WELDING THE HY STEELS

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This report is the third cooperative publication of ASTM and DMIC. The first was the ASTM Data Series Publication, "The Elevated-Temperature Properties of Selected Superalloys", DS 7-S1, issued in July, 1968. The Second, "Compilation of Chemical Compositions and Rupture Strengths of Superalloys", DS 9E, was issued in October, 1970.

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R. W. Flax, R. E. Keith, and M. D. Randall*

SUMMARY

The principal advantages of the HY-steels are their good combination of strength and toughness over a wide temperature range and their good weldability in heavy sections with little preheat and no postweld heat treatment. This class of steels includes Ni-Cr-Mo steels designated HY-80 and HY-100 and a Ni-Cr-Mo-V steel tentatively designated HY-130. They are low-carbon steels that achieve their strength and toughness through a quenching and tempering heat treatment.

The following welding processes and their proper application to the Hy-steels are discussed: (1) shielded metal-arc welding, (2) submerged-arc welding, (3) gas metal-arc welding, (4) Narrow-Gap welding, (5) gas tungsten-arc welding, (6) plasma arc welding, and (7) electron beam welding.

HY-80 and HY-100 have 80,000 psi and 100,000 psi minimum yield strengths respectively, and very similar chemical compositions. In general, these alloys are considered highly weldable, and their as-welded properties are very good when proper welding procedures are used. HY-130 is a higher alloy quenched-and-tempered steel having a minimum yield strength of 130,000 psi. Development of filler materials for joining HY-130 has been hampered by the difficulty of obtaining the combination of high toughness and high strength required in the as-welded condition.

Heat-affected-zone microcracking and weld- and base-metal delayed cracking have been problems in welding HY-80 and HY-100. These can, however, be controlled by proper melting and processing of the base materials during production and by exercising proper precautions during welding. HY-130 has shown sensitivity to weld-metal contamination by carbon, sulfur, phosphorus, hydrogen, oxygen, and nitrogen.

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INTRODUCTION

This report was prepared in response to a request from the Working Panel on Metals, Subgroup P on Materials, of The Technical Cooperation Program, and covers the metallurgical characteristics and mechanical properties of the HY-80, HY-100, and HY-130 steels and weldments made from these steels as presented in the open literature and in reports on Government-sponsored research. The emphasis is placed on base-metal weldability and mechanical properties of weldments. This report combined with DMIC Report 229[1] provides a comprehensive study of the weldability of steels ranging in yield strength from 80,000 psi to over 300,000 psi.

The principal advantages of the HY materials are their good combination of strength and toughness and their good weldability in heavy thicknesses with little preheat and no postweld heat treatment. The good weldability was designed into these materials during their development, and suitable filler metals and welding procedures were developed concurrently. These materials are presently being used by the U. S. Navy for submersibles and have industrial applications in pressure vessels.

The objectives of this report are to summarize the properties and weldability of HY-80, HY-100, and HY-130 steels, to review recent developments in welding each of these materials, and to point out major areas for future study.

GENERAL CONSIDERATIONS IN WELDING HY-80, HY-100, and HY-130 STEELS

The discussion in this section applies to the joining of all of the HY steels. Specific process requirements and weld-joint properties of the individual HY-steels are discussed in later sections of the report.

Welding Processes Used For the HY Steels

The purpose of this section is to discuss the basic arc welding processes and their applicability for joining the HY steels. The proper application of the following fusion welding processes is discussed: (1) shielded metal-arc welding (SMA) (covered electrode welding), (2) submerged-arc welding, (3) gas metal-arc (GMA) welding, (4) Narrow-Gap welding, (5) gas tungsten-arc (GTA) welding, (6) plasma arc welding, and (7) electron beam welding.

Shielded Metal-Arc Welding

More commonly known as "covered electrode" welding, the SMA welding process is the oldest of the fusion welding processes applicable to welding the HY steels. The electrode consists of a solid core wire covered with an extruded layer of flux. This flux covering, which may account for as much as half of the total weight of the electrode, is the important factor in the process as its composition controls such things as arc atmosphere, arc stability, weld-metal composition, fluxing and protection of the molten metal, type of welding current, properties of the slag produced, bead contour, and welding position. The elements of covered-electrode welding are shown in Figure 1.

For welding the HY steels, the electrode coverings should be of the "low hydrogen" type. These electrodes may be recognized by the inclusion of the digits 15, 16, or 18 in typical designations, such as E-XX18-M*. Covered electrodes are available under industrial specifications such as American Welding Society specification A5.5 and government specfications such as MIL-E-22200.

* The numbers preceding the electrode-covering designation (15, 16, or 18) relate to the tensile strength of the weld metal; for example, an E-9018 electrode will deposit weld metal having a 90,000-psi minimum tensile strength.

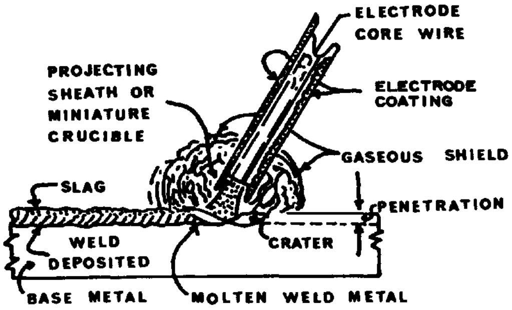


FIGURE 1. ELEMENTS OF COVERED ELECTRODE (SMA) WELDING.[2]

The E-XX15 electrodes, which are used on d-c reverse polarity (DCRP), are generally called low-hydrogen sodium type because sodium silicate is used as the binder in the flux. The E-XX16 electrodes are similar to the E-XX15 type, but potassium silicate is used as a binder. This modification makes it possible to use the electrodes on ac as well as DCRP. About 30 percent iron powder is added to the E-XX18 electrodes. This addition improves the deposition efficiency and also gives a quieter arc with low spatter. E-XX18 electrodes are usable on either ac or d-c straight polority (DCSP).

The chief difference between ordinary electrodes, such as the E-XX10 electrode, and the low-hydrogen type is that materials containing hydrogen in any form are either minimized or eliminated from the flux covering. While the protective atmosphere for an E-XX10 electrode is obtained from the burning of cellulose, the desired CO_2 atmosphere for an E-XX18 electrode is obtained by additions of inorganic materials, such as calcium carbonate, to the flux covering. Sodium silicate and potassium silicate are used as binders in low-hydrogen electrodes but the amounts are kept to a minimum because of their hygroscopic properties. While electrodes, such as E-XX10, can contain from 3 to 7 percent water, low-hydrogen electrodes for the HY steels generally have a specified maximum water content of 0.2 percent.

Care of Electrodes. Packaging and storage of low-hydrogen electrodes are very important. Hermetically sealed containers are used to preserve the low moisture content that existed at the time of manufacture. These electrodes should be stored at about 100 F at not greater than 50 percent relative humidity. Once the original container has been opened, the electrodes must be stored at approximately 400 F to avoid moisture pickup from the atmosphere. If storage conditions have been unsatisfactory, then it is necessary to recondition the electrodes before use in order to insure satisfactory joints. Recommended reconditioning procedures for low-hydrogen electrodes generally consist of heating in the range of 650 to 800 F for 1/2 to 2 hours. Specific procedures for reconditioning electrodes may be obtained from electrode manufacturers or applicable electrode specifications. If the electrodes have been exposed so that a great deal of moisture may have been absorbed, they should be held at 200 F for 2 hours prior to the high-temperature baking.

Welding Techniques. In all cases, the arc should be kept as short as possible. Lengthening of the arc may result in weld porosity. This is particularly noticeable if a whipping or weaving technique is used such that the electrode is lifted away from the puddle at the edges of the weld. A good general rule is to use a drag technique or hold a 1/8-inch or less arc.

Arc starting is also very important. The arc and puddle do not have the full protection of the electrode coating at the instant of starting, and porosity can result. A proven and recommended starting procedure is to strike the arc an inch or so ahead and then rapidly back-step to the desired starting spot. In this way, the small amount of metal deposited during the start will be remelted as welding progresses and cleansed of any gas or impurities.

A stringer-bead technique should be used. The use of a wide weave will slow down the progression of welding and, thus, will increase the heat input to the workpiece with subsequent degradation of the properties in the heat-affected zone.

Interpass cleaning is important. Slag, scale, etc., must be completely removed from previous beads before welding can continue.

A problem of toe cracking in fillet welds of high-strength materials is sometimes encountered when high-strength filler materials are used. This is due to the highly restrained nature of a fillet weld and the stresses that develop during cooling. Since fillet welds are usually lower stressed than butt joints, it may be possible to use a lower strength, more ductile filler metal than would ordinarily be selected for the particular steel.

Submerged-Arc Welding

The essential elements of the submerged-arc welding process are an automatically fed, continuous electrode wire, a separate granular flux or welding composition, and a suitable source of welding power.

The flux may be preplaced over the prepared weld joint, but usually it is delivered to the area just ahead of the welding electrode. The arc is initiated between the electrode and the workpiece and is protected from the atmosphere by the flux blanket. A quantity of the flux, melted by the heat from the welding arc, enters into a reaction with the weld puddle. This reaction results in a cleansing action and also may be used to add certain alloying constituents to the weld metal. The main features of the submerged-arc process are shown in Figure 2.

The flux acts as a very efficient insulator and, thus, does not allow the rapid dissipation of the heat of the arc. Therefore, relatively high welding speeds and deep penetration result. As a rule, the amount of the flux that is fused during welding is approximately the same as the weight of the electrode deposited.

The proper weld-metal chemical composition may be obtained in submerged-arc welding by using either a mild-steel wire with an alloyed flux or an alloyed wire with a neutral flux. If an alloy flux is used, the efficiency of alloy transfer from flux to the weld deposit will vary with the arc voltage. Therefore, welding conditions must be controlled very closely in order to obtain the desired weld properties when using the alloy flux.

Gas Metal-Arc Welding

Gas metal-arc (GMA) welding is a process that produces fusion by heating with an electric arc between a consumable spooled-wire electrode and the work. The arc and weld puddle are shielded from the atmosphere by a gas. The shielding gas protects the molten weld metal from oxidation or contamination by the surrounding atmosphere. The process was formerly known as metal inert-gas (MIG) welding. The elements of the equipment used in the process are shown in Figure 3.

GMA welding is generally performed with d-c reverse polarity (DCRP), i.e., the positive terminal of the d-c power supply is attached to the electrode or torch. Direct-current straight polarity (electrode negative, DCSP) results in a relatively unstable globular transfer having quite shallow penetration.

The GMA welding process was first used only in the "spray transfer" mode. The process proved much more versatile with the development of the short-circuiting and pulsed-current transfer modes.

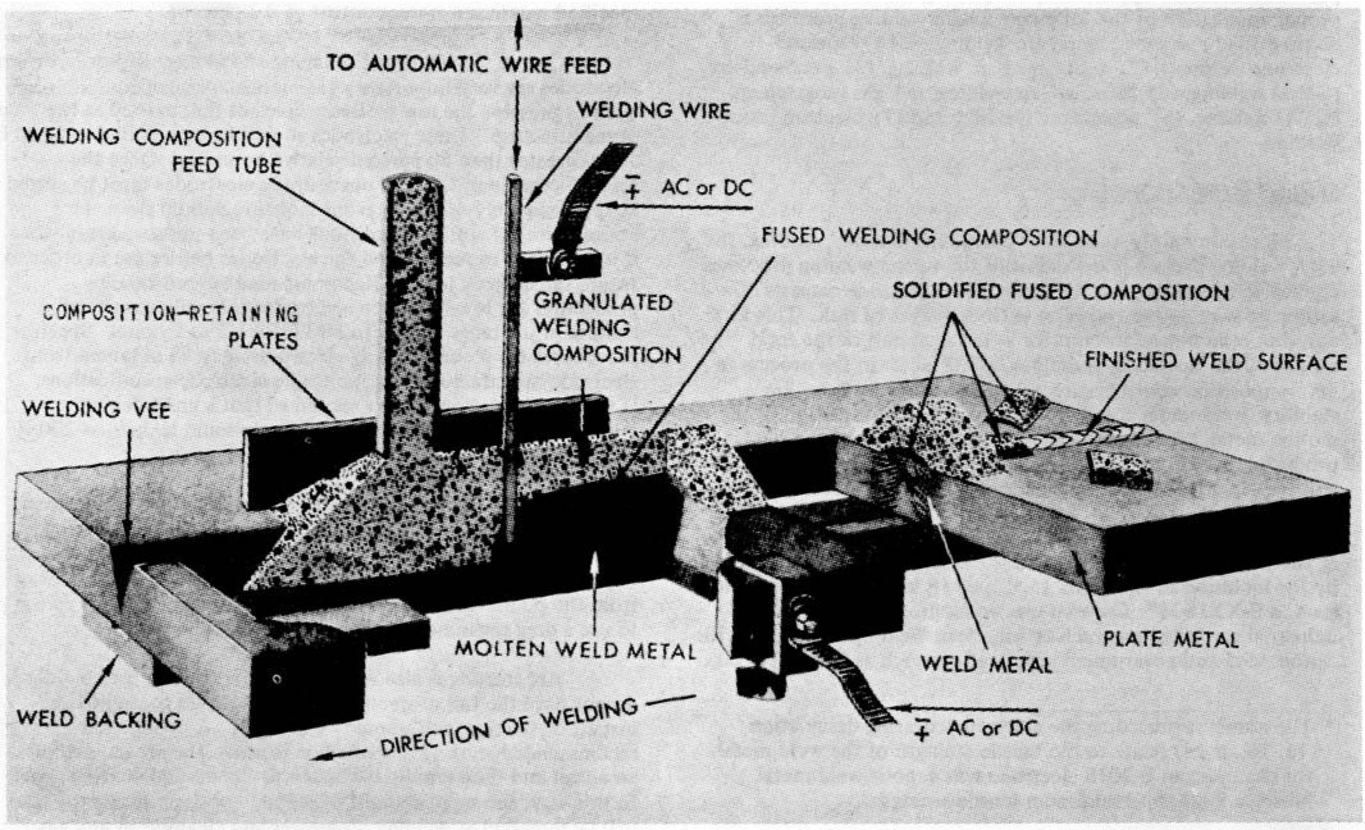


FIGURE 2. ELEMENTS OF THE SUBMERGED-ARC PROCESS.(2)

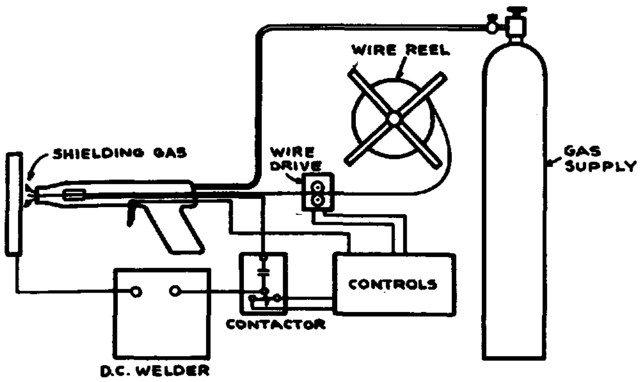


FIGURE 3. ELEMENTS OF THE GAS METAL-ARC (GMA) PROCESS.(2)

Spray Transfer. Spray-transfer welding in predominantly argon or helium shielding gases for a given wire size can only occur above a certain transition current. Above this current the molten filler wire is projected smoothly across the arc in small droplets. Below this current the continuous spray is not possible and metal transfer occurs as large globules. Transition currents in a shielding gas mixture of argon-5 oxygen (95 Ar-5 O_2) for various diameters of steel filler wires are shown in Table 1. While a spray arc can be achieved at these current values, it is common to exceed them by 50 to 75 amperes in order to obtain a practical welding condition. Arc voltages in spray-transfer welding are generally in excess of 25 volts. The spray-mode of metal transfer results in a hot, fluid puddle which, for steel, can be used only in the flat position or for horizontal fillets. This restriction limited the use of the GMA process somewhat until the short-circuiting mode of transfer was developed.

