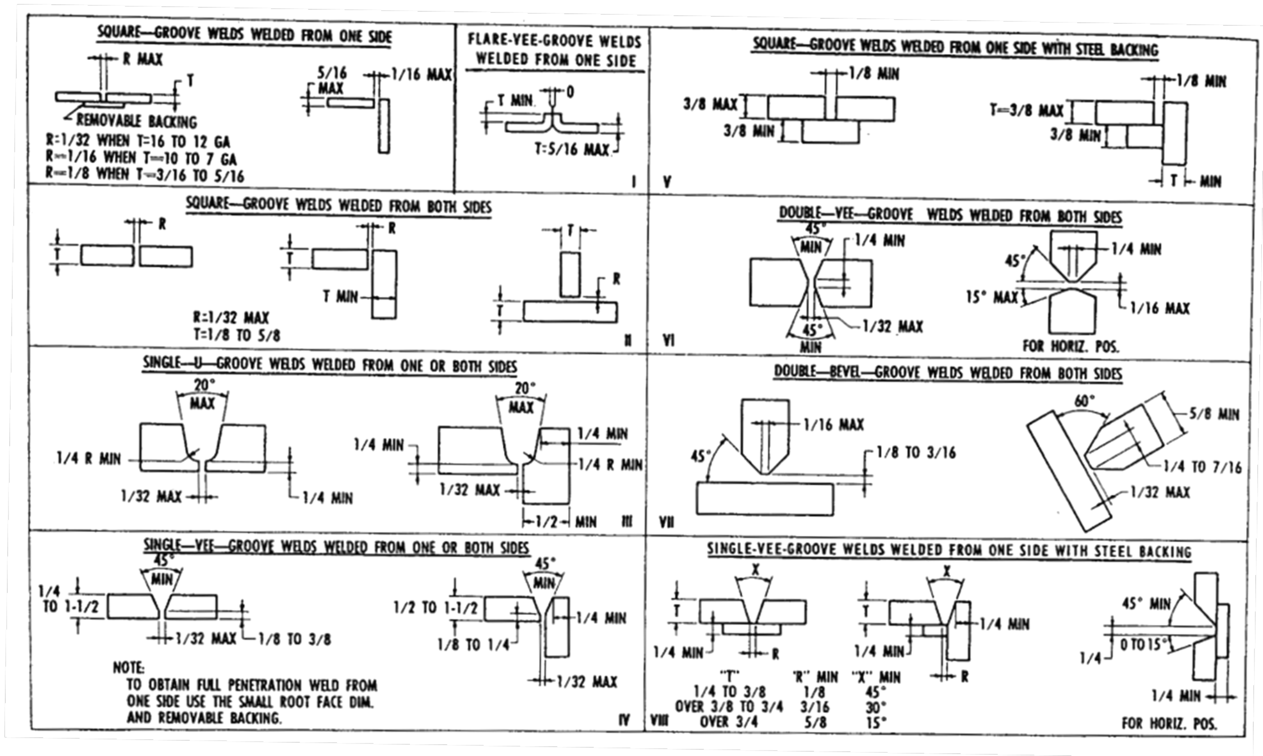



*Figure 43 Recommended proportions of grooves for submerged arc welding of steel [59].*

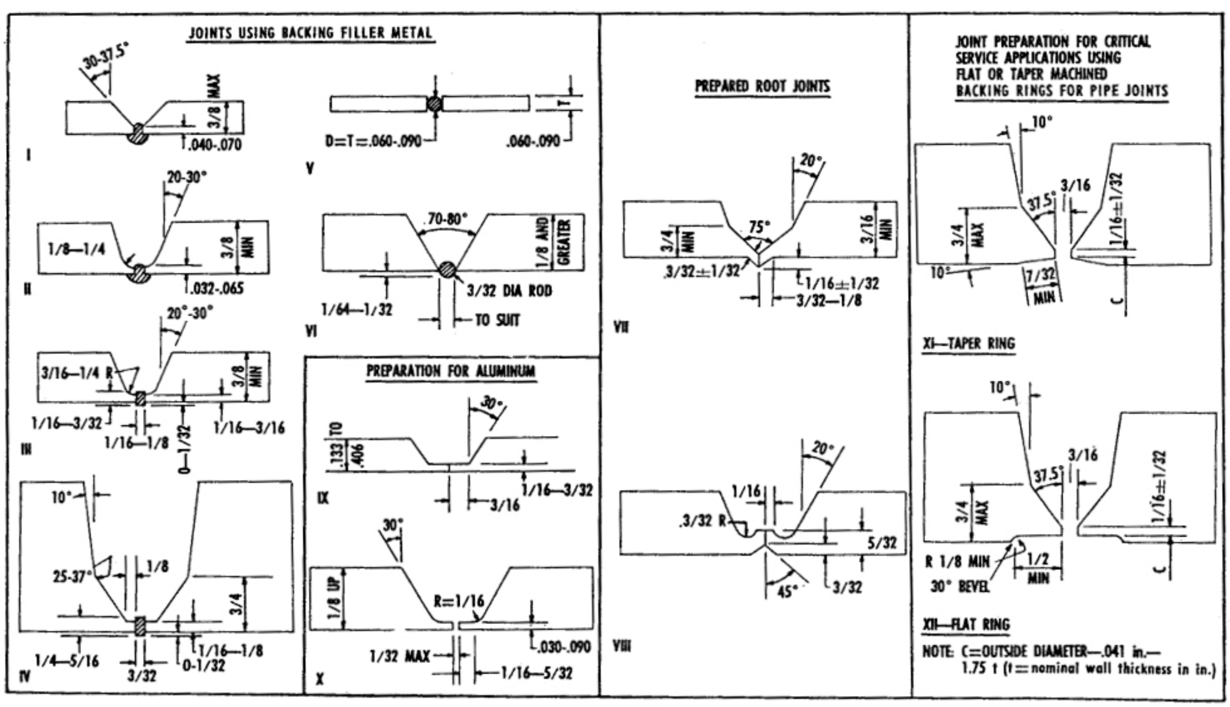



*Figure 44 Recommended proportions of grooves for metal-arc welding processes used to obtain controlled and complete penetration. Note: For steel except as noted [59].*

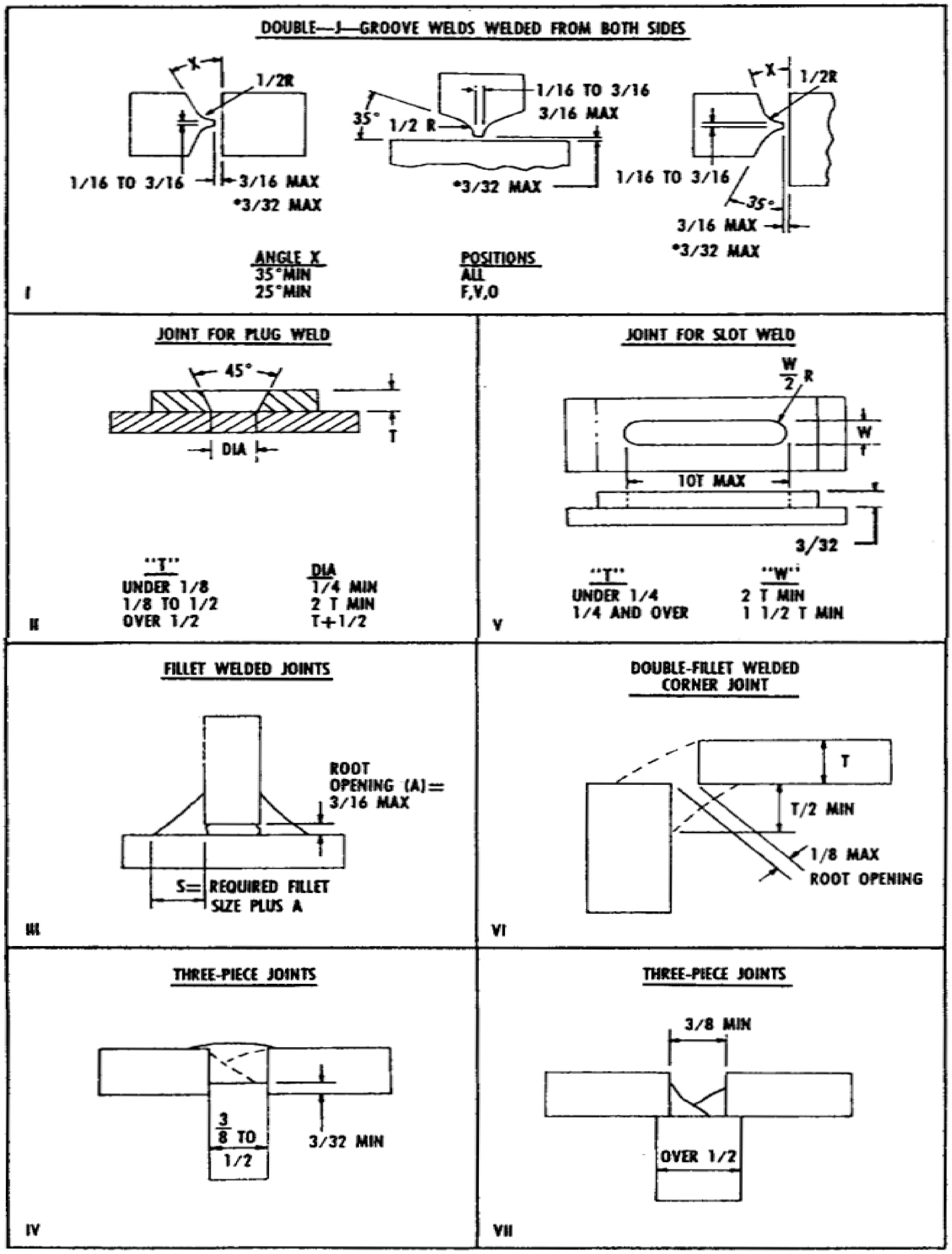



*Figure 45 Recommended proportions of grooves for shielded metal-arc, gas metal-arc, gas tungsten-arc, flux-cored arc, and gas welding (except pressure gas welding). Note: Dimensions marked * are exceptions that apply specifically to gas metal-arc welding [59].*