Short-Circuiting Transfer. In the short-circuiting-transfer mode, the metal transfer occurs during a short-circuit when the arc is extinguished. This type of transfer is also known as "short arc transfer" or "dip transfer". Short-circuiting transfer welding is generally carried out in the range of 50 to 175 amperes DCRP with some applications as high as 250 amperes. The arc voltage is generally in the range of 16 to 25 volts. Wire diameters generally range 0.030 to 0.045 inch, although 1/16-inch-diameter wire is sometimes used.

The short circuits usually occur at a frequency of 50 to 150 cps. To weld under these conditions, it is necessary to have a power supply of the constant-potential type with either an adjustable or a fixed voltage/current slope, and an inductor. These features serve to control the short circuit current during arc outages and to provide a stable arc and a fluid puddle.

Figure 4 shows a typical short-circuiting-transfer welding cycle. This is an idealized version of an oscillograph trace and serves to illustrate the relationship of voltage and current during the cycle. Also illustrated is the droplet detachment from the end of the electrode to the work as the surge of short-circuit current occurs. This single cycle occupies a time of approximately 1/100 to 1/150 sec in most cases.

The net effect of the short-circuiting mode of operation is to give a usable welding condition at a lower operating current than would be available with spray-arc metal transfer. Thus the weld puddle is smaller and less fluid. Therefore, short-circuiting arc welding finds wide use because it can be used in all welding positions. In addition, since the heat input is relatively low, distortion is minimized. Another advantage is the ability to handle wide gaps in fabrications where fit-up difficulties are encountered.

Pulsed Transfer. Pulsed-arc welding is accomplished by using two different sources of d-c power which may be assembled in the same cabinet. One power supply, called the pulse unit, is used to produce single phase, half-wave rectified direct current. Most commonly, this appears as a series of current pulses, at a frequency of 60 cps (line frequency), separated by a low current value during the time when the pulse unit does not deliver current. The magnitude of these pulses will be greater than the minimum transition current necessary to achieve spray transfer for the wire size used. In parallel with the pulse unit, a second power supply called the "background unit" is used to produce full-wave rectified direct current at a lower amperage and voltage. This is illustrated in Figure 5.

Shielding Gases. The shielding gas in GMA welding protects the arc and molten weld pool from the air. The type of shielding gas affects arc characteristics, the depth and shape of weld penetration obtained, the fluidity and weldability of the molten weld pool, and the chemical composition and mechanical properties of the deposited weld metal. The shielding gases used are argon, helium, carbon dioxide, or mixtures of these gases. Small additions of oxygen (1 to 5 percent) are often added to argon or argon-helium mixtures when using spray and pulsed-arc transfer to improve arc stability and improve wetting of the molten weld pool with the base material. Similarly, carbon dioxide is added to argon in quantities up to 50 percent of the mixture to improve arc stability and wetting and to increase weld penetration. However, additions of carbon dioxide in excess of about 10 percent are usually used only for short-circuiting transfer.

The addition of active gases (oxygen and carbon dioxide) to the inert gases (argon and helium) can increase the porosity and decrease the notch toughness of the weld. Increased porosity results from a loss of filler-wire deoxidizers such as manganese and silicon from oxidation by the active gas in the arc. Then the quantity of deoxidizers remaining may be insufficient to insure a sound weld deposit. Many commercial filler wires for gas metal-arc welding have compositions that are properly adjusted for use in shielding gases containing oxygen or carbon dioxide.

The loss of weld-metal notch toughness with additions of oxygen and/or carbon dioxide is attributed to increased oxide inclusions in the weld metal.

Narrow-Gap Welding

The Narrow-Gap welding process is an adaptation of the GMA process.(3) It derives its name from the type of joint layup which consists of a square-butt joint with a small gap approximately 5/16 inch wide. The use of this joint results in a substantially smaller quantity of filler metal required to fill the joint than that required when a conventional U- or V- groove joint design is used. The economy of the Narrow-Gap joint increases greatly with plate thickness. Narrow-Gap welding may be used in all positions (flat, vertical, horizontal, and overhead).

TABLE 1. TRANSITION CURRENTS FOR SPRAY-TRANSFER GMA WELDING OF STEEL(2)

Wire Diameter, inch	Current DCRP, amperes
0.030	150
0.035	175
0.045	200
1/16	275
3/32	350

Shielding gas is 95 percent argon - 5 percent oxygen.

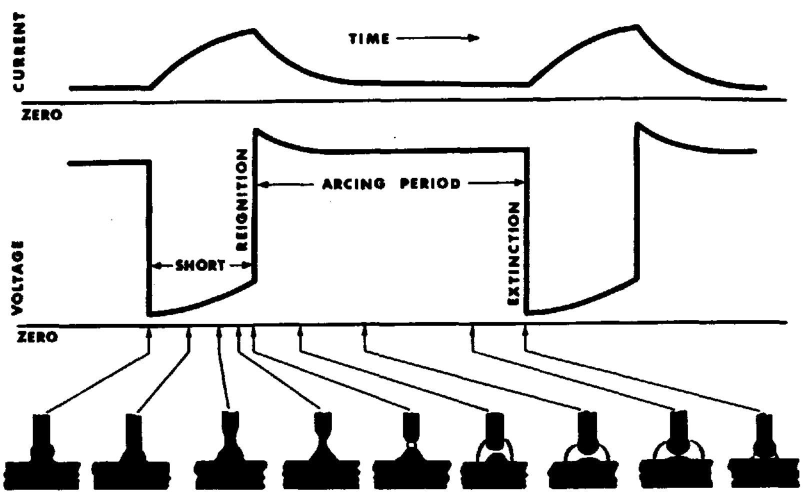


FIGURE 4. SHORT-CIRCUITING GAS-METAL-ARC (GMA) PROCESS.(2)

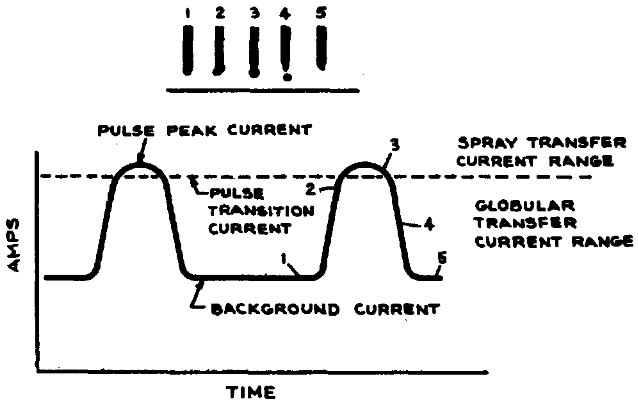
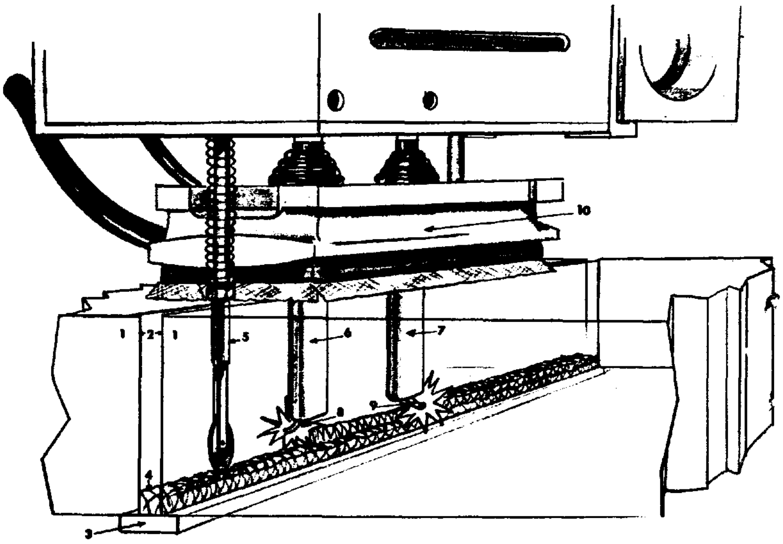


FIGURE 5. PULSE-ARC OSCILLOGRAPH.(2)



1 - Parent Metal	6 - Right Guide Shield
2 - 1/4 - 3/8 in. Gap	7 - Left Guide Shield
3 - Backup Strip (if needed)	8 - Right Wire Electrode
4 - Weld-Metal Buildup	9 - Left Wire Electrode
5 - Depth-Control Follower	10 - Gas Shield

FIGURE 6. NARROW-GAP WELDING CONCEPT

Narrow-Gap welding is carried out using two contact tubes and two electrode wires simultaneously. The electrodes are oriented so that one weld bead is deposited against one sidewall and the other weld bead against the opposite sidewall. The concept is illustrated in Figure 6. Narrow-Gap welding may also be done using a single contact tube centered in the weld joint. The weld is completed from one side of the plate. Electrode diameters may range from 0.035 to 0.062-inch. Narrow-Gap welding operates in the spray-transfer current range.

Narrow-Gap welding equipment generally uses standard commercial GMA welding components combined with unique contact tubes, guidance systems, and gas-shielding facilites. The contact tubes are water cooled and electrically insulated and are thin enough for insertion into a 5/16-inch-wide weld joint. Guidance systems are employed to maintain good sidewall fusion in the joint and to maintain constant contact tube-to-work distance. A special shielding-gas nozzle is used to force the shielding gas to the bottom of the joint in a laminar flow to avoid the aspiration of air. The efficiency of the gas shield has been demonstrated in flat- and horizontal-position welds in 8-inch-thick material. Other features of the Narrow-Gap welding equipment include a special wire-drive system to maintain accurate and consistent placement of the electrode wires, and automatic sequencing controls.

Gas Tungsten-Arc Welding

Welding heat in gas tungsten-arc (GTA) welding* is produced by an arc between a virtually nonconsumable tungsten electrode and the workpiece. The arc and weld puddle are protected by a shroud of suitable inert shielding gas that is directed by the welding torch or electrode holder. In general, the inert shielding gases are used to protect the tungsten electrode and molten weld metal from contamination. The elements of the GTA process are shown in Figure 7.

* GTA welding is often called TIG (tungsten-inert gas) welding.

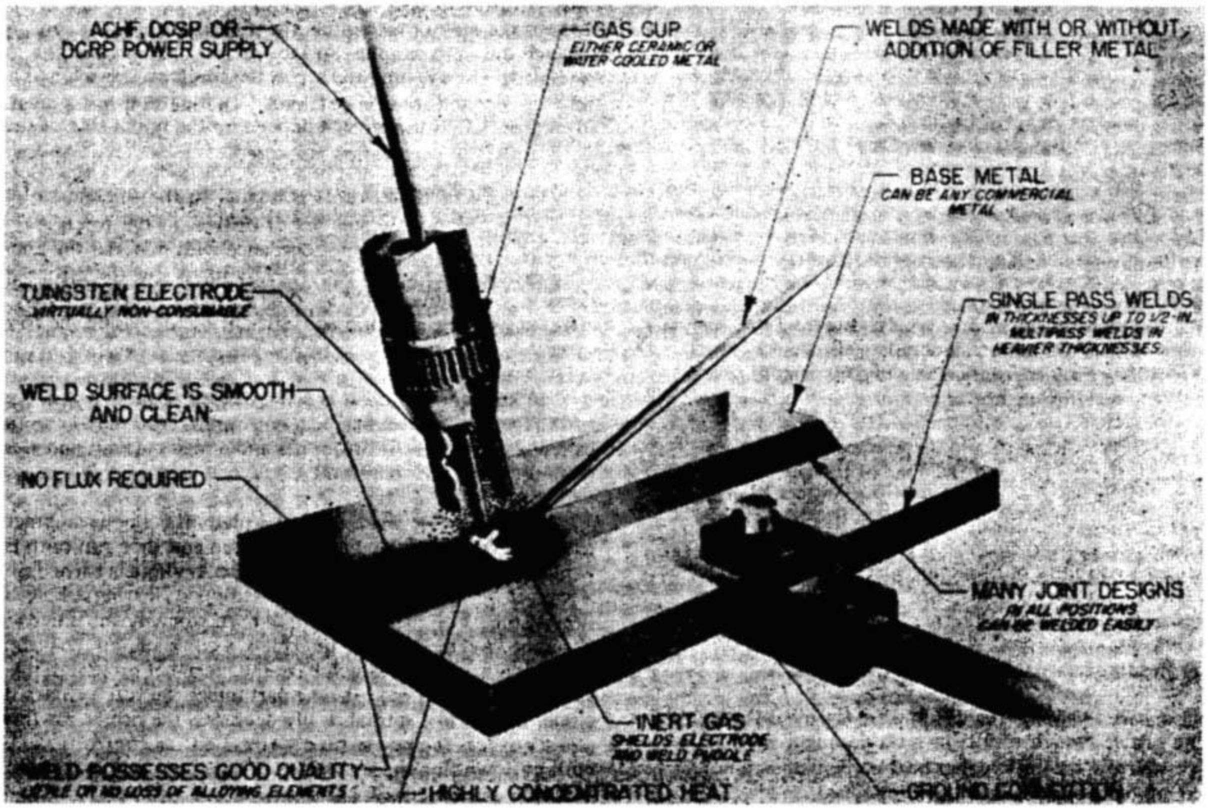


FIGURE 7. ELEMENTS OF THE GAS TUNGSTEN ARC (GTA) PROCESS.(2)

Argon or helium may be used as the shielding gas. Argon is preferred for manual welding because small changes in arc length have less effect on the arc heat than when the shielding gas is helium. For mechanized welding with closely controlled arc lengths, helium or helium-argon mixtures are preferred.

Filler metal, if needed, is added to the puddle outside the arc column. This is an advantage because alloy-transfer efficiency under these conditions can be high; thus control over the composition of the weld deposit is excellent.

For the welding of the HY steels, DCSP (electrode negative) is used for most applications. With this system, the major portion of the heat is directed toward the workpiece because the electron flow is from the electrode to the work. This results in a deeply penetrated weld. While DCRP can be used, the flow of electrons to the electrode requires the use of large electrode diameters to compensate for the electrode heating. The penetration when using DCRP for GTA welding is quite shallow.

The power supply used for GTA welding can be any constant-current or drooping-characteristic generator or rectifier. If it is suitable for SMA (covered-electrode) welding, then it may be used also for GTA. As a convenience, superimposed high-frequency current may be used to start the arc. This has the advantage of preventing contamination of the tungsten electrode or obtaining tungsten inclusions in the weld because the arc is initiated without touching the electrode to the work. However, a skilled manual operator can start the arc efficiently by a striking motion. For mechanized welding, either high-frequency or retract starting is used. Retract starting is combined with an automatic, voltage-control (arc length) head that drives the torch downward toward the work until the electrode touches, and then withdraws it to start the arc.

The electrodes used for the welding of steel are usually 98 percent tungsten and 2 percent thoria. This particular composition is used because the thoria is a good electron emitter that assists in arc starting and gives good, low-current stability. Several other suitable types of tungsten-alloy electrodes are available.

Filler-Wire Addition. Filler wire may be added to the weld puddle in two ways. The conventional method is called "cold wire addition" wherein the wire is added to the leading edge of the puddle. This method is used in manual and mechanized GTA welding. The term "cold" in this case refers to the fact that the filler wire is electrically and physically cold as it enters the weld puddle. Thus the welding arc between the tungsten electrode and the workpiece must provide all of the heat necessary to melt the wire. Maximum metal-deposition rates for this type of welding are on the order of 3 lb per hour. Travel speeds are correspondingly slow.