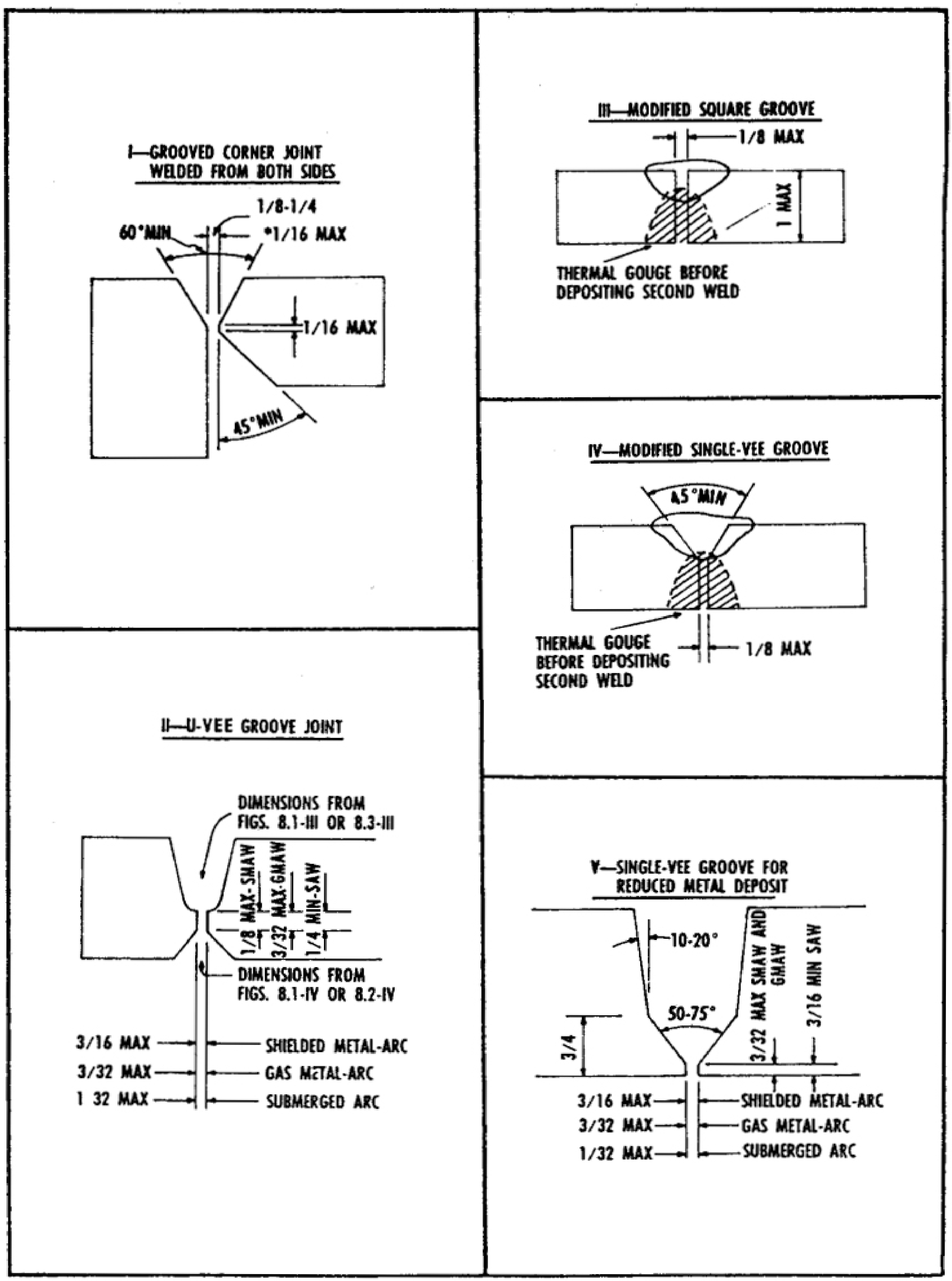
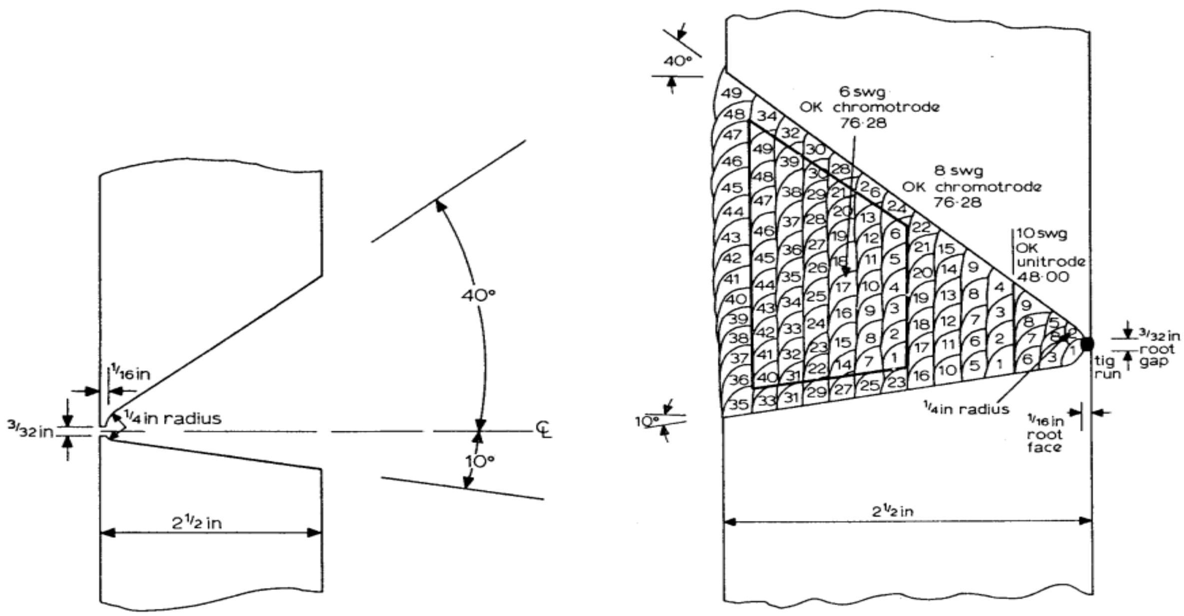



*Figure 46 Recommended proportions of mixed grooves for metal-arc welding processes [59].*

Sometimes two or more quality details may be located so close together that one is not detected during inspection. After the known indications are removed, the production weld may penetrate through the sound metal between the indications to expose the undetected indication. When this occurs, welding should be stopped until the entire potentially non-conforming area can be removed [51].

## Fabrication Welding

Horizontal position welding is employed more widely in cast-weld fabrications because the large sizes and awkward shapes make manipulation difficult. The weld preparation shown in Figure 47a has been utilized successfully for this type of position with the smaller casting located on top and no movement of the assembly during welding. In this case the gas tungsten-arc welding process was used to deposit the root pass of each butt weld. The use of backing strips is avoided in this manner. A typical welding sequence for this weld (which was also employed as a ASME Section IX welder qualification test) is illustrated in Figure 47b.




a. Horizontal-vertical butt welding profile.

b. Cross-section of a typical welding sequence (also employed as welder qualification test).

*Figure 47 Horizontal Weld Groove and Welding Sequence Used in Cast-Weld Fabrication in the Horizontal Welding Position [50]*

Joining of parts in cast-weld fabrication follows standard welding methods. The weld area should be free from problematic indications; when required, chipping, grinding, or arc or flame-gouging are used. The standard smooth tapering of the sides of the weld toward the bottom of the groove is required for all except special welding procedures such as electroslag. Sharp inside corners and narrow grooves are apt to produce cracks, slag inclusions, or lack of penetration. Joining of thin and thick sections should be avoided, and weld seams should be located away from corners.

Grooves of the required shape are generally cast at the edges of parts to be joined to avoid the cost of removing the metal. The castings are also produced with matching contours and assembly location points to facilitate correct positioning of mating parts.

## Preheat

Arc welding involves the application of a high intensity short duration localized source of heat to the casting. This results in rapidly cooled weld metal and rapid heating and cooling of the surrounding base metal. These thermal effects can lead to cracking during welding (hot cracking) or after welding (cold cracking), a high hardness weld and heat affected zone with a correspondingly detrimental effect on mechanical properties, residual stresses, and distortion of the part being welded. Preheat minimizes these undesirable effects by reducing the thermal gradient between the molten weld metal and cooler base metal, and by lowering the cooling rate. In addition, preheat provides more time for hydrogen to diffuse from the weld zone, and it reduces the moisture content on the surface of the base metal, which is a source of hydrogen absorption into the weld. Hydrogen levels must be controlled when welding crack-sensitive metals to prevent hydrogen embrittlement.

Preheating can be accomplished by two general methods: furnace preheating, which involves heating the entire casting; and local preheating, which utilizes torches or induction heaters to heat a localized area surrounding the weld joint. The availability of furnaces, casting size, and ability to maintain preheat upon removal of the casting from the furnace are a few items that should be considered when deciding on the method of applying preheat. It should be stated, however, that furnace preheating is preferable since it minimizes localized stresses and provides more reliable insurance that the required preheat temperature is attained.

Reference [60] contains suggested minimum preheat temperatures for carbon steel and low alloy steel casting materials and is highly recommended to complement this report. Excerpts are presented in Table 39. Table 39 lists the welding procedures for carbon and low alloy steels of AISI, SAE, and API grades and the cast carbon and low alloy steels complying with the following ASTM Specifications A27-77, A148-73, A216-75, A217-75, A352-76, A356-75, A486-74, A487-76, A389-74, and A643-75. Many wrought steels are also listed in the tables of Reference [49]. An index of the types of steels for which the welding procedure is listed precedes the table of procedures. The steels discussed are limited to 0.5% maximum carbon and 5.0% maximum alloy of any given alloy except the stainless chromium and 8.5% nickel steel grades. It is possible that special steels may be cast that are not listed on one of the casting specifications. However, nearly all compositions are listed in the wrought grade lists and the welding procedure can be obtained from the wrought steel of that composition. The welding procedures are limited to thicknesses of a minimum of 0.25 to a maximum of 4”, or the maximum thickness of the specification if this is lower. The welding procedures for each grade include suggested preheat and inter-pass temperatures, post-weld heat treatment, and peening where required. Preheat and inter-pass temperatures are listed for welding with low hydrogen and other types of electrodes. The preheat and inter-pass temperatures for the low hydrogen grades are normally lower because of the reduced cracking propensity. Post-weld heat treatments are suggested in three categories: optional, desirable, or required. When post weld heat treatments are used, the weld metal should contain no more than 0.05% vanadium to avoid embrittlement.

The suggested preheat temperature depends on the properties of the casting and weld metal and on the size and shape of the casting. Some general rules exist for selecting the correct preheat temperature. In the first place, it should be as low as practically possible, because, with increasing temperature, it is more difficult to lay a weld bead without undercut, and protection for the welding operator becomes a problem. While the use of the minimum preheating temperature is desirable for the above reasons, a temperature of 50-100°F above the minimum will seldom do any harm. Other sources of welding procedures are available [61], but Reference [60] is the most complete.

The chemical composition of the casting is a major factor in selecting preheat. Steels low in carbon and alloy contents do not tend to quench harden excessively nor to form cold cracks. They require either no preheat or much less preheat than needed for a high-carbon, high-alloy castings. This reasoning also applies to the deposited weld metal, particularly in multi-pass welds.

Thickness and shape of the casting also must be considered. Thicker castings have greater heat-absorbing capacities, and therefore, in effect, greater quenching powers. As a rule, the thicker the casting (provided it needs preheat at all), the higher the preheat should be. Simple shapes with fairly uniform cross sections will cool uniformly and require a minimum of preheat. Complex castings consisting of alternating thin and thick sections will cool more rapidly in the thin sections, which may lead to severe internal stresses. In such a case, a higher preheat should be used than for castings with a more uniform shape. Also, such castings should be protected from drafts during welding and cooled slowly.

Another factor influencing the selection of a preheating temperature is the size of the unacceptable indication in relation to the thickness of the casting. A small weld cools more rapidly than a large one. Thus, tack welding on a crack-sensitive steel can be a dangerous procedure and casting failures have resulted from cracks started from a tack weld made without preheat.

To obtain correct preheat temperatures, furnaces with accurate controls can be used with thermocouples attached to the casting for measuring preheat temperature. Temperature-sensitive crayons are normally used with local preheating methods. These crayons leave a mark that melts when the part reaches the required temperature.

## Inter-pass Temperature

The inter-pass temperature, i.e., the temperature between passes in multi-pass welds, should be considered along with preheat. To maintain the desirable conditions developed by preheat, the inter-pass temperature should never be below the preheat temperature. The inter-pass temperature can safely exceed the preheat temperature by 100-200°F, depending on the particular casting, and frequently does. The inter-pass temperature should not be allowed to go so high that the side walls of the weld groove will be severely undercut. Reference [60] contains suggested inter-pass temperatures for carbon and low alloy cast steels.

*Table 39 Summary of Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications [60]*

| Suggested Welding Conditions | | | | | | |
|---|---|---|---|---|---|---|
| | | | Minimum Preheat and Interpass Temperature, °F | | | |
| Steel Specification | For Carbon Range, % (Note 1) | For Thickness Range, Inch (Note 2) | Low Hydrogen | Other than Low Hydrogen | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
| ASTM A27-73 Mild to medium strength carbon steel castings for general application | Up to 0.25, Incl. (Total residual alloys less than 0.50%) | Up to 1, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 300°F | Desirable 1100/1250 | Yes |
| | 0.26-0.30, Incl. (Total residual alloys less than 0.50%) | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | 0.31-0.35, Incl. (Total Residual alloys less than 0.50%) | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 300°F | Desirable 1100/1250 | Yes |
| | Up to 0.25, Incl. (Total residual alloys between 0.50 and | Up to 1, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | 0.26-0.30, Incl. (Total residual alloys between 0.50 and 1.00%) | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 300°F | Desirable 1100/1250 | Yes |
| | 0.31-0.35, Incl. (Total residual alloys between 0.50 and 1.00%) | Up to 1/2, Incl. | 100°F | 300°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F | 400°F | Desirable 1100/1250 | Yes |
| | Notes:<br>1. If total Mn+Si+Cu+Ni+Cr+Mo exceeds 2.0%, compare analysis to nearest matching AISI specifications for selecting welding conditions.<br>2. Thickness refers to that at point of welding. | | | | | |
| | | | | | | |
| ASTM A148-73 High-strength steel castings for structural purposes | Compare analysis to nearest macthing AISI specifications for selecting welding conditions. | | | | | |
| | Notes:<br>1. Thickness measured at point of welding.<br>2. Specification limits defect depths which may be repair welded without consent of purchaser and requires stress relief or other heat-treatment after welding | | | | | |
| 1% Cr - 1% Mo-V ASTM A356-75 A389-74 A405-70 (1976) | Up to 0.15, Incl. | Up to 1/2, Incl. | 150°F | 300°F | Required 1150/1350 | |
| | | Over 1/2 to 1, Incl. | 200°F | 350°F | Required 1150/1350 | |
| | | Over 1 to 4, Incl. | 300°F | 450°F | Required 1150/1350 | Yes |
| | 0.16-0.20, Incl. | Up to 1/2, Incl. | 300°F | 350°F | Required 1150/1350 | |
| | | Over 1/2 to 1, Incl. | 400°F | 450°F | Required 1150/1350 | |
| | | Over 1 to 4, Incl. | 500°F | 550°F | Required 1150/1350 | Yes |
| | Notes:<br>1. Post-weld heat-treatment of these grades of steel should be done with caution.<br>2. Use chromium-molybdenum electrodes where compatible high-temperature properties are required in weld metal. | | | | | |

**Suggested Welding Conditions**

| Steel Specification | For Carbon Range, % | For Thickness Range, Inch | Minimum Preheat and Interpass Temperature, °F: Low Hydrogen | Minimum Preheat and Interpass Temperature, °F: Other than Low Hydrogen | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
|---|---|---|---|---|---|---|
| ASTM A216-75 Carbon Steel Casting Suitable For Fusion Welding for High Temperature Service | For Total Residual Alloys Less Than 0.50% | | | | | |
| | Up to 0.20, Incl | Up to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 200°F | Desirable 1100/1250 | Yes |
| | 0.21-0.25, Incl. | Up to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| ASTM A660-76 Centrifugally Cast Carbon Steel Pipe For High Temperature Service | 0.26-0.30, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 400°F | Desirable 1100/1250 | Yes |
| | For Total Residual Alloys Over 0.50% | | | | | |
| | Up to 0.30. Incl. | Up to 2, Incl. | 100°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 400°F | Desirable 1100/1250 | Yes |
| | Notes:<br>1. Thickness refers to that at point of welding.<br>2. For welding and post-weld heat-treatment requirements for boilers or pressure vessels fabricated from this material, refer to appropriate section of ASME Boiler & Pressure Vessel Code. | | | | | |
| ASTM A217-75 Alloy Steel Castings for Pressure Containing Parts Suitble for High-Temperature Service | WC1 Up to 0.20, Incl. | Up to 2, Incl. | 100°F | 300°F | Required 1150/1350 | |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Required 1150/1350 | Yes |
| | WC1 0.21-0.25, Incl. | Up to 2, Incl. | 200°F | 300°F | Required 1150/1350 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 400°F | Required 1150/1350 | Yes |
| | WC4 Up to 0.20, Incl. | Up to 1/2, Incl. | 200°F | 300°F | Required 1150/1350 | |
| | | Over 1/2 to 1, Incl. | 300°F | 350°F | Required 1150/1350 | |
| | | Over 1 to 4, Incl. | 400°F | 450°F | Required 1150/1350 | Yes |
| | WC6 Up to 0.15, Incl. | Up to 1/2, Incl. | 100°F | 300°F | Required 1150/1350 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Required 1150/1350 | |
| | | Over 1 to 4, Incl. | 300°F | 400°F | Required 1150/1350 | Yes |
| | WC6 0.16-0.20, Incl. | Up to 1/2, Incl. | 300°F | 350°F | Required 1150/1350 | |
| | | Over 1/2 to 1, Incl. | 300°F | 350°F | Required 1150/1350 | |
| | | Over 1 to 4, Incl. | 400°F | 450°F | Required 1150/1350 | Yes |
| | WC5 Up to 0.15, Incl. | Up to 1/2, Incl. | 200°F | 300°F | Required 1150/1350 | |
| | | Over 1/2 to 1, Incl. | 300°F | 350°F | Required 1150/1350 | Yes |
| | | Over 1 to 4, Incl. | 400°F | 450°F | Required 1150/1350 | Yes |
| | WC5 0.16-0.20, Incl. | Up to 1/2, Incl. | 300°F | 350°F | Required 1150/1350 | Yes |
| | | Over 1/2 to 1, Incl. | 400°F | 450°F | Required 1150/1350 | Yes |
| | | Over 1 to 4, Incl. | 500°F | 550°F | Required 1150/1350 | Yes |
| | WC9 Up to 0.15, Incl. | Up to 4, Incl. | 500°F | 550°F | Required 1150/1350 | Yes |
| | WC9 0.15-0.18, Incl. | Up to 4, Incl. | 600°F | 650°F | Required 1150/1350 | Yes |
| | C5 Up to 0.20, Incl. | Up to 4, Incl. | Note 2 | Not Available | Transfer Directly to Post-Weld Heat-Treatment at 1350/1400 | Yes |
| | C12 Up to 0.20, Incl. | Up to 4, Incl. | Note 2 | Not Available | Transfer Directly to Post-Weld Heat-Treatment at 1350/1400 | Yes |
| | Notes:<br>1. Thickness refers to that at point of welding.<br>2. Use electrodes of compatible composition where compatible high-temperature properties are required in weld metal.<br>3. For welding and post-weld heat-treatment requirements for boilers or pressure vessels fabricated from this material, refer to appropriate section of ASME Boiler & Pressure Vessel Code. | | | | | |