A relatively new development in GTA welding is the addition of "hot wire." In this method, the filler wire is provided with its own a-c power supply and is heated to the melting point by resistance heating as it enters the trailing edge of the weld puddle. This is shown schematically in Figure 8. To preserve the integrity of the wire, the heating is done in an inert atmosphere. This heating also volatizes surface contaminants on the wire and thus eliminates hydrogen pickup from this source. The arc is left to concentrate on fusing the workpiece since it need only supply approximately 15 percent of the energy necessary to melt the wire as it enters the puddle.

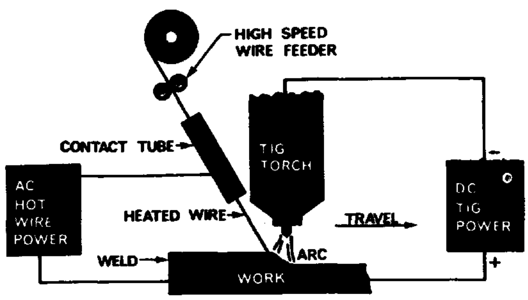


FIGURE 8. ELEMENTS OF HOT-WIRE (GTA) WELDING.(2)

Deposition rates for hot-wire GTA welding can be as high as 18 lb per hr, but they are more characteristically held between 8 to 12 lb per hr. Travel speed increases of 300 percent over that of cold-wire welding are not uncommon.

Hot-wire GTA welding should be practiced with voltage-controlled heads for the best results. One of the advantages of the processes is that the wire-deposition rate can be varied widely independent of arc current since the wire has its own power supply. Therefore, reinforcement can be controlled, and there exists the possibility of obtaining special properties such as improved corrosion resistance or improved cracking resistance through controlled weld-metal dilution.

Plasma Arc Welding

In plasma arc welding, the welding arc is forced through a constricting orifice, which results in a stable, highly concentrated arc. The plasma arc, having a higher heat content than a non-constricted arc, thus allows higher welding speeds.

Figure 9 compares the arc geometries in the GTA and plasma arc welding processes. The plasma arc has a columnar shape which varies little in diameter between the point where it leaves the orifice and the point at which it contacts the work. The arc in GTA welding, by contrast, is quite conical and covers a relatively wide area on the work. The concentration of the plasma arc means that the torch-to-work distance in plasma arc welding can vary to a fairly wide degree and affect the heat input to the work to only a small extent. A small change in torch (or electrode)-to-work distance with GTA arc has a significant effect on the area of the arc which impinges on the work. Therefore, the heat input varies widely as the GTA torch height is changed. Plasma arc welding can be applied more easily than GTA where torch-to-work distance cannot be controlled closely.

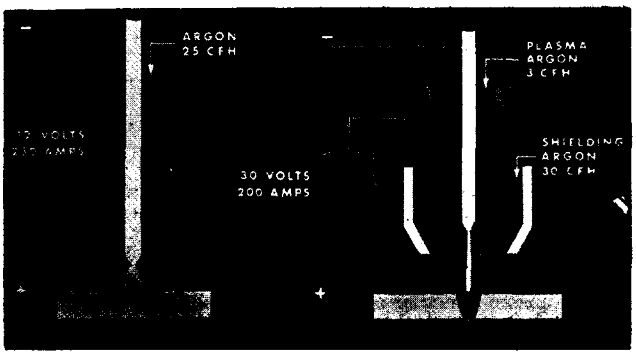


FIGURE 9. COMPARISON OF THE ARC GEOMETRIES OF THE GTA AND PLASMA ARC PROCESSES.(2)

Welding Techniques. Plasma arc welding can be applied with two different techniques. The first is called the "melt-in" mode where the arc impinges on the work and melts or penetrates the surface to some depth. This method of application is quite similar to the way GTA welding is used. The second technique, called the "keyhole" mode, produces an entirely different effect. Using a higher orifice gas flow than that for the melt-in technique, the plasma arc is forced entirely through the weld puddle. Surface-tension forces cause the keyhole to close behind the arc as the torch progresses, and a fully penetrated weld is obtained. The method has a great advantage in that the arc can be seen on the under side of the work; thus, full penetration is assured.

The size of the keyhole is related to the thickness of the workpiece. Various diameters of orifices in the torch are available and are chosen in accordance with material thickness. The keyhole size may be increased by increasing the orifice size, the orifice gas flow, or the welding current. A decrease may be effected by using a multiport orifice or by increasing the travel speed.

In keyhole welding it is often desired to modify the size and shape of the underbead. A wide underbead may be obtained by using a low flow of orifice gas and a high current, and vice versa for a narrow underbead.

When keyhole welding on flat plate, it is the usual practice to develop the keyhole on a starting tab and then run onto the workpiece. At the end of the weld the keyhole is carried onto a run-off tab and the operation is stopped, leaving a hole in the run-off tab. For a circumferential part, some means is needed to close the keyhole in order to achieve a complete joint. Welding controls are available which have the means of programming various weld functions. As the part under the torch comes full circle, the control automatically decreases the orifice gas flow and sequences the power supply (through the control's current down-sloping capability). Thus, the keyhole is closed gradually in a length of 2 or 3 inches, and a complete joint results.

Filler-wire additions may be made to the plasma arc puddle using precisely the same technique as used in GTA welding. While simple fusion passes in plasma arc welding may be made on all plate thicknesses without the addition of filler wire, some filler is needed to provide weld reinforcement for plate thicknesses in excess of 1/8 inch.

Electron Beam Welding.

Electron beam welding is a fusion joining process in which the workpiece is bombarded with a dense stream of high-velocity electrons as shown in Figure 10. Welding usually takes place in an evacuated chamber with both the generating-beam focusing devices and the work in the vacuum environment. Welding in a chamber provides a pure and inert environment in which metal may be welded without fear of contamination.

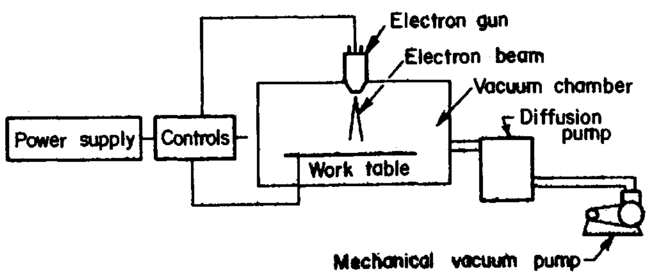


FIGURE 10. SCHEMATIC OF AN ELECTRON-BEAM-WELDING MACHINE.

The outstanding feature of the process is its ability to make very narrow, deep welds. The electron beam is capable of such intense local heating that it can almost instantly vaporize a hole through the entire joint thickness. The walls of the hole are molten and, as the hole is moved along the joint, more metal on the advancing side of the hole is melted. This flows around the bore of the hole and solidifies along the rear, thus making the weld. The intensity of the beam can be diminished, if desired, to give a partially penetrated weld of the same narrow configuration.

Arcs used in conventional welding melt little more than the surface of the part. Additional depth of fusion is obtained by conduction of heat in all directions from this surface molten spot and, thus, the fusion-zone width increases as the required depth of penetration increases.

Heat input in electron beam welding is controlled by four basic variables: the number of electrons per second (beam current) impinging on the workpiece; the electron speed at the moment of impact (accelerating potential); the diameter of the beam at, or within, the workpiece (beam spot size); and the speed of travel.

Weldment Evaluation

The most important criterion for judging the performance of a weldment is the degree to which it performs the functions required for its intended service. A service-performance test, therefore, is really the final test. However, the need for weldment evaluation exists long before the final structure is complete and actual service begins. Some type of test that will give the best information on how the product will perform during fabrication and service must be used before fabrication to provide indications of the efficiency of design, welding procedures, expected mechanical properties, and behavior during service.

Numerous reports are available on weldment-evaluation methods, but these usually are limited to a specific test method for a limited application. When considering evaluation methods for weldments, it is difficult to obtain information on the wide variety of test specimens or evaluation methods that are available and that will fulfill the designer's or fabricator's requirements. DMIC Report 244 is a comprehensive report that reviews the broad range of test specimens and evaluation methods that are available or are of special current interest for evaluating welds.[4] Tension, shear, bend, toughness, fatigue, creep, stress-rupture, and cracking tests widely used for the evaluation of welded joints are discussed. No discussion of the mechanical-test specimens or procedures used for the HY-80, HY100, and HY-130 weldments is given in the present report. The test methods are too numerous to discuss here and the reader is referred to DMIC Report 244 for such discussions. The mechanical-property data obtained with HY-80, HY-100, and HY-130 weldments are reported in subsequent sections of this report.

WELDING OF HY-80 and HY-100 STEELS

The HY-80 and HY-100 steels are quite similar in composition and are generally described in the same specifications. The principal differences are closer control of residual elements and slightly higher nickel content range for the HY-100 material. The welding procedures and processes applicable to HY-80 are also applicable to HY-100 when allowance is made for the additional strength. These materials are therefore discussed together in this section.

Composition

HY-80 and HY-100 steels were the first high-strength quenched-and-tempered steels approved for use by the U. S. Navy for construction of large ocean vessels. They are low-carbon steels that achieve their strength and toughness through a quenching-and-tempering heat treatment. HY-80 and HY-100 shapes and plate materials are available under the following military specifications:

(1) Plate - MIL-S-16216

(2) Extrusions - MIL-S-22664

(3) Rolled Sections - MIL-S-22958

(4) Castings - MIL-S-23008

(5) Forgings - MIL-S-23009

The commercial grades of HY-80 and HY-100 plate are covered by ASTM Specification A543, and the commercial forging material by ASTM A541 and A508. The chemical-composition limits for HY-80 steel as specified by MIL-S-16216 and A-543 are shown in Table 2 along with a typical HY-80 composition. The chemical-composition limits for HY-100 steel as specified by MIL-S-16216 and A-543 are shown in Table 3.

In these steels, limitation of sulfur and phosphorus content is required to minimize the detrimental effects of these elements during welding. Manganese is used primarily to further control the effect of sulfur in the material. Molybdenum is used to increase temper resistance by retarding softening during tempering of the steel at high temperatures and also contributes significantly to hardenability. Nickel contributes to the excellent toughness of HY-80 and has the secondary effect of increasing hardenability. Silicon is used primarily as a deoxidizer.

TABLE 2. CHEMICAL-COMPOSITION LIMITS OF HY-80 STEEL PLATE

Element	Specification Limits		Typical Composition
	MIL-S-16216	A543 (Grade A)	
Carbon(a)	0.18 max.	0.23 max.	0.16
Manganese	0.10 - 0.40	0.40 max.	0.28
Silicon	0.15 - 0.35	0.20 - 0.35	0.23
Nickel	2.00 - 3.25	2.60 - 3.25	2.97
Chromium	1.00 - 1.80	1.50 - 2.00	1.68
Molybdenum	0.20 - 0.60	0.45 - 0.60	0.45
Phosphorus(b)	0.025 max.	0.035 max.	0.015
Sulfur(b)	0.025 max.	0.040 max.	0.016
Titanium	0.02 max.	--	0.005
Vanadium	0.03 max.	0.03 max.	0.005
Copper	0.25 max.	--	0.05
Iron	Remainder	Remainder	

(a) 0.20 max. for plates 6 in. thick and over.
(b) The percent of combined phosphorus and sulfur shall be 0.045 max.

TABLE 3. CHEMICAL-COMPOSITION LIMITS OF HY-100 STEEL PLATE

Element	Specification Limits	
	MIL-S-16216	A543 (Grade B)
Carbon	0.20 Max.	0.23 Max.
Manganese	0.10 - 0.40	0.40 Max.
Silicon	0.15 - 0.35	0.20 - 0.35
Nickel	2.25 - 3.50	2.60 - 3.25
Chromium	1.00 - 1.80	1.5 - 2.0
Molybdenum	0.20 - 0.60	0.45 - 0.60
Phosphorus(a)	0.025 Max.	0.02 Max.
Sulfur(a)	0.025 Max.	0.02 Max.
Titanium	0.02	--
Vanadium	0.03	0.03 Max.
Copper	0.25	--
Iron	Remainder	Remainder

(a) The percent of combined phosphorus and sulfur shall be 0.045 max.

The wide ranges for several of the elements permit steel makers to adjust the hardenability of the steel to the thickness of plate being produced.[5] Smaller amounts of alloying elements are required for complete hardenability in plates 1-1/4 inches thick than are required for adequate hardening in plates 3 inches thick.

Metallurgical Characteristics

HY-80 and HY-100 are fully killed, low-alloy steels that attain a good combination of strength and toughness through quenching and tempering. The microstructures are a combination of tempered bainite and tempered martensite in all section thicknesses.

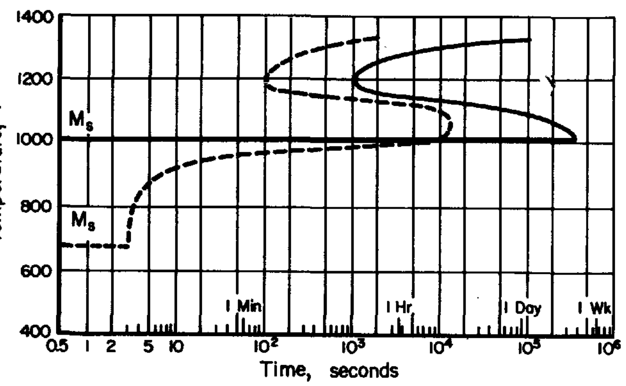
Procedures for the final quenching-and-tempering heat treatment used to obtain the required mechanical properties are left to the discretion of the steel manufacturer.[5] Only two limitations are imposed by MIL-S-16216:

(1) The final tempering temperature shall be not less than 1100 F for HY-80, and not less than 1050 F for HY-100.

(2) The microstructure at midthickness of the plate must contain not less than 80 percent martensite.

Heat treatments for HY-80 generally consist of austenitization at approximately 1650 F followed by a water quench[6] and tempering in the range of 1150 F to 1250 F followed by a water quench[5].

A time-temperature-transformation (TTT) diagram for HY-80 steel was developed by Emmanuel in a study of weld heat-affected-zone metallurgy.[7] This diagram is shown in Figure 11. Also included in Figure 11 is a curve showing the beginning of transformation on quenching from an austenitizing temperature of 1660 F.



	Solid Curve	Dotted Curve*
C	0.16	0.13
Mn	0.34	0.16
P	0.014	0.009
S	0.024	0.013
Si	0.25	0.10
Ni	2.87	3.08
Cr	1.52	1.76
Mo	0.41	0.49
Austenitizing Temperature	2400 F	1650 F

* Compiled from published information by Reference 7.

FIGURE 11. TIME - TEMPERATURE - TRANSFORMATION DIAGRAMS FOR HY-80 SHOWING BEGINNING OF TRANSFORMATION[7]

Note that increased transformation time and M_s temperature result from increased austenitization temperature.

The diagrams show the sluggishness with which HY-80 transforms as well as a high martensite transformation temperature when the peak austenitizing temperature is 2400 F. M_s and Mf temperatures of 750 F and 645 F, respectively, have been reported for an austenitizing temperature of 1650 F.[7] The slight discrepancy between these temperatures and the M_s shown by the dotted curve in Figure 11 is believed to be due to the use of materials of different compositions.