| Suggested Welding Conditions | | | | | | |
|---|---|---|---|---|---|---|
| | | | Minimum Preheat and Interpass Temperature, °F | | | |
| **Steel Specification** | **For Carbon Range, %** | **For Thickness Range, Inch** | **Low Hydrogen** | **Other than Low Hydrogen** | **Post-Weld Heat-Treatment Range, °F** | **Peening May Be Necessary** |
| ASTM A352-76 Ferritic Steel Castings for Pressure Containing Parts Suitable for Low Temperature Service | LCA, LCB, LCC Up to 0.25, Incl. | Up to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1150/1250 | |
| | | Over 1 to 2, Incl. | 50°F | 100°F | Optional 1150/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 200°F | Desirable 1150/1250 | Yes |
| | LCB 0.26-0.30, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1150/1250 | |
| | | Over 1/2 to 1, Incl. | 50°F | 100°F | Optional 1150/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Desirable 1150/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Desirable 1150/1250 | Yes |
| ASTM A356-75 Heavy-Walled Carbon and Low Alloy Steel Castings for Steam Turbines | Grade 1 Up to 0.25, Incl. | Up to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1150/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1150/1250 | |
| | | Over 2 to 4, Incl. | 150°F | 250°F | Desirable 1150/1250 | Yes |
| | Grade 1 0.26-0.30, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1150/1250 | |
| | | Over 1/2 to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Desirable 1150/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Desirable 1150/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Desirable 1150/1250 | Yes |
| | Grade 1 0.31-0.35, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1150/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 200°F | Desirable 1150/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Desirable 1150/1250 | Yes |
| | | Over 2 to 4, Incl. | 250°F | 350°F | Desirable 1150/1250 | Yes |
| | Note:<br>1. Grades 2 thru 10 included in this specification are carbon-molybdenum or chromium-molybdenum graes. Welding recommendations for those grades given elsewhere in the table. | | | | | |
| ASTM A486-74 Steel Castings for Highway Service (Note 2) | Up to 0.20, Incl. | Up to 2, Incl. | Ambient, Above 10°F | 200°F | Optional 1150/1250 | Yes Over 1 in. |
| | | Over 2 to 4, Incl. | 100°F | 300°F | Optional 1150/1250 | Yes |
| | 0.21-0.25, Incl. | Up to 1, Incl. | 100°F | 300°F | Optional 1150/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Optional 1150/1250 | Yes |
| | | Over 2 to 4, Incl. | 250°F | 350°F | Optional 1150/1250 | Yes |
| | 0.26-0.30, Incl. | Up to 1/2, Incl. | 100°F | 300°F | Optional 1150/1250 | |
| | | Over 1/2 to 1, Incl. | 150°F | 300°F | Optional 1150/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 350°F | Optional 1150/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 400°F | Desirable 1150/1250 | Yes |
| | 0.31-0.35, Incl. | Up to 1/2, Incl. | 100°F | 300°F | Optional 1150/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 350°F | Desirable 1150/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 400°F | Desirable 1150/1250 | Yes |
| | | Over 2 to 4, Incl. | 350°F | 450°F | Desirable 1150/1250 | Yes |
| | Notes:<br>1. Thickness refers to that at point of welding.<br>2. Welding conditions shown apply to Class 70 material. Class 90 and Class 120 material are low-alloy grades and welding conditions are dependent on chemical composition. Consult casting producer for welding recommenations or compare composition to nearest matching AISI specification for selecting welding conditions. | | | | | |

**Suggested Welding Conditions**

| Steel Specification | For Carbon Range, % | For Thickness Range, Inch | Minimum Preheat and Interpass Temperature, °F | | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
|---|---|---|---|---|---|---|
| | | | Low Hydrogen | Other than Low Hydrogen | | |
| ASTM A487-76 Steel castings suitable for pressure service | 1N up to 0.20, Incl. (1Q - Use temperatures shown in parenthesis when given) (Note 1) | Up to 1, Incl. | Ambient, Above 10°F | 100°F (Ambient, Above 10°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 200°F (100°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F (100°F) | 300°F (200°F) | Desirable 1100/1250 | Yes |
| | 1N 0.21-0.25, Incl. (1Q - Use temperatures shown in parenthesis when given)(Note 1) | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F (Ambient, Above 10°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | Ambient, Above 10°F | 200°F (100°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F (Ambient, Above 10°F) | 300°F (200°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 250°F (150°F) | 350°F (250°F) | Desirable 1100/1250 | Yes |
| | 1N 0.26-0.30, Incl. (1Q Use temperatures shown in parenthesis when given) (Note 1) | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F (100°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F (Ambient, Above 10°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F (100°F) | 300°F (200°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F (200°F) | 400°F (300°F) | Desirable 1100/1250 | Yes |
| | 2N up to 0.20, Incl. (2Q - Use temperatures shown in parenthesis when given) | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F (Ambient, Above 10°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | Ambient, Above 10°F | 200°F (100°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F (Ambient, Above 10°F) | 300°F (200°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F (100°F) | 350°F (250°F) | Desirable 1100/1250 | Yes |
| | 2N 0.21-0.25, Incl. (2Q - Use temperatures shown in parenthesis when given) | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F (100°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F (Ambient, Above 10°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F (100°F) | 300°F (200°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F (200°F) | 400°F (300°F) | Desirable 1100/1250 | Yes |
| | 2N 0.26-0.30, Incl. (2Q - Use temperatures shown in parenthesis when given) | Up to 1/2, Incl. | 100°F (Ambient, Above 10°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F (100°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F (200°F) | 350°F (250°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F (300°F) | 450°F (350°F) | Desirable 1100/1250 | Yes |
| | 4N, 6N, 9N, 10N, Up to 0.20, Incl. (4Q, 4QA, 6Q, 9Q, 10Q - Use temperatures shown in parenthesis when given) | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F (100°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F (Ambient, Above 10°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F (100°F) | 300°F (200°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F (200°F) | 400°F (300°F) | Desirable 1100/1250 | Yes |
| | 4N, 6N, 9N, 10N, 0.21-0.25, Incl. (4Q, 4QA, 6Q, 9Q, 10Q - Use temperatures shown in parenthesis) | Up to 1/2, Incl. | 100°F (Ambient, Above 10°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F (100°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F (200°F) | 350°F (250°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F (300°F) | 450°F (350°F) | Desirable 1100/1250 | Yes |
| | 4N, 6N, 9N, 10N, 0.26-0.30, Incl. (4Q, 4QA, 6Q, 9Q, 10Q - Use temperatures shown in parenthesis) | Up to 1/2, Incl. | 200°F (100°F) | 300°F (200°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 300°F (200°F) | 350°F (250°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 400°F (300°F) | 450°F (350°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 500°F (400°F) | 550°F (450°F) | Desirable 1100/1250 | Yes |
| | 4N, 6N, 9N, 10N, 0.31-0.38, Incl. (4Q, 4QA, 6Q, 9Q, 10Q - Use temperatures shown in parenthesis) | Up to 1/2, Incl. | 300°F (200°F) | 350°F (250°F) | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 400°F (300°F) | 450°F (350°F) | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 500°F (400°F) | 550°F (450°F) | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 600°F (500°F) | 650°F (550°F) | Desirable 1100/1250 | Yes |
| | 7Q | Up to 1, Incl. | 100°F | Not Recommended | Optional 1050/1100 | |
| | | Over 1 to 2, Incl. | 150°F | Not Recommended | Optional 1050/1100 | Yes |
| | | Over 2 to 4, Incl. | 200°F | Not Recommended | Optional 1050/1100 | Yes |

| Suggested Welding Conditions | | | | | | |
|---|---|---|---|---|---|---|
| **Steel Specification** | **For Carbon Range, %** | **For Thickness Range, Inch (Note 1)** | **Minimum Preheat and Interpass Temperature, °F** | | **Post-Weld Heat-Treatment Range, °F (Note 2)** | **Peening May Be Necessary** |
| | | | **Low Hydrogen** | **Other than Low Hydrogen** | | |
| ASTM A487-76 Steel Castings suitable for pressure service (cont'd.) | 8N Up to 0.15, Incl. (8Q - Use temperatures shown in parenthesis) | Up to 4, Incl. | 400°F (300°F) | 450°F (350°F) | Desirable 1300/1400 | Yes Over 1 Inch |
| | 8N 0.16-0.20, Incl. (8Q - Use temperatures shown in parenthesis) | Up to 4, Incl. | 500°F (400°F) | 550°F (450°F) | Desirable 1300/1400 | Yes Over 1 Inch |
| | Notes:<br>1. Post-weld heat-treatment of these grades of steel should be done with caution.<br>2. For welding and post-weld heat-treatment requirements for pressure vessels fabricated from certain grades of this steel refer to appropriate section of ASME Boiler and Pressure Vessel Code. | | | | | |
| | | | | | | |
| ASTM A643-75 Steel castings, heavy walled, carbon and alloy for pressure vessels | Grade A Up to 0.20, Incl. | Up to 2, Incl. | 100°F | 250°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | Grade A 0.21-0.25, Incl. | Up to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 400°F | Desirable 1100/1250 | Yes |
| | Grade B Up to 0.20, Incl. | Up to 2, Incl. | 300°F | 450°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F | 500°F | Desirable 1100/1250 | Yes |
| | Grade B 0.21-0.25, Incl. | Up to 2, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F | 500°F | Desirable 1100/1250 | Yes |
| | Grade D Up to 0.20, Incl. | Up to 2, Incl. | 150°F | Not Recommended | Desirable 1100/1150 | Yes |
| | | Over 2 to 4, Incl. | 300°F | Not Recommended | Desirable 1100/1150 | Yes |
| | Grade C of this specification is a Chromium-Molybdenum steel. Welding recommendations are, therefore, given with the Chromium-Molybdenum (2-1/4Cr-1Mo) steels given elsewhere in this table. | | | | | |
| | Notes:<br>1. Minimum specification thickness 2 inches.<br>2. For welding and post-weld heat-treatment requirements for pressure vessels fabricated from this material, refer to appropriate section of ASTM Boiler and Pressure Vessel Code. | | | | | |

**Suggested Welding Conditions**

| Steel Designation | For Carbon Range, % | For Thickness Range, Inch | Minimum Preheat and Interpass Temperature, °F | | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
|---|---|---|---|---|---|---|
| | | | Low Hydrogen | Other than Low Hydrogen | | |
| AISI-SAE 1010 1011 1012 1013 | Within Specification | Up to 2, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 150°F | Optional 1100/1250 | Yes |
| AISI-SAE 1015 1016 | Within Specification | Up to 2, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 200°F | Optional 1100/1250 | Yes |
| AISI-SAE 1017 1018 1019 | Within Specification | Up to 2, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 150°F | Optional 1100/1250 | Yes |
| AISI-SAE 1020 1021 1022 1023 | Within Specification | Up to 2, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Optional 1100/1250 | Yes |
| AISI-SAE 1024 1027 | 0.18-0.25, Incl. | Up to 1, Incl. | Ambient, Above 10°F | 100°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Optional 1100/1250 | Yes |
| | 0.25-0.29, Incl. | Up to 1/2, Incl. | 50°F | 150°F | Optional 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 150°F | 300°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 300°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 300°F | 350°F | Optional 1100/1250 | Yes |
| AISI-SAE 1025 1026 | Within Specification | Up to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 100°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 200°F | Optional 1100/1250 | Yes |
| AISI-SAE 1029 1030 | 0.25-0.30, Incl. | Up to 1, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | 0.31-0.34, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 250°F | 350°F | Desirable 1100/1250 | Yes |
| AISI-SAE 1035 1037 | Within Specification | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 400°F | Desirable 1100/1250 | Yes |
| AISI-SAE 1036 1041 | 0.30-0.35, Incl. | Up to 1/2, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 150°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | 0.36-0.40, Incl. | Up to 1/2, Incl. | 150°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 350°F | 400°F | Desirable 1100/1250 | Yes |
| | 0.41-0.44, Incl. | Up to 1/2, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 300°F | 350°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 350°F | 400°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |

**Suggested Welding Conditions**

| Steel Designations | For Carbon Range, % | For Thickness Range, Inch | Minimum Preheat and Interpass Temperature, °F: Low Hydrogen | Minimum Preheat and Interpass Temperature, °F: Other than Low Hydrogen | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
|---|---|---|---|---|---|---|
| AISI-SAE 1038 1039 1040 | 0.34-0.40, Incl. | Up to 1/2, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 400°F | Desirable 1100/1250 | Yes |
| | 0.41-0.44, Incl. | Up to 1/2, Incl. | 150°F | 250°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |
| AISI-SAE 1042 1043 | Within Specification | Up to 1/2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 1/2 to 1, Incl. | 250°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 1 to 2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |
| AISI-SAE 1044 1045 1046 | Within Specification | Up to 1/2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | | Over 1/2 to 4, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |
| AISI-SAE 1048 1049 1050 1052 1053 | 0.43-0.50, Incl. | Up to 1/2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | | Over 1/2 to 4, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |
| AISI-SAE 1108 1109 1110 | Within Specification | Up to 2, Incl. | Ambient, Above 10°F | Not Recommended | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | Not Recommended | Optional 1100/1250 | Yes |
| AISI-SAE 1116 1117 1118 1119 | Within Specification | Up to 1, Incl. | Ambient, Above 10°F | Not Recommended | Optional 1100/1250 | |
| | | Over 1 to 4, Incl. | 200°F | Not Recommended | Optional 1100/1250 | Yes |
| AISI-SAE 1132 1137 1139 1140 1141 1144 1145 1146 1151 | 0.27-0.30, Incl. | Up to 1/2, Incl. | 50°F | Not Recommended | Optional 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | Not Recommended | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 250°F | Not Recommended | Desirable 1100/1250 | Yes |
| | 0.31-0.35, Incl. | Up to 1/2, Incl. | 100°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 150°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | Not Recommended | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | Not Recommended | Desirable 1100/1250 | Yes |
| | 0.36-0.40, Incl. | Up to 1/2, Incl. | 150°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1 to 4, Incl. | 300°F | Not Recommended | Desirable 1100/1250 | Yes |
| | 0.41-0.45, Incl. | Up to 1/2, Incl. | 200°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 300°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1 to 4, Incl. | 350°F | Not Recommended | Desirable 1100/1250 | Yes |
| | 0.45-0.50, Incl. | Up to 1/2, Incl. | 300°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 400°F | Not Recommended | Desirable 1100/1250 | |
| | | Over 1 to 4, Incl. | 450°F | Not Recommended | Desirable 1100/1250 | Yes |
| AISI-SAE 1211 1212 1213 1215 B1111 B1112 B1113 | Within Specification | Up to 2, Incl. | Ambient, Above 10°F | Not Recommended | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | Not Recommended | Optional 1100/1250 | Yes |

**Suggested Welding Conditions**

| Steel Designation | For Carbon Range, % | For Thickness Range, Inch | Minimum Preheat and Interpass Temperature, °F: Low Hydrogen | Minimum Preheat and Interpass Temperature, °F: Other than Low Hydrogen | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
|---|---|---|---|---|---|---|
| AISI-SAE 12L13 12L14 | Within Specification | Up to 2, Incl. | Ambient, Above 10°F | Not Recommended | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | Not Recommended | Optional 1100/1250 | Yes |
| | Note: Due to lead content, manufacturing operations involving elevated temperatures in the range of those encountered in gas cutting or welding should be carried out under adequate ventilation. | | | | | |
| AISI-SAE 1330 1335 1340 1345 | 0.27-0.33, Incl. | Up to 1/2, Incl. | 250°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1/2 to 1, Incl. | 300°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1 to 2, Incl. | 350°F | Not Recommended | Desirable 1025/1050 | Yes |
| | 0.33-0.38, Incl. | Up to 1/2, Incl. | 300°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1/2 to 1, Incl. | 400°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1 to 2, Incl. | 400°F | Not Recommended | Desirable 1025/1050 | Yes |
| | 0.38-0.43, Incl. | Up to 1/2, Incl. | 350°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1/2 to 1, Incl. | 450°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1 to 2, Incl. | 550°F (Note 1) | Not Recommended | Desirable 1025/1050 | Yes |
| | 0.43-0.49, Incl. | Up to 1/2, Incl. | 400°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1/2 to 1, Incl. | 500°F | Not Recommended | Desirable 1025/1050 | |
| | | Over 1 to 2, Incl. | 600°F (Note 1) | Not Recommended | Desirable 1025/1050 | Yes |
| | Note: 1. Hold at temperature for one hour after welding completed. | | | | | |
| AISI-SAE 1513 1518 1522 1525 | Up to 0.20, Incl. | Up to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 100°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 100°F | 200°F | Optional 1100/1250 | Yes |
| | 0.21-0.25, Incl. | Up to 1, Incl. | Ambient, Above 10°F | 100°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Optional 1100/1250 | Yes |
| | 0.26 to 0.29, Incl. | Up to 1/2, Incl. | 50°F | 150°F | Optional 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 150°F | 300°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 300°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 300°F | 350°F | Optional 1100/1250 | Yes |
| AISI-SAE 1524 1526 1527 | Up to 0.25, Incl. | Up to 1, Incl. | 50°F | 100°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Optional 1100/1250 | |
| | | Over 2 to 4, Incl. | 200°F | 300°F | Optional 1100/1250 | Yes |
| | 0.26-0.29, Incl. | Up to 1, Incl. | 150°F | 250°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 300°F | Desirable 1100/1250 | |
| | | Over 2 to 4, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| AISI-SAE 1536 1541 | Up to 0.35, Incl. | Up to 1/2, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 150°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 300°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | 0.36 to 0.40, Incl. | Up to 1/2, Incl. | 150°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 350°F | 400°F | Desirable 1100/1250 | Yes |
| | 0.41 to 0.44, Incl. | Up to 1/2, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 300°F | 350°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 350°F | 400°F | Desirable 1100/1250 | Yes |
| | | Over 2 to 4, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |

| Suggested Welding Conditions | | | | | | |
|---|---|---|---|---|---|---|
| | | | Minimum Preheat and Interpass Temperature, °F | | | |
| Steel Designation | For Carbon Range, % | For Thickness Range, Inch | Low Hydrogen | Other than Low Hydrogen | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
| AISI-SAE 1547 | 0.43 to 0.52, Incl. | Up to 1/2, Incl. | 300°F | 350°F | Desirable 1100/1250 | |
| | | Over 1/2 to 4, Incl. | 400°F | 450°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4012 | 0.09-0.14, Incl. | Up to 1, Incl. | Ambient, Above 10°F | Ambient, Above 10°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4023 4024 4027 4028 | 0.20-0.25, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 250°F | Desirable 1100/1250 | Yes |
| | 0.26-0.30, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 150°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 150°F | 250°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 300°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4032 | 0.30-0.35, Incl. | Up to 1/2, Incl. | 50°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 175°F | 275°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 275°F | 325°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4037 | 0.35-0.40, Incl. | Up to 1/2, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4042 | 0.40-0.45, Incl. | Up to 1/2, Incl. | 150°F | 250°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 250°F | 400°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 350°F | 500°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4047 | 0.45-0.50, Incl. | Up to 1/2, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 300°F | 500°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 400°F | 600°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4118 | 0.17-0.23, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4130 | 0.27-0.33, Incl. | Up to 1/2, Incl. | 300°F | 400°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 400°F | 500°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 450°F | 550°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4135 4137 4140 4142 4145 4147 4150 | 0.32-0.40, Incl. | Up to 1/2, Incl. | 350°F | 450°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 450°F | 550°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 500°F | 600°F (Note 1) | Desirable 1100/1250 | Yes |
| | 0.41-0.45, Incl. | Up to 1/2, Incl. | 400°F | 500°F | Desirable 1100/1250 | |
| | | Over 1/2 to 2, Incl. | 550°F | 600°F (Note 1) | Desirable 1100/1250 | Yes |
| | 0.46-0.50, Incl. | Up to 1/2, Incl. | 450°F | 550°F | Desirable 1100/1250 | |
| | | Over 1/2 to 2, Incl. | 600°F | 700°F (Note 1) | Desirable 1100/1250 | Yes |
| | Note: 1. Hold at temperature one hour after welding completed. | | | | | |
| AISI-SAE 4320 | 0.17-0.22, Incl. | Up to 1/2, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 300°F | 400°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 400°F | 500°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4340 E4340 | 0.36-0.44, Incl. | Up to 2, Incl. | 550°F | 600°F (Note 1) | Desirable 1100/1250 | Yes |
| | Note: 1. Hold at temperature one hour after welding completed. | | | | | |