Base-Material Properties

The mechanical properties required by MIL-S-16216 and A543 for HY-80 plate material are shown in Table 4 along with typical properties. The Charpy V-Notch impact requirements for HY-80 and HY-100 are shown in Table 5. Specification A543 does not provide for minimum impact requirements. Mechanical property requirements for HY-100 are shown in Table 6. HY-80 retains excellent toughness to -120 F as shown by the curve in Figure 12.

Weldability

Numerous studies have been conducted on the effects of the welding heat on HY-80 base material. (7-15) In general, HY-80 is considered highly weldable when proper welding procedures are used, and its as-welded properties are very good.

HY-80 (and HY-100) is generally preheated for welding. The minimum preheat temperature depends on plate thickness, as shown in Table 7. The maximum preheat and interpass temperature is usually 300 F. Use of a 200 F minimum preheat for all thicknesses will insure that the weld joint is free of water (hydrogen) and will aid in preventing weld-metal cracking in restrained welds. No welding should be done when the ambient temperature is below zero F. Interpass temperatures greater than 300 F adversely affect the ballistic properties of thin (less than 1 3/8 in.) HY-80 materials.[7]

TABLE 4. SPECIFICATION LIMITS FOR THE MECHANICAL PROPERTIES OF HY-80 STEEL

Property	Specification Limits: MIL-S-16216	Specification Limits: A543 (Grade A)	Typical Value, 2-in.-thick material[7]
Tensile Strength, ksi	NS[a]	105/125	111.5
Yield Strength 0.2% Offset, ksi	80/95[b]	85 min	95.5
Elongation in 2 in., min percent	20[b]	14	25.0
Reduction in area, percent			
Longitudinal	55[b]	NS	
Transverse	50[b]	NS	

(a) NS - not specified

(b) These values for plate thicknesses 5/8 inch and over.

TABLE 5. CHARPY V-NOTCH IMPACT REQUIREMENTS FOR HY-80 AND HY-100 STEELS FROM SPECIFICATION MIL-S-16216

Plate Thickness	Impact Strength, ft-lb, min.
1/4 to 1/2 in. Excl.	(a)
1/2 to 2 in. Incl.	50 at -120 F
Over 2 in.	30 at -120 F

(a) Tests with the half-size Charpy specimen (10 x 5 mm) are required for information only. Tests are not required for materials less than 1/4 inch thick.

TABLE 6. SPECIFICATION LIMITS FOR THE MECHANICAL PROPERTIES OF HY-100 STEEL

Property	Specification Limits	
	Mil-S-16216	A543 (Grade B)
Tensile strength, ksi	NS [(a)]	115/135
Yield Strength (0.2% Offset, ksi)	100/115[(b)]	100 Min.
Elongation in 2 in., min percent	18[(b)]	14
Reduction in area, min percent		
Longitudinal	50[(b)]	NS
Transverse	45[(b)]	NS

(a) Not specified

(b) Values for plate thicknesses 5/8 inch and over.

TABLE 7. MINIMUM PREHEAT TEMPERATURES FOR WELDING HY-80 AND HY-100 STEELS[(2,16)]

Plate Thickness, inches	Minimum Preheat or Interpass Temp., F
To 1/2	75
1/2 to 1-1/8	125
Over 1-1/8	200

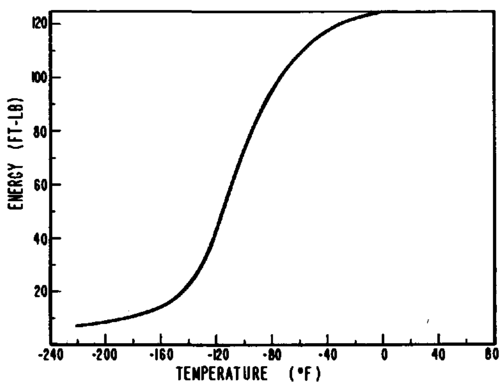


FIGURE 12. TYPICAL RELATIONSHIP OF CHARPY V-NOTCH ENERGY TO TEST TEMPERATURE FOR 1-INCH-THICK HY-80 PLATE.[(5)]

To ensure adequate notch toughness in the heat-affected zones of welded joints in HY-80, maximum heat inputs should be limited to 45,000 joules/inch* for plates over 1/2 inch thick.[(3)] These maximum heat inputs combined with the preheat limits will insure adequate cooling rates for the formation of martensite in the heat-affected zone. The relatively high martensite-formation temperature (see Figure 11) allows for some self tempering of the heat-affected-zone structures thus providing good as-welded properties.

HY-80 weldments generally do not require stress relieving.[(3)] Stress relieving may be required, however, for applications where a weldment must retain its shape to close tolerances during machining. Stress-relieving temperatures should not exceed 1150 F[(3)] since excessive time in the 700 F to 900 F range may cause temper embrittlement[(17)]. Extended exposure at these temperatures will result in a significant loss of impact strength.

Properties of Weldments

Most of the arc-welding processes discussed previously have been used for welding HY-80 steel. Only very limited data are available on welding HY-100 steel. The following paragraphs present impact and mechanical properties of welds deposited in HY-80 plate by each of the welding processes. Data on fatigue, corrosion, stress-corrosion, and explosion-bulge results for HY-80 are given in subsequent sections on HY-130 steel for comparative purposes. Few comparable data for HY-100 steel weldments are available.

Shielded Metal-Arc Welding

Only low-hydrogen-type covered electrodes should be used for welding HY-80 and HY-100. These electrodes are generally of the AWS E-XX18 type, but may also be E-XX15or E-XX16. The AWS E-10018 and E-11018 electrodes are commonly used to insure 100 percent efficiency in a highly stressed joing in HY-80. Electrodes lower in strength, such as E-9018, are often adequate (as in filler welds under longitudinal shear loads for example).[(3)] The lower strength weld metal is also frequently desired to prevent cracking in highly restrained fillet welds.[(3)] Typical mechanical properties of SMA weld deposits in HY-80 using E-9018 and E-11018 electrodes are shown in Table 8. Impact properties of these weld deposits are shown in Table 9. The variations in properties are generally due to variations in chemical composition of the weld deposits from electrodes produced by various manufacturers. The AWS E-11018 electrodes are generally used in welding HY-100 to insure 100 percent efficiency in the weld joint.

The care of welding electrodes for joining HY-80 and HY-100, discussed under "General Considerations In Welding", should be strictly observed. The E-XX15, E-XX16, and E-XX18 electrodes generally have sufficiently low hydrogen contents to avoid cracking in the weld and base metal provided that the electrodes were supplied in hermetically sealed containers which have not been damaged and the electrodes have not been exposed to the air. The rapid absorption of moisture from the air into the electrode coatings has been discussed previously.

TABLE 8. MECHANICAL PROPERTIES OF SMA WELDS DEPOSITED IN HY-80 STEEL WITH E-9018 AND E-11018 ELECTRODES

Specimen Type[(a)]	Electrode Type	Yield Strength 0.2% Offset, ksi	Tensile Strength, ksi	Elongation in 2 In., percent	Reference
W	E-9018	81.5	91.1	26	7
W	E-9018	91.7	100.8	19.5	7
W	E-11018	108.5	113.0	22	7
W	E-11018	105.0	117.0	25	7
T	E-11018	89[(b)]	112	21	18

(a) Joint Type - T transverse butt-welded plate
W All-weld-metal specimen.

(b) Fractured in base metal.

TABLE 9. CHARPY V-NOTCH IMPACT PROPERTIES OF SMA WELDS DEPOSITED IN HY-80 STEEL WITH AWS E-9018 AND E-11018 ELECTRODES

Specimen Type[(a)]	Electrode Type	Impact Strength, ft-lb			Reference
		30F	0 F	-60 F	
W	E-9018	--	--	62	7
W	E-9018	--	--	82	7
W	E-11018	--	--	45	7
T	E-11018	56	46	--	18

(a) Joint Type - T - Transverse butt-welded plate
W - All-weld-metal specimen.

*

$$\text{joules/inch} = \frac{\text{arc voltage x arc current (amperes) x 60}}{\text{travel speed in inches/minute}}$$

Gas Metal-Arc Welding

The GMA welding process has been discussed previously under "General Considerations in Welding". Both spray and short-circuiting types of metal transfer have been used in joining HY-80 steel. (10,19-27) Argon plus 1 or 2 percent oxygen is generally preferred as the shielding gas for spray-transfer welding, and 10 to 12 lb/hr of metal can be deposited under typical flat-position welding parameters[21] Weld-metal mechanical and impact properties are shown in Table 10.

Short-circuiting transfer GMA welding is generally done in a 60 percent He - 38 percent Ar - 2 percent O_2 shielding gas.[4] This gas mixture has the inherent characteristics of high heat transfer imparted by the helium, ease of ionization imparted by the argon, and arc stabilization imparted by the oxygen.[20] Hazlett reports that the addition of 5 percent CO2 to this gas mixture helps prevent incipient lack of fusion between passes in multipass welds.[20] The CO2 addition also reduces spatter. An Ar-02-CO2 mixture has been successfully used in welding a large HY-80 pressure sphere.[26] Telford reports that gases containing large amounts of CO_2, such as 75 percent Ar - 25 percent CO_2, should be avoided.[27] Welds made in such atmospheres may pick up several points of carbon and may have significantly reduced impact resistance in multipass welds. Mechanical and impact properties of short-circuiting transfer weld deposits are shown in Table 10.

Much of the work in the development of the Narrow-Gap welding process has been carried out with HY-80 steel. (28-31) Weld joint mechanical properties from flat-position welds are shown in Table 11. The impact properties of the Narrow-Gap weld-metal are adequate but are slightly lower than those of the flat-position spray-transfer weld-metal shown in Table 10. This may be due in part to the high CO2 concentration required in the shielding gas. The impact properties of the Narrow-Gap welds at -80 F are comparable to those of the short-circuiting transfer welds, thus making the Narrow-Gap welding process highly attractive for all-position, automated, welding applications.

Filler metals for GMA welding HY-80 steel are covered by specifications MIL-E-19822 and MIL-E-23765/2. MIL-E-23765/2 also covers filler metals for welding HY-100. The use of electrodes comforming to MIL-E-19822 to weld HY-80 should be avoided in structures which must be stress relieved after welding.[22] Weld deposits from these materials are subject to temper embrittlement because of their vanadium content. Deposits from electrodes conforming to either specification provide adequate as-welded properties.

Gas Tungsten-Arc Welding

GTA welding has generally been used only for laboratory evaluations of the weldability and crack susceptibility of HY-80. (32-34) While the process is capable of depositing very high

TABLE 10. MECHANICAL AND IMPACT PROPERTIES OF AS-WELDED GMA WELDS DEPOSITED IN HY-80 STEEL BY SPRAY- AND SHORT-CIRCUITING TRANSFER IN THE FLAT POSITION

Filler Metal[a] Specification	Specimen Type[b]	Transfer[c] Mode	Mechanical Properties: Yield Strength 0.2% Offset, ksi	Ultimate Tensile Strength, ksi	Elongation in 2 In., percent	Reduction of Area, percent	Impact Properties, Charpy V-Notch, ft-lb: Room Temp	0 F	-60 F	-100 F	Reference
2	W-A	ST	104	110	21	65	140	--	105	85	27
2	W-A	SC	104	108	22	70	140	--	105	70	27
2	W-B	ST	109	115	20	61	190	125	110	85	27
2	W-B	SC	113	119	20	65	--	95	85	55	27
2	W-C	ST	101	107	23	70	190	155	140	120	27
2	W-C	SC	103	107	23	70	--	135	105	55	
1	W	ST	115	120	18	50	--	--	--	--	21
2	W	ST	101	106-108	23-25	67-75	190	160	130	--	26
2	W	SC	103	106	22-25	70-75	--	140	108	--	26

(a) Filler-Metal Specifications - 1 - MIL-E-19822
2 - MIL-E-23765/2

(b) Specimen Type - W-All Weld Metal
Second letter represents filler-wire heat number for direct comparison of the properties obtained with different transfer modes.

(c) Transfer Mode - ST - Spray Transfer
SC - Short-Circuiting Transfer

TABLE 11. MECHANICAL PROPERTIES OF FLAT-POSITION NARROW-GAP WELDS IN HY-80 STEEL

Filler Wire	Plate Thickness, inch	Tensile Properties: Yield Strength 0.2% Offset, ksi	Ultimate Strength, ksi	Elongation in 2 In., percent	Reduction of Area, percent	Charpy V-Notch Toughness, ft-lb: 80F	0F	-40F	-60F	-80F	Reference
A	1-1/2	91.7	107.1	19.5	70	47	30	20	20	17	29
A[a]	1-1/2	--	--	--	--	76	76	65	64	58	29
B	2	--	113.1	--	--	66	65	--	--	61	31

(a) Same as above but with reduced heat input

NOTE: All welds made using twin-wire procedure with 80 percent Ar + 20 percent CO_2 Shielding Gas.

quality welds, it is seldom used for fabricating large, thick-plate structures because of the low deposition rate with resulting high costs of the process. The GTA process is usually used with the addition of filler metal. However, Thompson notes in passing that melted HY-80 material without the addition of filler metal is highly crack susceptible.(34) GTA welding may be useful in critical applications if a crack-resistant filler material is added in the process.

The hot-wire GTA process employing a resistance-heated filler wire is reported to offer deposition rates and weld properties comparable to those of the GMA process.(35) The properties are summarized below:

Yield Strength 0.2% Offset, ksi	Ultimate Tensile Strength; ksi	Elongation in 2 In., percent	Reduction in Area, percent	Impact Strength Charpy V-Notch, ft-lb
97	105	23	74	105 at 0 F

Note: 15-lb/hr deposition rate employed.

Submerged-Arc Welding

In submerged-arc welding HY-80 steel, the alloy content in the weld metal may be obtained by using either a mild-steel wire with an alloyed flux or an alloyed wire with a neutral flux.(2) The latter method is generally preferred since the use of an alloy flux must be very closely controlled in order to fix the amount of flux melted and thus the quantity of alloy transferred per pound of wire. Early studies by Lewis, et al, using an alloy wire, neutral flux combination showed lower than expected weld-metal notch toughness.(36) This was attributed to the number of inclusions in the welds and the oxygen content of the weld metal. Subsequent work by Lewis on the development of filler wires and fluxes significantly increased the impact strength of the as-welded and the stress-relieved welds.(37) All weld-metal properties of a typical multipass submerged-arc weld in HY-80 steel are presented below:(2)

Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2 In., percent	Reduction in Area, percent	Charpy V-Notch Impact Strength, ft-lb at -60F
98	92	20	55	35

This weld was deposited by a MIL-100S-1 electrode (MIL-S-23765/2) and a neutral flux.

In a thorough analysis of submerged-arc welding procedures, weld-metal notch toughness was found to correlate with both weld-metal oxygen content and weld microstructure.(38) The impact strengths were high in welds with low oxygen contents and fine-grained microstructures, and low in welds with higher oxygen contents and coarser microstructures. In this study, both conditions occurred simultaneously and no evaluation of the relative effects of each was given.

Problems in Welding HY-80

Microcracking

The welding of HY-80 steel is relatively trouble free when the proper precautions are observed in applying the respective welding processes. The one seemingly inherent problem in welding commercially produced HY-80 steel is heat-affected-zone microcracking.

Masubuchi examined metallographically 17 HY-80 weldments of different design and fabricated with different welding procedures.(8) Macrocracks were found in a few weldments, but microcracks were found in most of the weldments. The microcracks were intergranular and were located in the heat-affected zone adjacent to the fusion line. These microcracks appeared to be formed as a result of hot tearing. Masubuchi concluded that grain-boundary liquation caused by inclusions in the HY-80 steel may have been responsible for the microcracking. He observed that welding procedures appeared to have little influence on the severity of microcracking.