**Suggested Welding Conditions**

| Steel Designation | For Carbon Range, % | For Thickness Range, Inch | Minimum Preheat and Interpass Temperature, °F | | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
|---|---|---|---|---|---|---|
| | | | Low Hydrogen | Other than Low Hydrogen | | |
| AISI-SAE 4419 4422 4427 | 0.18-0.24, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Required 1200/1350 | |
| | | Over 1/2 to 1, Incl. | 100°F | 200°F | Required 1200/1350 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Required 1200/1350 | Yes |
| | 0.25-0.29, Incl. | Up to 1/2, Incl. | 100°F | 200°F | Required 1200/1350 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Required 1200/1350 | |
| | | Over 1 to 2, Incl. | 300°F | 400°F | Required 1200/1350 | Yes |
| AISI-SAE 4615 4617 4620 | Within Specification | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 350°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4621 | 0.18-0.23, Incl. | Up to 1/2, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 400°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4718 | 0.16-0.21, Incl. | Up to 1/2, Incl. | 100°F | 300°F | Required 1150/1300 | |
| | | Over 1/2 to 2, Incl. | 250°F | 400°F | Required 1150/1300 | Yes |
| AISI-SAE 4720 | 0.17-0.22, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4815 4817 | Within Specification | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 200°F | 300°F | Desirable 1100/1250 | Yes |
| AISI-SAE 4820 | 0.18-0.23, Incl. | Up to 1/2, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 350°F | Desirable 1100/1250 | Yes |
| AISI-SAE 5015 | 0.12-0.17, Incl. | Up to 2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| AISI-SAE 5046 | 0.43-0.48, Incl. | Up to 1/2, Incl. | 300°F | 400°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 350°F | 450°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 400°F | 500°F | Desirable 1100/1250 | Yes |
| AISI-SAE 5115 | 0.13-0.18, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 2, Incl. | 100°F | 200°F | Desirable 1100/1250 | |
| AISI-SAE 5120 | 0.17-0.22, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 250°F | 300°F | Desirable 1100/1250 | Yes |
| AISI-SAE 5130 5132 | Within Specification | Up to 1/2, Incl. | 200°F | 300°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 300°F | 400°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 400°F | 500°F | Desirable 1100/1250 | Yes |
| AISI-SAE 5140 | 0.38-0.43, Incl. | Up to 1/2, Incl. | 300°F | 400°F | Desirable 1100/1250 | |
| | | Over 1/2 to 2, Incl. | 400°F | 500°F | Desirable 1100/1250 | Yes |
| AISI-SAE 5145 5147 5150 | 0.43-0.50, Incl. | Up to 1/2, Incl. | 350°F | 450°F | Desirable 1100/1250 | |
| | | Over 1/2 to 2, Incl. | 450°F | 550°F | Desirable 1100/1250 | Yes |
| AISI-SAE 6118 | 0.16-0.21, Incl. | Up to 1, Incl. | Ambient, Above 10°F | 100°F | Desirable 1100/1250 (Note 1) | |
| | | Over 1 to 2, Incl. | 100°F | 200°F | Desirable 1100/1250 (Note 1) | Yes |

Note:
1. Post-weld heat-treatment of this grade of steel should be done with caution.

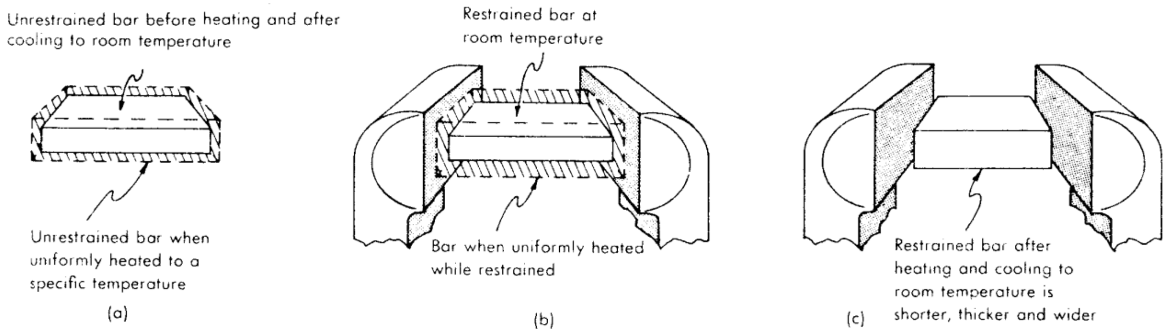
| Suggested Welding Conditions | | | | | | |
|---|---|---|---|---|---|---|
| Steel Designation | For Carbon Range, % | For Thickness Range, Inch | Minimum Preheat and Interpass Temperature, °F | | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary |
| | | | Low Hydrogen | Other than Low Hydrogen | | |
| AISI-SAE 6150 | 0.46-0.50, Incl. | Up to 1, Incl. | 300°F | 500°F | Desirable 1100/1250 (Note 1) | |
| | | Over 1 to 4, Incl. | 450°F | 600°F | Desirable 1100/1250 (Note 1) | Yes |
| | Note:<br>1. Post-weld heat-treatment of this grade of steel should be done with caution. | | | | | |
| AISI-SAE 8115 | 0.13-0.18, Incl. | Up to 2, Incl. | Ambient, Above 10°F | 200°F | Optional 1100/1250 | |
| AISI-SAE 8615 | Up to 0.20, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 150°F | Optional 1100/1250 | |
| 8617 | | Over 1/2 to 2, Incl. | 100°F | 300°F | Optional 1100/1250 | Yes |
| 8620 | 0.21-0.25, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F | Optional 1100/1250 | |
| 8622 | | Over 1/2 to 1, Incl. | 100°F | 300°F | Optional 1100/1250 | |
| 8625 | | Over 1 to 2, Incl. | 200°F | 350°F | Optional 1100/1250 | Yes |
| 8627 | 0.26-0.33, Incl. | Up to 1/2, Incl. | 200°F | 300°F | Optional 1100/1250 | |
| 8630 | | Over 1/2 to 1, Incl. | 250°F | 350°F | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 300°F | 400°F | Optional 1100/1250 | Yes |
| AISI-SAE 8637 | 0.35-0.40, Incl. | Up to 1/2, Incl. | 200°F | 400°F | Desirable 1100/1250 | |
| 8640 | | Over 1/2 to 1, Incl. | 300°F | 450°F | Desirable 1100/1250 | |
| 8642 | | Over 1 to 2, Incl. | 350°F | 500°F | Desirable 1100/1250 | Yes |
| 8645 | 0.41-0.45, Incl. | Up to 1/2, Incl. | 250°F | 450°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 350°F | 500°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 400°F | 550°F | Desirable 1100/1250 | Yes |
| | 0.45-0.48, Incl. | Up to 1/2, Incl. | 300°F | 500°F | Desirable 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 350°F | 550°F | Desirable 1100/1250 | |
| | | Over 1 to 2, Incl. | 400°F | 600°F | Desirable 1100/1250 | Yes |
| AISI-SAE 8720 | 0.18-0.23, Incl. | Up to 1/2, Incl. | Ambient, Above 10°F | 200°F | Desirable 1100/1251 | |
| | | Over 1/2 to 1, Incl. | 100°F | 300°F | Desirable 1100/1252 | |
| | | Over 1 to 2, Incl. | 200°F | 350°F | Desirable 1100/1253 | Yes |
| AISI-SAE 8742 | 0.38-0.46, Incl. | Up to 1, Incl. | 300°F | 500°F | Desirable 1100/1254 | |
| | | Over 1 to 2, Incl. | 400°F | 600°F | Desirable 1100/1255 | Yes |
| AISI-SAE 8822 | 0.20-0.25, Incl. | Up to 1/2, Incl. | 150°F | 300°F | Optional 1100/1250 | |
| | | Over 1/2 to 2, Incl. | 200°F | 400°F | Desirable 1100/1254 | Yes Over 1 inch |
| AISI-SAE E9310 | Within Specification | Up to 1/2, Incl. | Ambient, Above 10°F | Not Recommended | Optional 1100/1250 | |
| | | Over 1/2 to 1, Incl. | 100°F | Not Recommended | Optional 1100/1250 | |
| | | Over 1 to 2, Incl. | 150°F | Not Recommended | Optional 1100/1250 | Yes |

## Residual Stress, Distortion, and Restraint Problems

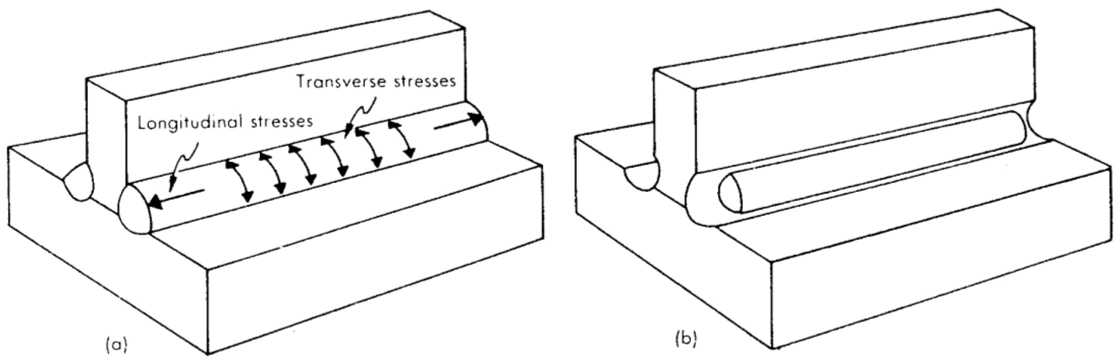
Steel castings being production welded or fabricated by welding undergo thermal and transformation stresses resulting from the welding process. These stresses produce residual tensile stresses in the weld and combined tension, compression and sometimes bending stresses in the weldment. These may result in significant distortion that can produce problems in weld fabrications. Distortion is of more concern in weld fabrication than in production welding of a casting; it has been discussed in detail in various welding texts [44] [62]. The behavior of weld metal under the restraint of the surrounding casting is illustrated in Figure 48A [62]. The resulting residual stress on a simple fillet weld is demonstrated in Figure 48B; the weld bead in this and in most other welds are in biaxial or even triaxial tension because the as-deposited weld is larger than the weld after it has solidified and cooled to room temperature. The distortion produced by welding is indicated in Figure 48C.

In production welding, the casting is usually larger than the weld and frequently surrounds the weld deposit except for the open face. Under these conditions, distortion is not great, but the residual stresses obtained can contribute to cracking in the weld or even in the surrounding metal. The more severe the restraint of the free contraction of the weld, the higher the tensile stress state in the weld. Figure 48A and B illustrate this fact. This condition makes production welds, particularly the larger welds in thick-walled castings, subject to cracking because of this restraint. Various means of lowering the stresses and cracking susceptibility are employed. The more severe the restraint, the greater the necessity for employing welding procedures that reduce the residual stresses. The various techniques used for this purpose include: higher preheating temperatures to lower thermal differences between the casting and the weld, reduced size of the deposited weld beads, the relief of stresses in a weld by the thermal effect of subsequent weld deposits, and peening the weld. The thermal stress relieving effect of subsequent weld beads and the lower stresses usually obtained with smaller weld deposits may require welding severely restrained areas with several small weld beads, as opposed to one or only a few larger weld passes to avoid cracking. The effect of different bead types and welding sequences on this thermal stress from subsequent welds is discussed in subsequent paragraphs. Peening the weld, as will be discussed in a subsequent paragraph, lowers residual tensile stresses in the weld, but cracking may occur before peening can be accomplished.