Microcracking has been related to steel composition by Masubuchi,(8) Emmanuel,(7) and Thompson.(34) Increased amounts of silicon and sulfur were found in some cracks. Thompson reported the association of microcracks with sulfide inclusions and banding in the base material.(34) Masubuchi reported no correlation between cracking and banding.(8) In the investigation of many experimental heats of HY-80, Emmanuel reported that the only heats that showed no cracking regardless of previous processing were those that contained very low sulfur.(7)

Savage has suggested that a significant number of microcracks in HY-80 do not nucleate in the heat-affected zone, but, instead, nucleate in a previously unrecognized region of the weld metal.(32) This is a region of melted base metal which is not mixed with the crack-resistant filler metal and is, thus, crack sensitive. Cracking is related to segregation in the grain boundaries in the solidifying unmixed region. This theory differs from that of Masubuchi(8) in that Savage relates cracking to segregation in a bulk-melted region and Masubuchi relates cracking to grain-boundary liquation (partial melting).

Meitzner also observed heat-affected-zone microcracking which was attributed to liquation.(10) The degree of heat-affected-zone microcracking was found to be related to the bead contour with the SMA, GMA, and submerged-arc welding processes. The GMA welding process produced more microcracking in HY-80 than did either the SMA or the submerged-arc process. The difference, also, could be related to bead-contour variations. These results indicate that the weld-bead contour is influential in determining the local stress pattern in the heat-affected zone immediately after welding. The results also point out the necessity of keeping restraint at a minimum during welding and of using welding procedures which produce good weld-bead contours to minimize heat-affected-zone microcracking.

Rare-earth additions during melting have been effective in reducing heat-affected-zone microcracking in HY-80.(13, 14, 33) It is believed that the rare-earth additions react with the sulfur to form a slag that is removed prior to pouring the ingot thus reducing the total sulfur content of the steel. Small additions of columbium (0.06 percent) have not been significant in reducing the microcracking tendency, and larger additions (0.23 percent) have increased the cracking tendency.(12) The larger addition of columbium formed a low-melting-point intergranular phase, which resulted in microcracking due to liquation.

Delayed Cracking

Delayed cracking may occur in HY-80 when improper welding materials or techniques are used. Delayed cracking originates in the hard zones of the heat-affected zone or weld metal after the metal cools below its transformation temperature.(11) Such cracking may occur even several days after the weld is completed. All investigators agree that some degree of restraint plus the presence of hydrogen is required for delayed cracking.(8, 10, 11, 15, 22, 25) Delayed cracking may appear as microcracks or gross macrocracks,(25) and it is generally transgranular rather than intergranular.

Delayed cracking may or may not initiate from small microcracks. Masubuchi showed macrocracks that appeared to start as intergranular cracks and change to transgranular cracks.(8) Meitzner reported there was no evidence to indicate that delayed cracking initiates at small microcracks.(10)

Hydrogen introduced into the weld zone in any form may cause delayed cracking. Beachum reported that hydrogen, introduced into restrained welds during welding as gaseous hydrogen, in water vapor, or in propane, caused delayed cracking.[25] Meitzner introduced hydrogen into a GMA weld by cathodically charging the electrode wire in H_2SO_4 prior to welding.[10] It was found that only 3.3 ppm hydrogen in the electrode will cause delayed cracking in highly restrained welds. Increased restraint generally lowers the quantity of hydrogen required to cause delayed cracking.

This discussion serves to emphasize the need for proper welding procedures and materials. All materials in contact with the high-temperature portions of the weld and the heat-affected zone must be free of all hydrogen-containing substances.

WELDING OF HY-130 STEEL

During the past decade, the upgrading of the HY-80 class of Naval hull-construction alloys to the 130-ksi yield-strength level has been the subject of a major development effort, first at Westinghouse Electric Corporation[39-41] and then at United States Steel Corporation.[42] This work has resulted in new base-metal and welding-filler-wire compositions, and in the accumulation of a large amount of data on the mechanical and corrosion properties of base plate and weldments as influenced by primary working, heat treatment, and welding practice. Alloys are still considered developmental, however, and there are no applicable military specifications for HY-130 type materials at present. Alloy designations for this class of material are not yet standardized and the designations 5Ni-Cr-Mo-V, HY-150, HY-140, HY-130/150, and HY-130(T) are all being used to describe the same alloy in different stages of development.

Composition

Development of the HY-130(T) alloy has been the result of a series of statistically designed experiments, first with laboratory-size heats, and then with large heats melted using commercial practice. The steel is of the medium-alloy Ni-Cr-Mo-V type, with the alloying elements adjusted to give optimum properties. The purposes of the alloying elements are similar to those for HY-80. The latest reported nominal composition for HY-130(T) base plate is given in Table 12.[43] This composition was selected to avoid embrittlement of the base plate during stress-relief heat treatment.

TABLE 12. CHEMICAL COMPOSITION OF STRESS-RELIEVABLE HY-130(T) STEEL[43]
(Check Analysis - Heat No. 5P2628)

Chemical Composition, weight percent	
Element	Composition
C	0.094
Mn	0.18
P	0.002
S	0.007
Si	0.30
Ni	5.60
Cr	0.78
Mo	0.35
V	0.070
Al(a)	0.014
N	0.010
O(b)	67
As	0.003
Sb	0.0004
Sn	0.003

(a) Total aluminum
(b) Parts per million

For reference, compositions of three 80-ton heats are given in Table 13. It will be noticed that levels of all of the major alloying elements differ from those of the embrittlement-resistant composition, although the principal significant compositional difference between stress-relievable HY-130(T) and earlier HY-130(T) compositions is a decrease in the manganese level of the stress-relievable grade. Undersiable impurity elements, such as sulfur, phosphorus, nitrogen, and oxygen must be held to the lowest possible commercial levels to maintain adequate toughness at the 130-ksi yield-strength level. United States Steel Corporation does not consider the stress-relievable HY-130 to be produceable by conventional air-melting practice, vacuum melting being necessary to maintain the residual-element contents at the required low levels.[45]

TABLE 13. CHEMICAL COMPOSITION OF TYPICAL HY-130(T) HEATS[44]

	Weight Percent(a)		
Element	Heat 5P0481	Heat 5P0747	Heat 3P0074
Carbon	0.11	0.11	0.11
Manganese	0.84	0.85	0.78
Phosphorus	0.007	0.009	0.008
Sulfur	0.005	0.007	0.004
Silicon	0.30	0.23	0.29
Copper	ND	ND	ND
Nickel	4.84	4.91	5.03
Chromium	0.55	0.58	0.56
Molybdenum	0.59	0.58	0.42
Vanadium	0.04	0.05	0.05
Titanium	ND	ND	ND
Aluminum (acid soluble)	0.014	0.017	0.012
Nitrogen (Kjeldahl)	0.009	0.009	0.011
Oxygen	0.0015	0.0033	0.0034

(a) ND - not determined

Metallurgical Characteristics

HY-130(T) is in many ways a development from HY-80. Like HY-80, it is intended for use in the quenched-and-tempered condition, in which it has a martensitic microstructure. In the center of 4-inch plates, as much as 40 percent lower bainite may also be present. Typical calculated ideal diameters for HY-130(T) are around 15 inches. Table 14, taken from a 1964 paper, summarizes some of the constants and properties of HY-130 type material not elsewhere obtainable.[46] It will be noted that the recommended austenitizing and tempering temperatures are somewhat lower than those for HY-80 steel (austenitization at about 1650 F and tempering in the range 1150-1250 F, as described on page 5).

Base-Metal Properties

The target base-metal properties during the development of HY-130(T) recognized the need for a combination of yield strength, toughness, fatigue resistance, freedom from stress corrosion, produceability in the desired form, and reasonable cost. The desired yield strength was apparently progressively lowered from 150 to 130 ksi during the development program because of inherent limitation in toughness of this class of alloy steel at high yield strengths. This limitation arises from the carbon-strengthened martensitic hardening mechanism.

The quantitative target properties for HY-130(T) appear to have been:

(1) A yield strength of at least 130 ksi at the center of a quenched-and-tempered 4-inch plate.

TABLE 14. GENERAL PROPERTIES OF HY-130-TYPE STEEL[46]

A_{C1} Temperature, F	1210
A_{C3} Temperature, F	1415
M_s Temperature, F	715
Recommended Final Austenitizing Temperature, F	1500
Recommended Quenching Medium	Water
Microstructure (as-quenched)	
Midthickness of 1/2-in.-thick plate	Martensite 100 percent
Midthickness of 4-in.-thick plate	60 to 75 percent martensite, remainder bainite
Recommended Tempering Temperature Range, F	1000 to 1150
Coefficient of Linear Expansion (80 to 1100 F)	7.1×10^{-6} in./in./F
Density (at 30 C)	7.89 g/cc
Magnetic Properties	
B_{sat}	20,520 gauss
H_{sat}	2,190 oersteds
B_r (when B_{max} = 15,000 gauss)	10,850 gauss
H_c (when B_{max} = 15,000 gauss)	11.0 oersteds
μ_{max}	630
Compressive Yield Strength (0.2 percent offset)	About 10 to 15 ksi higher than tensile yield strength
Elevated-Temperature Yield Strength (0.2 percent offset)	
400 F	131 ksi
500 F	132 ksi
600 F	125 ksi
700 F	121 ksi
800 F	113 ksi
Machinability	About the same as quenched and tempered AISI 4140 steel at 36Rc

(2) A maximum fracture-transition-plastic temperature of 0 F.

(3) A maximum nil-ductility temperature of -100 F.

(4) A Charpy-V notch impact energy absorption of 60 ft-lb at 0 F in the ductile fracture region ("shelf").

Figure 13 shows the yield strength and toughness of base plate as influenced by tempering temperature.[47] The data were obtained from an 80-ton production heat in the form of 1/2-inch plate. The lower transverse toughness properties are typical for this class of material, and can be made to approach the longitudinal properties by cross rolling.

Figure 14 shows the effect of increasing plate thickness on yield strength and toughness.[47] It will be noted that Charpy results are for two test temperatures. The data are from several heats, some with deliberate variations from the nominal composition. For a given heat, the difference between longitudinal and transverse impact toughness may be considerably greater than would appear from Figure 14 unless the material is given a considerable amount of cross rolling. See Figure 15.[42]

A linear relationship has been shown between the normalized values of the plane-strain stress-intensity factor, K_{Ic}, and the Charpy V-notch energy absorption, CVN, for several high-strength steels. See Figure 16.[42] For a nominal 130-ksi yield strength, the experimental point shown for HY-130(T) corresponds to a 78 ft-lb Charpy energy and a K_{Ic} of 300 ksi$\sqrt{\text{inch}}$.

Table 15[43] shows the mechanical properties of an 80-ton heat of stress-relievable HY-130 (chemical analysis for the same heat is given in Table 12).

The fatigue properties of HY-130(T) are given in Figure 17.[42] It will be noted that the fatigue strengths, expressed in terms of strain range, are higher than those of HY-80 over the entire range of cycle lives.

Welding Characteristics

Preheat and interpass temperatures for welding HY-130(T) are similar to those for HY-80; a minimum of 200 F is recommended for 1-inch plate,[48] Grotke[9] refers to a stipulated maximum preheat temperature of 300 F, although some investigators[49] have found it necessary to go to preheat temperatures as high as 400 F to avoid transverse cracking. The moisture content of SMA electrodes should not exceed 0.10 percent, and the hydrogen content of GMA welding wire should be below 3 ppm. Welding input energy should be limited to 50 kilojoules/inch. Welding defects likely to be encountered with HY-130(T) are chiefly weld-metal cracking and porosity. This differs from HY-80, in which the most severe welding problems have involved heat-affected-zone cracking.

Filler metals for use with HY-130 steels have been developed to match the base-plate properties. Because of the solidification cycle through which the weld fusion zone must pass and the inability to duplicate the base-metal processing, weld-metal composition differs from that of the base metal. Actual weld-metal compositions are intermediate between those of the base plate and the filler wire because of dilution. Carbon content of the filler wire is below that of the base metal because of carbon's tendency to cause cracking. Similarly, manganese content is relatively high because it imparts toughness; nickel content is lowered to avoid cracking known to be caused by high nickel contents, and chromium content is raised for increased hardenability. The desired weld-metal microstructure is stated by Dorschu and Lesnewich to consist of low-temperature bainite.[50] The composition range reported in 1964 for filler metal by these investigators was:

C	0.05/0.09	Si	0.25/0.45
Mn	1.90/2.20	Mo	0.50/0.60
Ni	2.00/2.50	Cr	1.00/1.25

with 0.010 maximum phosphorus and sulfur. This is substantially the composition of Air Reduction Company's (Airco) AX-140 electrode wire. The same metal composition was also used successfully for SMA electrodes.

The requirement that there be no embrittlement during stress-relief treatment following welding has necessitated changes in electrode composition as well as in base plate. Table 16 gives the analyses of three such heats of electrode filler wire.[45] It will be noted from the low manganese, high nickel, and inclusion of vanadium that these materials are considerably different from the 2Mn-2Ni type of electrode material.

Comparison of Welding Processes for HY-130

At the 130-ksi yield-strength level, the submerged-arc process has not been considered capable of producing weldments with adequate yield strength and toughness. A submerged-arc welding study[45, 51] is currently in progress, however, using a newly developed flux. The SMA, GMA, and GTA processes and variations of them have all been used to produce HY-130 weldments.