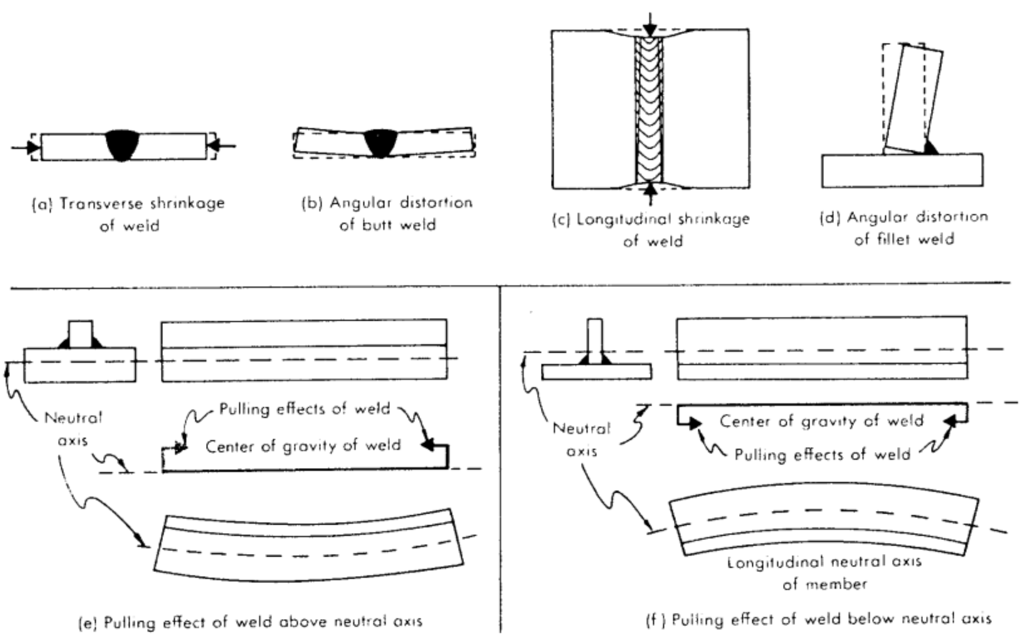
Distortion as demonstrated in Figure 48C is more of a problem in weld fabrication as employed in cast-weld construction. Various means of reducing this distortion are employed [44] [62]. These procedures are: using a minimum of weld metal, placing welds near the neutral axis, balancing stresses by balancing welds around the center of gravity, selecting a welding sequence to offset the distortion of each weld with subsequent welds, maintaining a high temperature on the steel during welding, and using various types of mechanical restraint. Peening the weld also reduces distortion [62].




A. Non Uniform Expansion and Contraction of Weld and Adjacent Base Metal.




B. Weld Metal Shrinkage Causes Longitudinal and Transverse Stresses




C. Examples of the Distortion of Various Fabrication Weldments

*Figure 48 Expansion, Contraction, Residual Stresses and Distortion in Weldments [62]*

## Residual Stress Relief

Since the residual stresses obtained by welding are additive to service stresses, the presence of the multiaxial tensile stresses in welds can lead to abrupt or fatigue failures. In addition, stress relief improves dimensional stability during machining and service and reduces susceptibility to stress corrosion cracking. For this reason, some means of relieving these stresses is desirable before the castings are placed in service. Thermal stress relieving treatments lower the hardness of the HAZ as well as stress relieving. Several means of lowering residual stresses in welded steel castings exist as listed below:

a) Thermal stress relieving treatments in the range of 1100-1150°F are employed to reduce the stress levels significantly [44]. Temperatures as high as 1250°F are required for essentially complete removal of the stresses but this low a stress level is frequently not needed, and the higher strength steels would be softened by this high a temperature.
b) Stainless steels are limited in the ability to stress relieve at these temperatures, since this can reduce the corrosion performance.
c) Other heat treatments, such as normalizing or austenitizing for quenching or tempering in the stress relief temperature range after welding, remove residual stresses.
d) Multi-pass welds are generally low in residual stresses because the latter welds thermally treat the prior welds. The effect of deposition technique on the relief of stress is discussed under a following heading.
e) Peening weld deposits converts residual tensile stresses to compressive stresses; it is used on single pass welds or the last passes of multi-pass welds for that purpose.
f) Vibratory stresses can be used to reduce residual stress levels under some limited conditions of shape, size, and capacity of the vibratory unit. This process is less costly and more rapid than thermal stress relief, but the process requires further development [63].
g) Mechanical stress relief by employing a small amount of permanent deformation across the part also is a very effective means under specific condition of shape and equipment.

## Welding Current and Heat Input

Some classes of electrodes require higher welding current for a given diameter than others. Also, larger diameter electrodes of a given class require more current than smaller ones. Increasing the current increases the welding heat input. This acts, to a lesser degree, like preheating, flattening out the temperature differential in the weld area and lowering the cooling rate. Therefore, other things being equal (which they frequently are not), the “hotter”, larger diameter electrodes should be selected for production welding.

The welding current used with different sizes of electrodes may also be varied somewhat when welding in a given position such as flat, as required by the weld being produced. It usually must be varied for welding in other positions, e.g., vertical, or overhead. Manufacturers usually print the recommended current ranges for their electrodes on the containers. These ranges tend to be fairly wide and will vary somewhat even for electrodes of the same class. The higher current is for down-hand welding under favorable conditions. Those on the lower side are for situations where careful control of the weld metal is needed, such as in vertical or overhead welding, or where the preheat is high. Experienced welders can select the proper current. A tendency exists to use higher current to increase productivity; however, poor quality welds may result. While higher welding currents obviously increase the rate and temperature of welding, only a relatively small variation is allowed for making a good weld with a given size and type of electrode in each position.

## Deposition Technique

Weld beads can be deposited in the cavity or fabrication groove by several techniques. The optimum procedure depends on the size of the groove, the thickness of the casting section, the properties of the casting and weld metal, and the position in which the weld is to be made. It is possible in some cases to position the required casting or fabrication, so that welding is conducted in the flat or down-hand position. Two basic factors that must be considered in selecting the proper deposition technique are the speed of welding and the volume of the weld. These two factors may be varied to help control welding heat effects. For a given size of weld bead, the higher the welding speed, the more rapid the cooling rate. This increases the under-bead hardness and tendency for under-bead cracking. On the other hand, it reduces the tendency to distortion by minimizing the volume of heat-affected base metal. When preheating is used, the welding speed is not as important – provided a sound, well-contoured bead is laid.

The effects of volume of the weld are like those of speed; a small weld produces effects similar to those with high speed, because, again, the cooling rate of the weld zone is relatively fast. Conversely, a large volume of weld metal deposited in a single pass results in considerably more heat in the weld zone. This results in a slower rate of cooling in the zone but higher shrinkage stresses. Unless the shrinkage stresses are sufficiently high to cause cracking in the weld metal or base metal, they are of no particular importance in casting production welding because the castings will usually be at least stress relieved after welding.

The two main types of weld beads are the stringer and weave beads. The stringer bead is laid in a continuous pass in one direction as shown in Figure 49. The weave bead also progresses in one direction but has a side-to-side motion. Many patterns of weave bead are employed including simple ones such as illustrated in Figure 50 and others that form figure eights, ellipses, etc. A modification of the weaving technique which can be used with many of the weave patterns is whipping, as illustrated in Figure 51. This is used to control the molten weld pool by removing the arc heat, while still maintaining the arc.

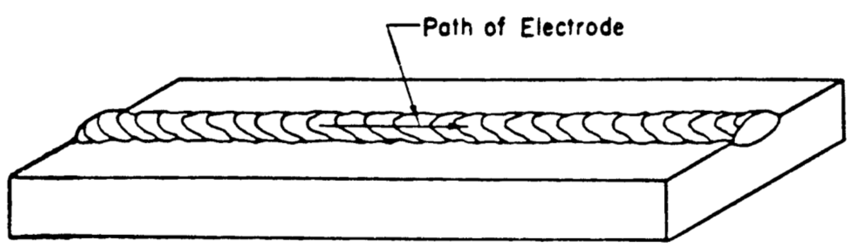



*Figure 49 String Bead Deposit*

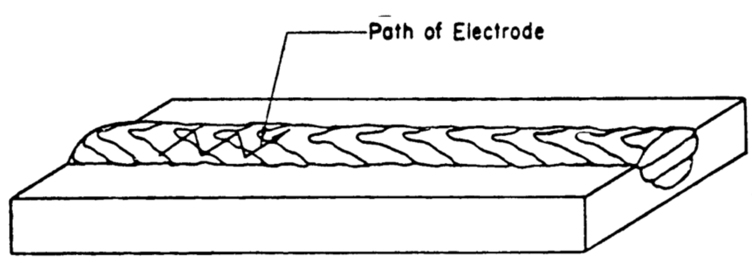



*Figure 50 Weave Bead Deposit*

Stringer and weave beads are used in single layers when the groove can be filled in a single pass. Where the groove is too deep or too wide to be filled in one pass, multiple layers are used. These may be laid with either stringer or weave beads, or a combination of the two. Nearly all production welds in castings can be made with string or weave beads laid from start to finish in single or multiple layers. The width of weaving is limited to 2.5 times the diameter of the coated electrode.

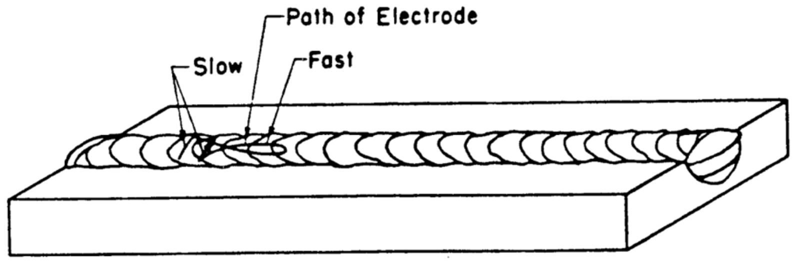


*Figure 51 Weave Bead Deposit with Whipping*

Still another way of controlling the welding heat effects by deposition technique is the welding sequence. This can be varied even in single-layer welds. The most common sequence for single-layer welds is simple string or weave beads laid in one direction. These are started at one end of the weld and continued to the other. Where the weld is long, several electrodes may be used. In this case, the beads are laid one after the other in the same direction. In long welds where it may be desirable to minimize longitudinal and transverse weld shrinkage effects, the backstep method can be used. In this procedure, short weld beads are deposited in the sequence shown in Figure 52. The first weld bead is deposited starting 2 to 4 inches inward from the edge of the part to be welded. Then, the next bead is deposited starting 2 to 4 inches further inward from the edge of the first weld. Succeeding weld beads are deposited in a similar manner, taking care to overlap the beginning of the previous bead.