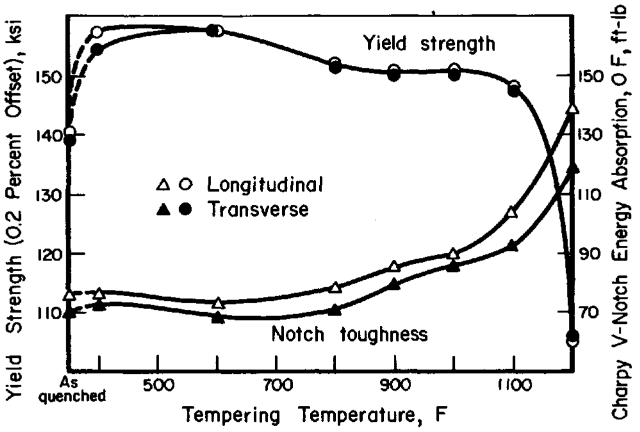


FIGURE 13. TEMPERING CHARACTERISTICS OF 5 Ni-Cr Mo-V STEEL.(47)

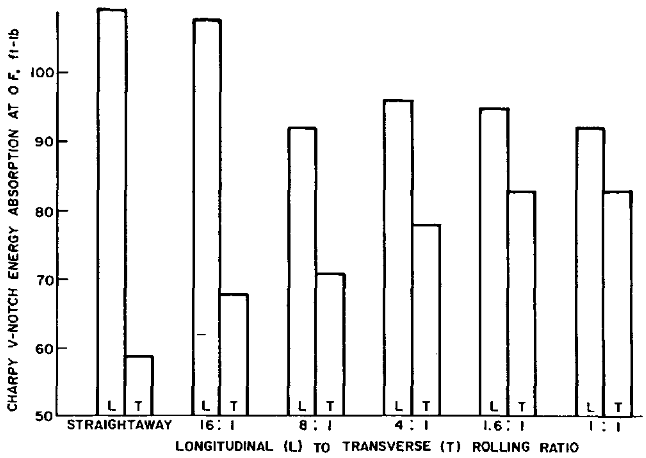


FIGURE 15. EFF'ECT OF ROLLING RATIO ON THE TOUGHNESS OF HY-130(T) STEEL.(42)

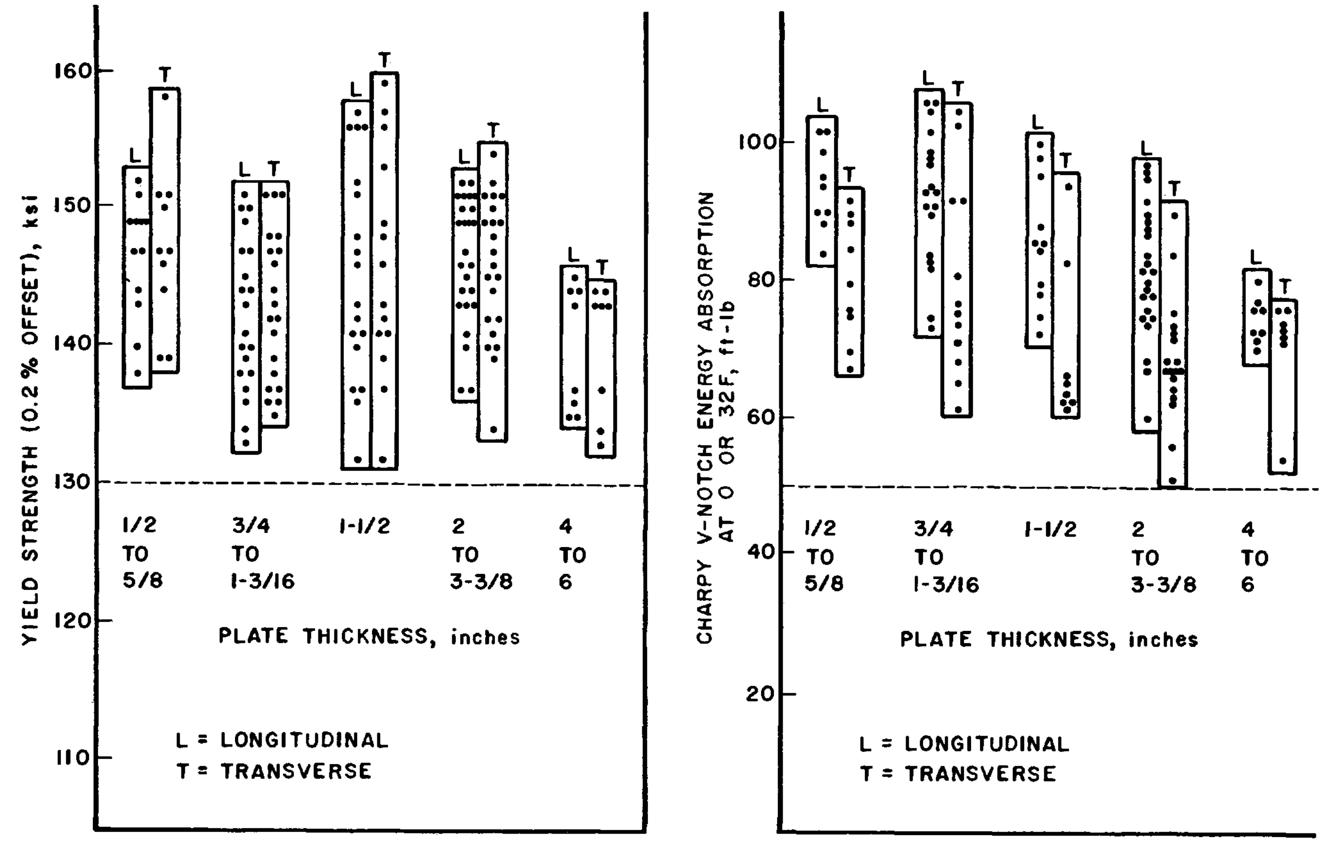


FIGURE 14. STRENGTH-TOUGHNESS SUMMARY FOR PRODUCTION PLATES OF 5Ni-Cr-Mo-V STEEL.(47)
Individual test values are shown.

TABLE 15. MILL MECHANICAL PROPERTIES OF 1-INCH-THICK STRESS-RELIEVABLE HY-130 PLATE(43)

		Tensile Properties				
Plate	Specimen Location and Orientation(a)	Yield Strength 0.2% Offset, ksi	Ultimate Tensile Strength, ksi	Elongation in 2 Inches, percent	Reduction of Area, percent	Charpy V-Notch Energy Absorption at 0 F, ft-lb
063574	T	140	152	18.0	63.9	53 55 57
	L	134	151	20.0	67.4	75 76 78

(a) T = Top of plate, transverse specimen.
L = Bottom of plate, longitudinal specimen.

TABLE 16. CHEMICAL COMPOSITION OF HEAT-TREATABLE HY-130 FILLER METALS(45)

Welding(a) Process	Chemical Composition, weight percent										
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Ti	Al(b)	N(c)
SMA(d)	0.08	0.62	0.007	0.008	0.40	7.97	0.58	0.53	0.070	ND	0.004	0.019
GMA(e)	0.11	0.58	0.002	0.005	0.36	7.93	0.47	0.45	0.075	0.020	0.002	0.006
GMA(e)	0.10	0.57	0.001	0.005	0.36	7.89	0.46	0.40	0.071	0.020	0.002	0.006

(a) SMA= Shielded Metal Arc; GMA = Gas Metal Arc.
(b) Total.
(c) Kjeldahl analysis.
(d) Composition determined from weld deposited.
(e) Ladle analysis of heats.

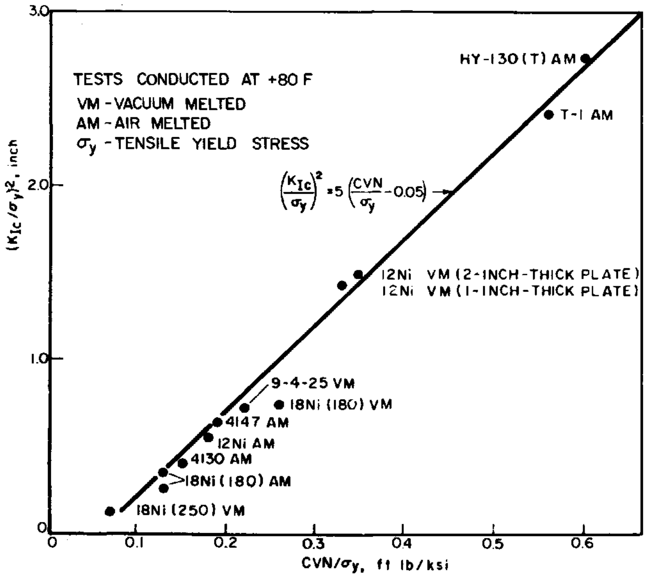


FIGURE 16. RELATION BETWEEN PLANE-STRAIN STRESS-INTENSITY FACTOR (K_{Ic}) AND CHARPY V-NOTCH ENERGY ABSORPTION (CVN) FOR SEVERAL HIGH-STRENGTH STEELS.(42)

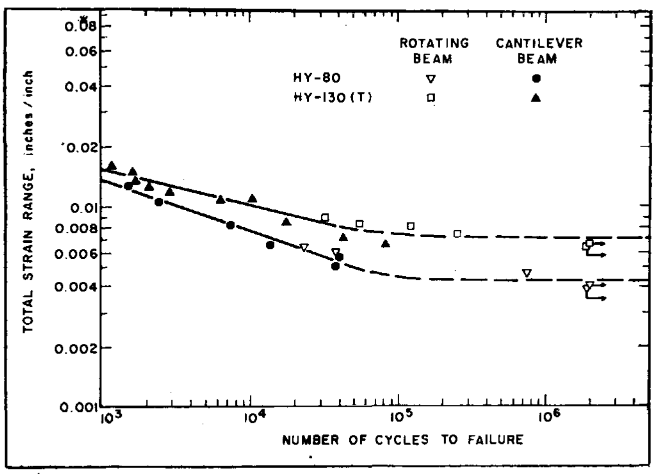


FIGURE 17. FATIGUE BEHAVIOR OF HY-80 AND HY-130(T) STEELS.(42)

Shielded Metal-Arc Welding

Manual SMA welding is the common shipyard-welding method. For this reason, suitable electrode and coating compositions were developed for use with HY-130(T) base metal. Obtaining sufficient weld-metal toughness at this strength level is a problem with the SMA process. Heuschkel has reported the SMA welding conditions used in the Westinghouse program, which appear as part of Table 17.(52) Coatings were of the E-XX18, or low-hydrogen, iron-powder type. SMA and GMA welding conditions used by United States Steel Corporation for plates up to 4 inches thick were given by Connor, Rathbone, and Gross (Table 18).(48) Recommended preheat and interpass temperatures and heat inputs are given in Table 19.

Maintenance of a low hydrogen content in the weld metal is critical with steels at high-yield-strength levels, such as HY-130(T). Table 20 gives the compositions of three types of coatings for SMA electrodes developed for this application.(42) The iron-powder type of coating, Class E-XXX18, results in higher toughness welds than do the other types (See Figure 18),(42) and most of the SMA welding of HY-130(T) has been done with this class of coating.

Gas Metal-Arc Welding

For a given yield strength, it is generally observed that a GMA weld will have greater toughness than an SMA weld. At yield-strength levels above 130 ksi, it appears that the GMA process will displace SMA for production welding.

TABLE 17. SUMMARY OF WELDING CONDITIONS USED BY WESTINGHOUSE ELECTRIC CORPORATION TO FABRICATE HY-150 WELDMENTS(52)

	Gas Tungsten-Arc (GTA)	Shielded Metal-arc (SMA)	Gas Metal-arc (GMA)
Filler Metal Diam, In.	3/16	3/16	1/16
Amps	400/420	200/250	275/485
Volts	12	22/27	24/32.5
Beads	16/22	13/14	6/12
Travel, ipm	5/6	8/10	11.5/18.0
Range, joules/in.	49000/54300	29050/37650	31200/74000
Avg., joules/in.	53200	31700	47200

TABLE 18. SUMMARY OF WELDING CONDITIONS USED BY UNITED STATES STEEL CORPORATION TO FABRICATE HY-130(T) STEEL WELDMENTS(48)

	Gas Metal-Arc (GMA)		Shielded Metal-Arc (SMA)		
Heat input, kilojoule/in.	40	60	25	30	40
Electrode diam, in.	0.045(0.062)(a)	0.062	1/8	5/32	3/16
Current, amp (dcrp)	240/280(300/320)(a)	300/350	120/140	160/180	200/220
Arc voltage, V	28/29	30/31	22/24	22/24	22/24
Travel speed, ipm	11/13	9/11	6/8	6/8	6/8
Shielding gas	Argon + 2 percent oxygen	Argon + 2 percent oxygen	--	--	--

(a) Weldments fabricated with electrodes A and B were welded with 0.062-in.-diam filler metal with a nominal heat input of 40 kilojoule/in.

TABLE 19. RECOMMENDED PROCEDURES FOR WELDING HY-130(T) STEEL(48)

Plate Thickness, in.	Preheat and Interpass Temp F	Heat Input, kilojoule/in.
Gas Metal-Arc Welding Procedures		
130-ksi minimum yield strength		
Up to 3/8	Not recommended(a)	
3/8 and including 5/8	125 to 150	35
Over 5/8 and including 7/8	150 to 200	40
Over 7/8 and including 1 1/2	200 to 275	45
Over 1 1/2	225 to 300	50
140-ksi minimum yield strength		
Up to 3/4	Not recommended(a)	
3/4 and including 1	125 to 200	35
Over 1 and including 1 1/2	200 to 275	40
Over 1 1/2	225 to 300	42
130-ksi minimum yield strength		
Less than 3/8	Not recommended(a)	
3/8 and including 5/8	125 to 150	30
Over 5/8 and including 7/8	150 to 200	35
Over 7/8 and including 1 1/4	200 to 275	35
Over 1 1/4 and including 4	225 to 300	40

(a) Welding of these light-gage plates by either gas metal-arc or shielded metal-arc processes is not recommended. For such welding, the gas tungsten-arc process with appropriate controls is recommended.

TABLE 20. COMPOSITION RANGES OF COATINGS FOR LOW-HYDROGEN COVERED ELECTRODES(42)

	AWS Class and Type of Coating, Weight Percent		
	Lime	Titania	Iron-powder
	(E-xxx15)	(E-xxx16)	(E-xxx18)
Calcium carbonate	10-30	10-30	10-30
Fluorspar	10-30	10-30	10-30
Titanium dioxide	0-8	15-30	0-8
Iron powder	0-5	0-5	15-30
Ferro alloys	15-30	15-30	15-30
Mineral silicates	5-10	5-10	5-10
Sodium and/or potassium silicate	5-15	5-15	5-15

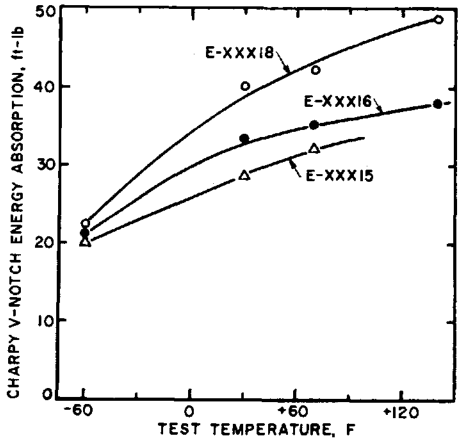


FIGURE 18. IMPACT PROPERTIES OF WELD METALS DEPOSITED WITH THREE COVERED-ELECTRODE SYSTEMS.(42)

Spray Transfer. The welding conditions developed on the United States Steel Corporation program for welding HY-130(T) by the GMA process under spray-transfer conditions are given in Table 19. Welding conditions used at Union Carbide Corporation's Linde Division by Enis and Telford(53) agree with those cited in Table 17 except that a slightly lower voltage is specified (in the 24 to 26 volt range).

In a rocket-motor-case-fabrication study carried out for NASA, Tiffany, et al., investigated several different welding processes for 1-inch-thick HY-150 plate.(54) They selected spray-transfer GMA as the preferred process, with an SMA root pass to accommodate fit up variations. Welding was limited to the flat position since no need for out-of-position welding was visualized for the application. Their welding conditions were substantially the same as the 40-kilojoules/inch conditions recommended in Table 18.

Short-Circuiting Transfer. Enis and Telford have also investigated GMA welding of HY-130(T) in the short-circuiting mode. Toughness of welds made in this manner was not as adversely affected by increases in carbon as that of welds made using the spray-transfer mode. A shielding gas composed of 60He-35Ar-5CO_2 was substituted for the Ar-CO_2 mixture used for spray transfer. A weaving-torch technique rather than a stringer-bead technique gave improved mechanical properties in the weld metal. For vertical welding in the dip-transfer mode, a 40-kilojoule/inch heat-input rate was optimum. The rate was raised to 65 kilojoules/inch for the root pass, the actual conditions being 125 amperes, 17 volts, and 2 ipm vertical travel speed. Subsequent passes were made at 150 amperes, 18 volts, and 4 ipm. A static power supply slope of 5 volts per 100 amperes gave the smoothest operation.

Pulsed-Arc Welding. Investigation of the pulsed-arc process for welding HY-130(T) type alloys is still in progress. The welding parameters, as reported by United States Steel Corporation, are given in Table 21.(45) Work done by the Air Reduction Company under somewhat different conditions provides additional information regarding use of the pulsed-arc process.(55) Airco used an Ar-2 percent O_2 shielding gas mixture, a 1/4-inch arc length, and a 3/4-inch contact-tip separation. They varied duty cycle at three frequencies for two different wire sizes (0.035 and 0.045 inch). Figure 19 shows the type of relationship observed among the welding variables. Increasing the duty cycle or the frequency narrows the acceptable range over which spray transfer can be obtained. A 20 percent dutycycle at 120 pulses per second is noted as appearing particularly promising for welding HY-130(T).

Gas Tungsten-Arc Welding

Because of its relatively low deposition rate, conventional GTA welding has not been seriously considered for ship construction. Its ability to produce fusion welds of the highest attainable quality has however, made GTA a candidate welding process for fabrication of large solid-fuel rocket-motor cases. GTA welding was also used in an Air Force-sponsored study at the Boeing Company to prepare weldments in 1-inch HY-150 and HP-150* plates.(56) Table 22 shows the joint design and the welding parameters used. A preheat between 250 and 300 F was used for both alloys. The welding conditions are somewhat different from those used in the earlier Westinghouse investigation (See Table 17).

Hot-Wire GTA Welding. United States Steel Corporation has conducted a study to optimize the process variable for the hot-wire GTA process.(57) This process is of interest because of its improved metal-deposition rate relative to that of conventional GTA welding. The investigators were able to achieve bead-on-plate welds of suitable contour at deposition rates as high as 11 pounds per hour from any of three sets of conditions. See Table 23. Conditions held constant during the study are given in Table 24.

Other Welding Processes

Narrow-Gap Welding. Hy-130 has been welded using the Narrow-Gap process.(45) The oxygen content of the resulting welds was between 312 and 438 ppm, indicating a need for an altered shielding-gas composition. The high thermal efficiency of the Narrow-Gap process results in high cooling rates of the weld metal. Use of the filler wire developed for GMA welding of HY-130 results in an overmatched weld (i.e., fusion-zone yield strengths are around 150 ksi), and in hydrogen embrittlement. A program is underway to develop a suitable 130-ksi filler metal for the Narrow-Gap process.

* HP-150 is a high-strength steel manufactured by Republic Steel Corporation. A typical composition is 0.22 C, 0.11 Mn, 3.0 Ni, 1.39 Cr, 0.87 Mo, 0.07 Cb, 0.019 Al, 0.007 S, 0.006 P.

TABLE 21. RECOMMENDED PULSED-ARC PARAMETERS FOR FABRICATING HY-130 STEEL WELDMENTS(45)

Parameter	Vertical-Up and Overhead Positions	Horizontal Position
Pulse Frequency, cps	120	120
Electrode Diameter, inch	0.045	0.045
Shielding Gas, percent	(75 Ar-25 He) plus 1 O_2(a)	(75 Ar - 25 He) plus 1 O_2(a)
Shielding-gas flow rate, cu ft/hr	30 to 50, depending on nozzle size	30 to 50, depending on nozzle size
Oscillation Amplitude, inch	3/8 to 5/8	Not more than required to produce a flat bead contour
Electrode Stick-Out, inch	1/2	1/2
Arc Length, inch	3/16	3/16
Average Current, amperes	130/150(b)	190/210(b)

(a) For maximum penetration, a gas mixture of 75% helium and 25% argon to which 1% oxygen is added is preferred; however, inexperienced welders may have more difficulty controlling the weld pool when using this gas.

(b) The wire-feed speed should be limited to about 150 ipm in the vertical-up and overhead positions, and to about 230 ipm in the horizontal position.

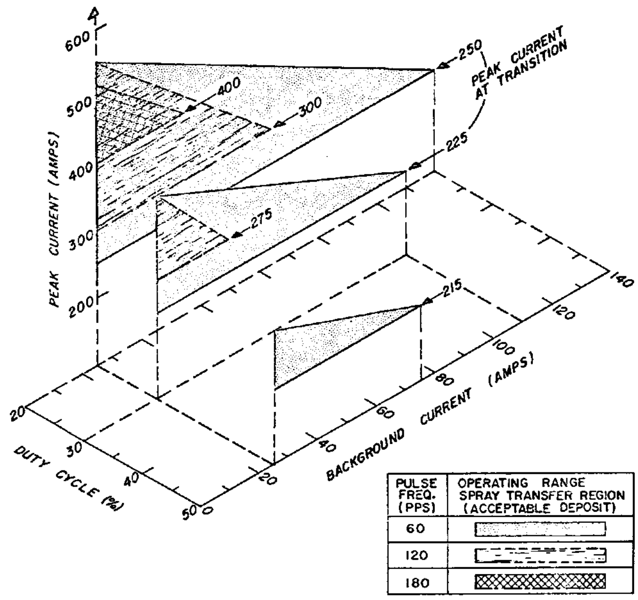
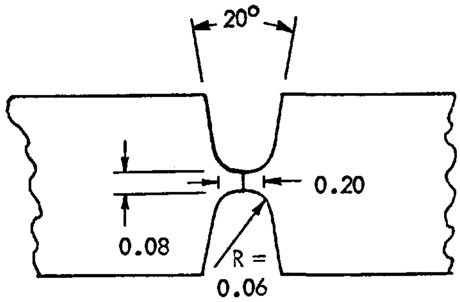


FIGURE 19. THREE-DIMENSIONAL REPRESENTATION OF THE INTERACTION OF DUTY CYCLE, PEAK CURRENT, BACKGROUND CURRENT AND PULSE FREQUENCY ON PULSED-ARC WELDING OPERATING RANGES (wire diam - 0.045 in.)(55)

TABLE 22. GTA WELDING PROCEDURE FOR HY-150 AND HP-150 STEEL PLATES(56)



Weld Amperes	180-210
Arc Voltage	11-14
Travel, In/Min.	6-10
Wire Feed, In/Min.	24 (.060 In. Dia.)
Tungsten Dia.	3/32
Torch Gas	90 CFH He
Backup Gas	25 CFH Ar
Trailing Gas	50 CHF Ar

TABLE 23. SETS OF HOT-WIRE GTA WELDING VARIABLES(57)

Deposition Rate - 11 lb per hr
Current - 500 amperes
AC Power to Wire - 2500 watts (approximate)

Set	Travel Speed, ipm	Voltage, volts
1	10.0-11.0	15.5-16.0
2	12.0-14.0	15.0-16.0
3	15.0-16.0	14.5-15.0

TABLE 24. WELDING CONDITIONS HELD CONSTANT IN HOT-WIRE GTA PROCESS STUDY(57)

Tungsten-Electrode Diameter, inch	5/32
Tungsten-Electrode Tip Angle, degrees	60
Tungsten-Electrode Stick Out, inch	3/4
Shielding-Gas Type	75 He + 25 percent Ar
Shielding-Gas Flow Rate, cfh	70
Hot-Wire-Shielding-Gas Type	100 percent Ar
Hot-Wire-Shielding-Gas Flow Rate, cfh	10
Initial Plate Temperature, F	75
Hot-Wire Diameter, inch	0.045
Hot-Wire Feed, ipm	
At 3 lb per hr	110
At 7 lb per hr	260
At 11 lb per hr	410

Navy Extended Electrode Technique (NEET). NEET uses a conventional GMA torch placed above the plates to be welded. A square-edge preparation is used on the plates. The unsupported 0.062-inch-diameter filler wire is extended into the 1/4 to 7/16-inch gap between the plates. Welds are made manually. The results of a preliminary investigation have been described by Schaper and Stern.(58)

Electron Beam Welding. Electron beam welds of promising quality have been produced in HY-130. Connor and Rathbone welded 2-inch plates and reported good strength and ductility, moderately good weld-metal toughness, and excellent heat-affected-zone toughness.(59) They concluded, however, that electron beam welding offered no metallurgical advantages over welding by the GMA process in material this thick. Connor and Haak used electron beam welding to join HY-130 that had been given a grain-refining heat treatment ("rapid heat treating"), presumably because they expected less heat-affected zone damage from electron beam welding than from other welding processes.(60) The weldments had excellent bend ductility and good toughness. Pollack and Stern made electron beam welds in several deep-submergence-vessel steels including HY-130 and they believe that electron beam welds can be produced having properties superior to those made by arc welding.(61) They also demonstrated that defective electron beam welds could be repaired successfully by GTA welding. All three of the studies cited were limited, laboratory-scale investigations. Successful production-scale electron beam welding of ship-hull steels will require specialized equipment and tooling.

Weldment Properties

In this section, typical properties of weldments prepared from HY-130-type steels are presented and discussed. There is no lack of data on developmental weldments. It is frequently difficult to select the most meaningful information since the data have often been obtained using base plates, filler metals, and, to some extent, welding practices that are still under development. Therefore, typical data are presented, with the understanding that they are in no sense design data, to serve merely as ranges and trends of properties available in HY-130 type weldments.

Weld Metal

The transformation kinetics and, therefore, the mechanical properties of the weld metal are strongly influenced by the cooling rate. The cooling rate at 1000 F after welding is taken as being indicative of the properties to be expected. Figure 20 shows the variation of yield strength with cooling rates in weld metal from 1- and 2-inch plates.(42) A minimum cooling rate

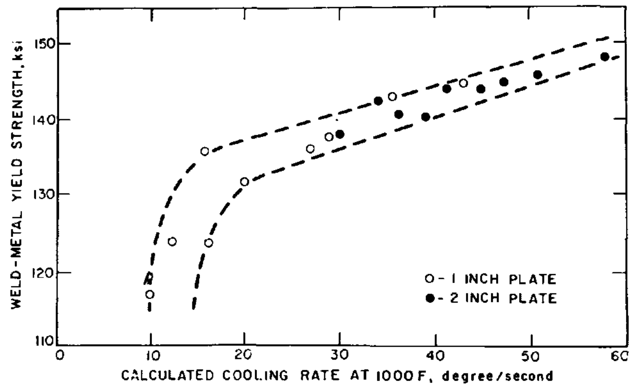


FIGURE 20. THE INFLUENCE OF COOLING RATE ON HY-130 WELD-METAL YIELD STRENGTH.(42)

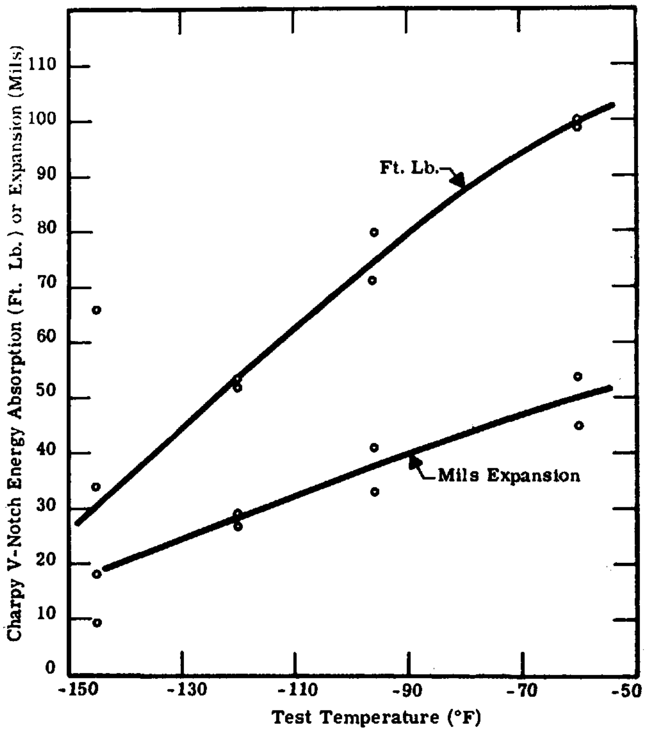
of 30 F/second has been specified for HY-130 weldments. It can be seen that lower cooling rates will result in weld-metal yield strengths below 130 ksi. The minimum cooling-rate requirement limits the maximum preheat temperature that can be used in welding.

Figure 21 shows the Charpy V-notch impact toughness as a function of temperature for one of the developmental filler-metal compositions.(50) The term "mils expansion" refers to the Poisson broadening of the transverse dimension of the specimen in the vicinity of the fracture, and is one measure of the ductility. The weld metal was deposited using the GMA process (310 to 330 amperes, 27 to 30 volts, 11 ipm, 50 kilojoules/inch, Ar-1 percent 02 gas). Notches in the transverse Charpy specimens were oriented perpendicular to the plate surface. Curves similar to the one presented for other filler-metal compositions (given in the reference) show that impact properties are strong functions of composition. It can be seen from Figure 21, however, that this filler metal appears to have adequate toughness. It has a yield strength of 130 ksi. In general, the toughness-yield strength tradeoff has been one of the major problems in filler-metal development as it has in base-plate development. This is illustrated in Figure 22 by the data from Gross, which shows the impact strengths from a number of weld-metal compositions and the resulting toughness-yield strength envelope.(42) It is this inability to obtain both a high yield strength and a high toughness index in HY-130 steels that has been responsible for the lowering of the target yield strength from 150 to 130 ksi. Weld metals deposited by the SMA process generally have toughness properties inferior to those of GTA weld metals (Figure 23).(41)

Heat-Affected Zone

Grotke has reported the impact properties of HY-150 heat-affected-zone microstructures obtained using specimens prepared by duplicating the known weld thermal cycles at different distances from the fusion zone.(9) Impact specimens that had been cycled to 1400 F and 2400 F peak temperatures were tested with and without a subsequent 1200 F temper. The energy-absorption and fracture curves for these specimens are shown in Figures 24 and 25. Analysis of the vacuum-teemed heat from which the specimens came was as follows: 0.17 C, 0.35 Mn, 3.53 Ni, 1.63 Cr, 0.31 Mo, 0.10 V, 0.22 Si, 0.005 Ti, 0.005 Al, 0.008 P, and 0.009 S.

Heat-affected-zone impact properties, also determined using simulated welding cycles, were studied by Connor, Rathbone, and Gross for 52 heats of Ni-Cr-Mo-V steels of varying composition.(62) Figure 26 shows the data obtained from one of these heats. The resulting curves can be considered as profiles of impact properties across the heat-affected zone. Although there is a minimum in the impact strengths for the peak temperature of 1300 F, all of the impact-energy absorption values are 60 ft-lb or higher. The weld heat-affected-zone cracking that has been a problem with HY-80 has not given difficulties with the HY-130 type steels. Adams and Corrigan have shown that the residual stresses are distributed differently in welds made in these two types of material.[63] They found that the stress in the fusion zone of HY-130/150 was lower than that in HY-80 by as much as a factor of 5, and that such stress maxima as existed in the HY-130/150 weldments that they examined were located in the heat-affected zones. They attributed the unusual stress distribution in HY-130/150 welds to the transformation of austenite at relatively low temperatures.