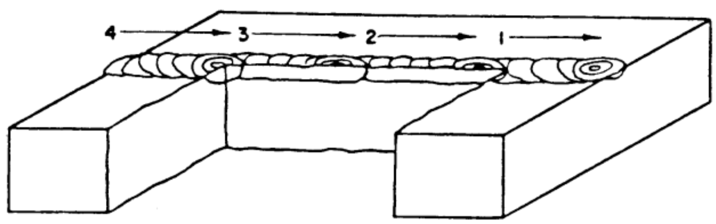


*Figure 52 Backstep Welding Sequence*

In multiple-layer welding, a greater variety of sequences may be used. String or weave beads laid in one direction are most commonly employed. The backstep sequence (Figure 52) can be utilized either as string beads or weave beads. Two other sequences designed primarily to minimize shrinkage in large groove welds are the block sequence and the cascade sequence. In the block sequence, the weld is built up by intermittent blocks which are subsequently joined by other blocks after the first group is completed, as illustrated in Figure 53. The chief benefit of the block sequence is to minimize longitudinal weld stresses. It does not have much effect on transverse shrinkage, except that the stresses in the lower passes are relieved by the welding heat from succeeding passes. The cascade sequence reduces both transverse and longitudinal shrinkage stresses as the weld progresses, particularly when employed with a weaving bead. The sequence is shown in Figure 54. By using the cascade sequence, the heat from the first half of any bead will temper, or stress relieve, the last half of the bead immediately before it. The net result is that all bead segments of the first pass are stress relieved by the next succeeding increment so that no major stresses can remain. Both methods require more welding time than ordinary multilayer welds. They should not be used, except where the greater reduction of stress warrants it. Preheating would largely eliminate the need for such special techniques.

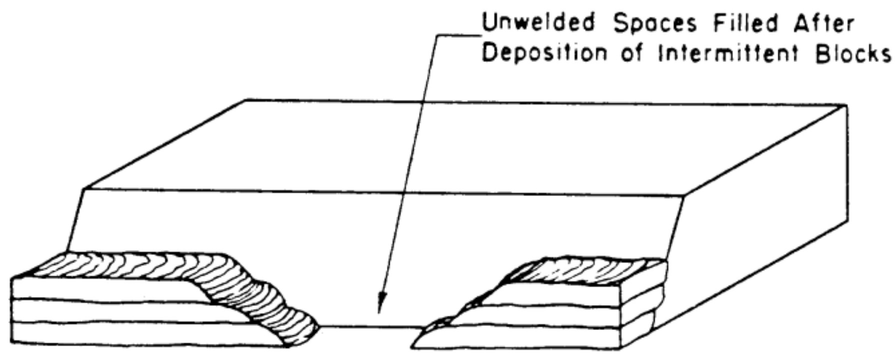



*Figure 53 Block Welding Sequence*

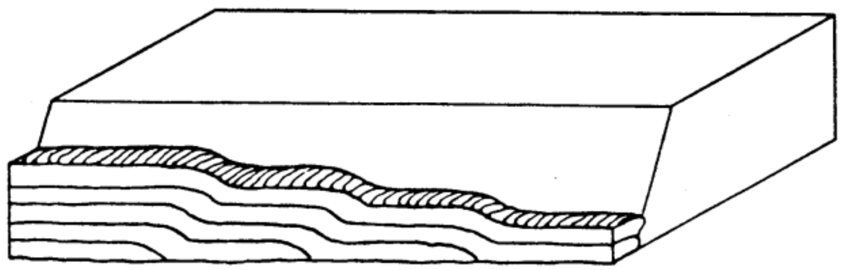


*Figure 54 Cascade Welding Sequence*

For multilayer welding of large grooves, any one of the deposition techniques discussed can be used. Sometimes, as a matter of convenience, it is simplest to run one bead in one direction and the next bead in the opposite direction. In general, the simplest procedure is to build up the weld in horizontal layers, such as illustrated in Figure 55. It has been claimed that the least stress is produced when the weld can be built up in spiral layers around the side, as shown in Figure 56.

Earlier in this section, the use of backings was discussed. In general, the presence of a backing does not markedly change the required deposition technique. However, particular care must be taken in laying the root passes. Where a backing is to become a part of the assembly, it is very important to obtain full penetration into the backing. Where a

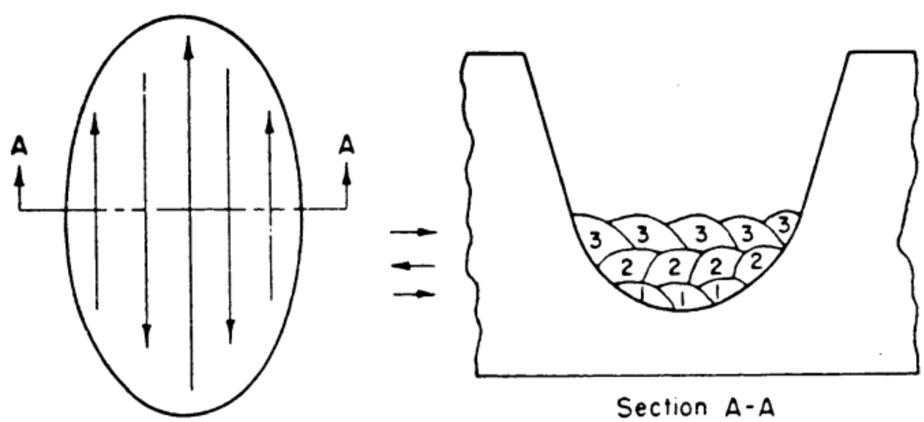



*Figure 55 Horizontal-weld layer deposition*

temporary backing of either ceramic or ceramic-washed metal is used, particular care should be taken to insure good fusion between the root pass and the side walls of the groove. If lack of fusion exists between the root pass and the side walls, the unfused sections will act as stress raisers and increase the possibility of cracking.

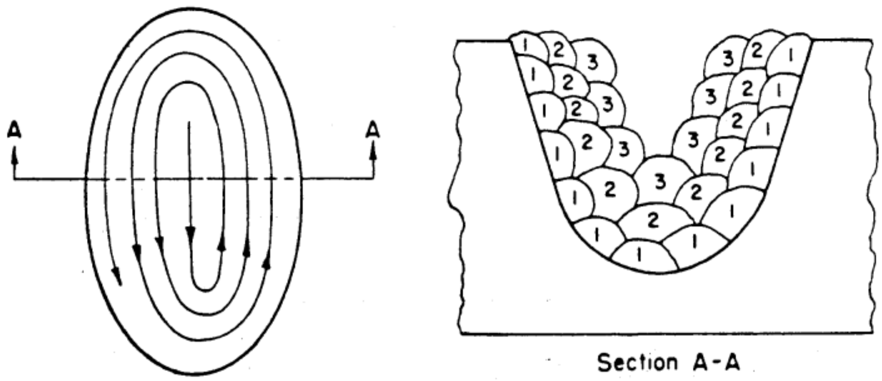



*Figure 56 Spiral-weld layer deposition*

Arc length is also an important consideration in weld deposition. Ordinarily, a good welder automatically holds a proper, or "normal" arc length. For the low-hydrogen type electrodes, the arc required for depositing high-quality weld metal is shorter than for other classes of electrodes. This important difference may be overlooked even by good welders, whose experience has been with the other classes of electrodes. The use of flux cored arc welding and gas-shielded metal-arc welding requires some dexterity and experience on the part of the operator. However, the arc length is determined by the equipment and the skill is no greater than that required for manual welding. The additional heat from the processes compared to shielded metal arc welding may require more shielding for the operator.

## Peening

Distortion can be minimized by peening the weld. Heavy peening after each pass will reduce distortion by offsetting the tensile stresses in the weld, thus counter-balancing its natural shrinkage. For castings thick enough to resist distortion, deep peening provides a mechanical stress relief. However, peening must be carefully controlled, because over-peening causes weld-metal cracking and is, therefore, worse than not peening at all. The permissible amount of peening is somewhat dependent on the mass of the casting. Heavier peening forces are required for heavier castings. Reference [60] indicates the conditions when peening may be necessary. Where severe distortion during welding may occur, for example, in filling a relatively large groove in a thin rangy casting, peening may be helpful in minimizing distortion. For castings which are to be at least stress relieved after welding, peening is not generally used. Peening and slag removal can be combined into one operation. Peening can significantly improve the fatigue life as seen in Figure 15 and Figure 16 earlier in this report.

## Post-Weld Heat Treatment

Post weld heat treatment, PWHT, reduces residual stresses and, provided the PWHT temperature is sufficiently high, it can increase the strength of the weld or lower the hardness and improve the toughness of the weld metal and heat affected zone. The various types of PWHT normally used are: stress relief (discussed earlier in Section 4. Electrodes and Fluxes), temper, normalize and temper, or quench and temper. Casting material specifications usually specify the PWHT required after production welding of castings. Reference [60] contains suggested PWHT temperature for carbon and low alloy cast steels. In general, PWHT of low carbon steels is intended to reduce the residual stresses rather than temper the weld metal or heat affected zone. PWHT for the hardenable low alloy steels is intended to improve toughness and ductility, in addition to reducing residual stresses.

The great majority of castings can be cooled to room temperature in still air after welding, but those of higher alloy content, which are more sensitive to cracking, should be cooled gradually from the welding temperature. This is primarily to provide greater insurance against cold cracking. Such retarded cooling may be accomplished in a furnace or oven, by heating with a flame or by burying the casting in some insulating material. However, since crack-sensitive steels require preheating as well, one of the best practices is to put the castings back in the preheating furnace as soon as they are welded.

Many castings are heat treated with their regular final heat treatment, such as normalizing or quenching and tempering after welding. Either of these treatments will eliminate the heat-affected zone and make the stress-relieving unnecessary. Though normalizing or quenching and tempering generally improves the base metal, they may reduce the weld metal properties, unless proper electrodes are chosen as discussed in Section 4. Electrodes and Fluxes.

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