Weld-Metal Composition

Element	Percent
C	0.06
Mn	1.67
Si	0.37
Ni	2.55
Cr	0.36
Mo	0.49
Cu	< 0.01
P	0.006
S	0.006

Tensile Properties

Yield strength 0.2% offset, ksi	130
Tensile strength, ksi	137
Elongation in 2 in., %	19
Reduction of area, %	64
Charpy V-notch impact properties Energy absorption at –60 F, ft-lb	100
Transition temp. at 20 ft-lb, F	<–150
Comments	Sound

FIGURE 21. NOTCH TOUGHNESS AND DUCTILITY OF EXPERIMENTAL HY-130 WELD METAL.[50]

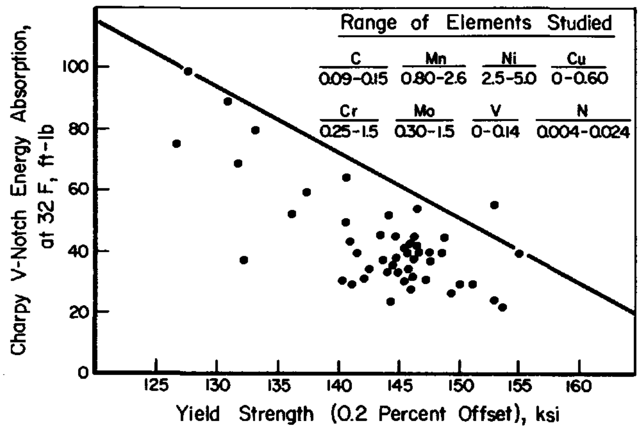


FIGURE 22. YIELD-STRENGTH-NOTCH-TOUGHNESS RELATION FOR HY-130-TYPE CARBON-MARTENSITE WELD METALS.[42]

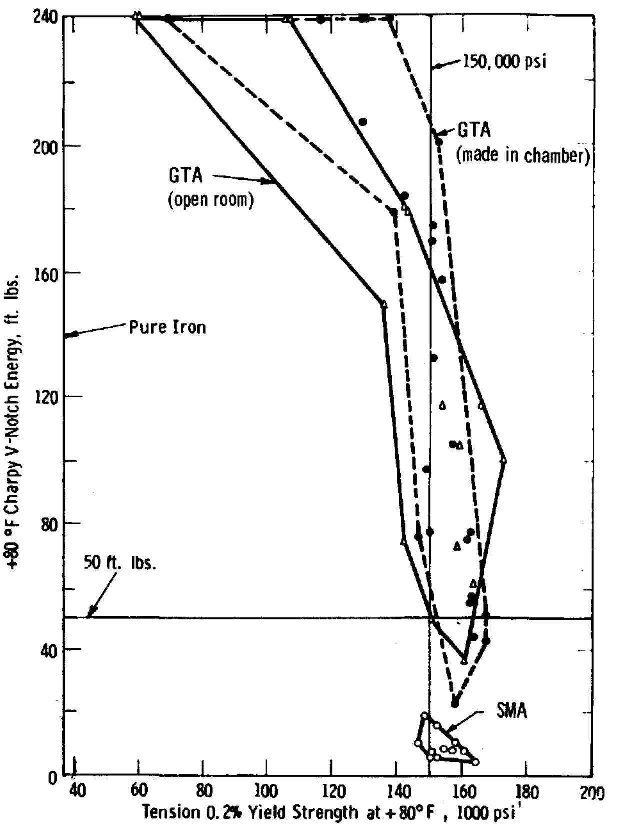


FIGURE 23. IMPACT ENERGY AND 0.2% YIELD STRENGTHS FOR AS-DEPOSITED HY-130 WELD METALS.[41]

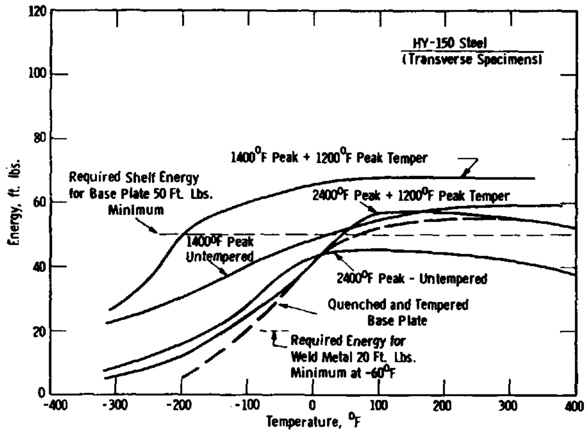


FIGURE 24. PERFORMANCE SUMMARY FOR SIMULATED HEAT-AFFECTED ZONES IN HY-150 STEEL IN VARIOUS CONDITIONS–ENERGY.(9)

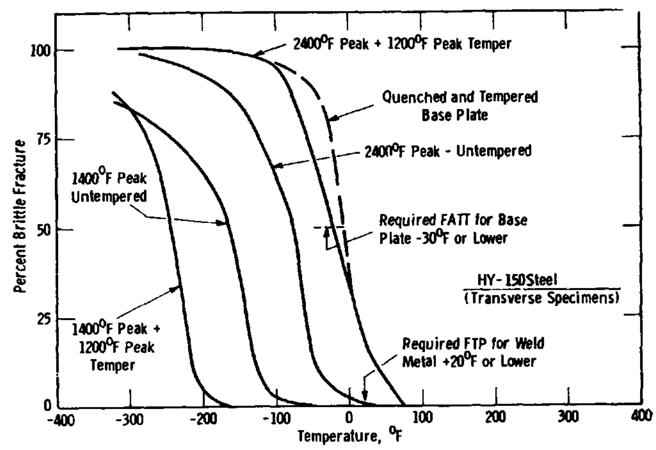


FIGURE 25. PERFORMANCE SUMMARY FOR SIMULATED HEAT-AFFECTED ZONES IN HY-150 STEEL IN VARIOUS CONDITIONS–FRACTURE APPEARANCE.(9)

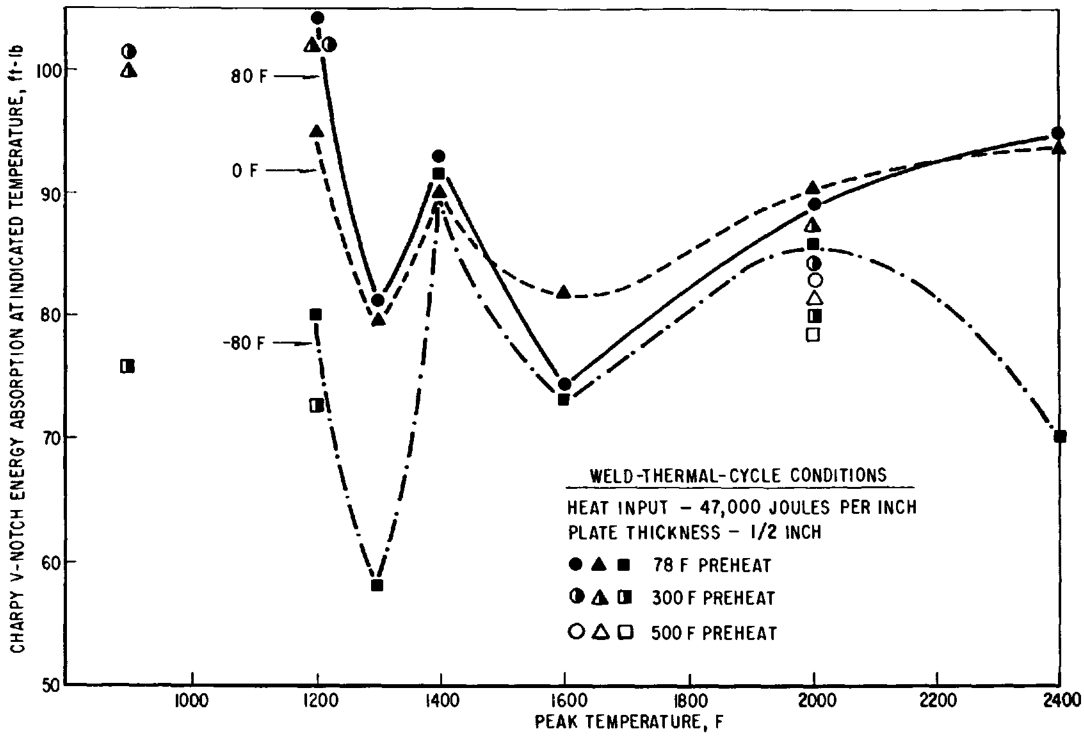


FIGURE 26. CHARPY V-NOTCH ENERGY ABSORPTION AT VARIOUS REGIONS IN THE HEAT-AFFECTED ZONE OF 5 Ni-Cr-Mo-V STEEL (HEAT NO X53185).(62)

Plane-Strain Fracture Toughness

Tiffany, Masters, and Regan estimated a K_{Ic} for GTA welds in 1-inch-thick HY-150 plate to be in excess of 250 ksi $\sqrt{\text{inch}}$.(56) In a test vessel having an artificially prepared surface crack 0.79 inch deep by 2.44 inches long in a longitudinal weld, the crack being submerged in seawater, they demonstrated the leak-before-failure characteristics of the material by pressurizing the vessel to 143 ksi before crack propagation through the thickness occurred. Experimental values of K_{Ic} obtained by United States Steel Corporation for HY-130(T) SMA welds were 142 and 163 ksi$\sqrt{\text{inch}}$, depending on notch orientation.(64)

Corrosion and Stress Corrosion

United States Steel Corporation(65) is studying corrosion and stress corrosion of unwelded plate and weldments of HY-80 and HY-130(T) steels exposed to seawater in total immersion, in the tide zone, in a trough with flowing water, and in a marine atmosphere. Tests, still in progress, will be continued for a total of 4 years.

In 2-year tests, the corrosion behavior of HY-130(T) steel specimens was substantially equivalent to that of the HY-80 steel. Weldments of HY-130(T) steel in 2-year, seawater tests showed less corrosion than did weldments of HY-80 steel. (See Figures 27 and 28). In seawater, the HY-80 steel weldments were corroded most in the weld metal and in the base metal, and considerably less in the heat-affected zone. For the HY-130(T) steel weldments, the difference in corrosion rates of the base metal, weld metal, and heat-affected zone was appreciably less than that for the HY-80 steel weldments.

In the marine atmosphere, the corrosion rates after 2 years of exposure were relatively low and about the same for the HY-80 and HY-130(T) steels.

Both steels–unwelded plate and welded HY-80 and HY-130(T) steels–were resistant to stress-corrosion cracking in marine atmospheres and in shallow seawater. In the deepsea corrosion and stress-corrosion tests, one set of HY-130(T) unwelded plate and welded specimens was exposed for 6 months at a nominal depth of 2500 feet and another set for about 1 year at a nominal depth of 6000 feet. The stress-corrosion specimens were U-bend specimens. There were no cracks in the unwelded plate or welded HY-130(T) steel specimens exposed at 2500 feet. One U-bend stress-corrosion specimen of HY-130(T) containing a transverse weld section failed by stress corrosion through the weld metal after exposure at the 6000-foot depth. There is a question whether a crack had been initiated during bending of the specimen, however, and the filler metal used had been one that later proved crack-susceptible. No other U-bend specimens have failed thus far. The specimens exposed at 2500 and 6000-foot depths showed only a moderate amount of corrosion. There was no indication of galvanic attack between base metal and weld metal. On the basis of these tests, corrosion and stress corrosion of HY-130(T) is not expected to be a serious problem.

United States Steel Corporation also has investigated the effect of notch orientation on the susceptibility of HY-130(T) weld metal to stress-corrosion cracking.(64) Notch orientation was studied because the possibility exists that stress-corrosion cracks may propagate parallel to the weldment surface in a structure as well as perpendicular to the surface. The welds were deposited by the SMA process using E-14018 covered electrodes. The weld metal was notched parallel to the weldment surface in one group of specimens and perpendicular to the weldment surface in another group. A fatigue crack was induced at the notch. The cantilever-beam specimens were dead-weight loaded to failure. The apparent critical plane-strain, stress-intensity factor, K_{Ic}, was determined for specimens loaded in air. The critical plane-strain, stress-corrosion-crack intensity factor, K_{Iscc}, was determined for specimens immersed in 3-percent sodium chloride solution. The results of these tests are shown in Figure 29. The results showed that the K_{Ic} and K_{Iscc} values were higher for specimens having the notch parallel with the weldment surface.

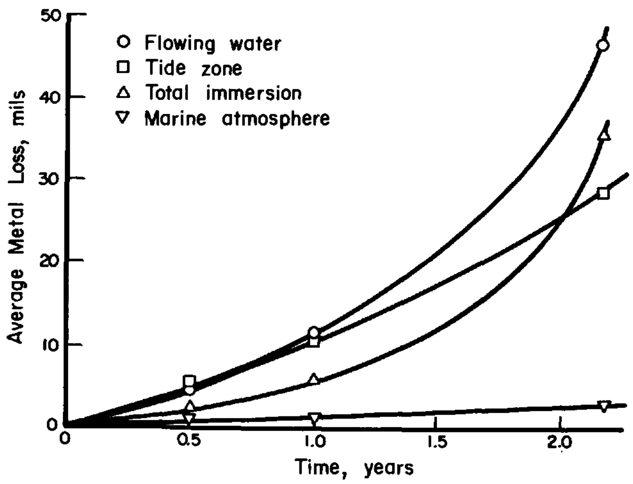


FIGURE 27. WELD-METAL CORROSION OF HY-80 STEEL WELDMENTS IN MARINE ENVIRONMENTS.(65)

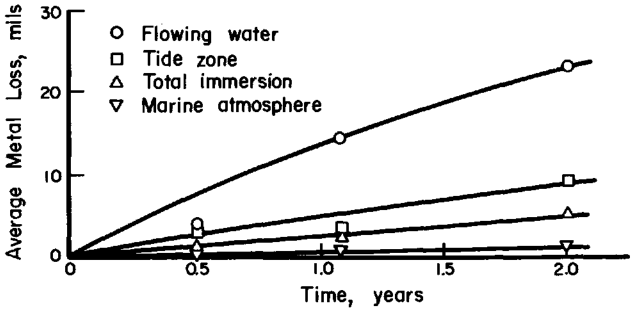


FIGURE 28. WELD-METAL CORROSION OF HY-130(T) STEEL WELDMENTS IN MARINE ENVIRONMENTS.(65)

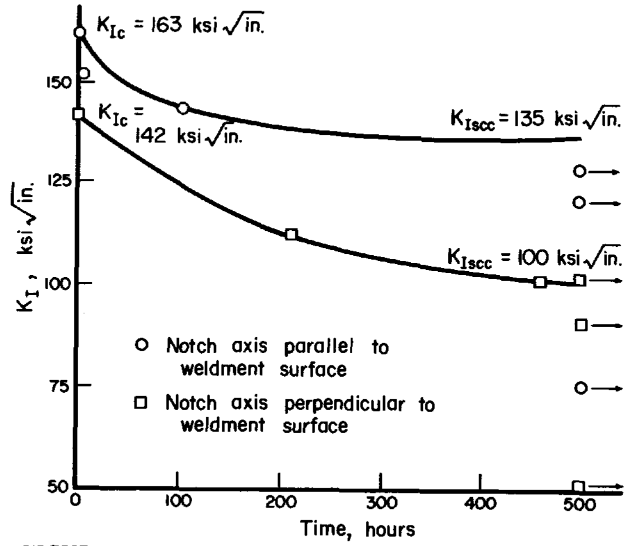


FIGURE 29. EFFECT OF NOTCH ORIENTATION ON K_{Iscc} BEHAVIOR OF HY-130(T) SMA WELD METAL.(64)

Explosion-Bulge Properties

Results of explosion-bulge tests of HY-130(T) weldments have been reported by Rathbone.(66) Test specimens from four heats of 2-inch plate were welded using the SMA process in the vertical position by three subcontractors on the United States Steel Corporation program; Air Reduction Company, Arcos Corporation, and The McKay Company. United States Steel Corporation prepared explosion bulge weldments of HY-80 using a Class E-11018 electrode material for reference. Each subcontractor used his preferred welding conditions, electrode composition, and coating. Base-plate compositions, welding conditions, weld-metal compositions, and weld-metal mechanical properties are given in Tables 25 through 28.

Weldment specimens were explosion-bulge tested at +30 F using an 18-inch-diameter circular die and a 17 inch standoff distance for the explosive charges. Size of the charges was adjusted to produce similar amounts of plastic deformation per shot. This resulted in a 42-lb Pentolite charge for the HY-130(T) and a 24-lb charge for the HY-80. A summary of the test results is given in Table 29. Complete descriptive information and photographs of the specimens are given in the original report. On the basis of the limited thickness reduction, the limited amount of bulging, and the frequent occurrence of fractures along the edge of the fusion zone, the author of the referenced report classified the explosion-bulge-test performance of the HY-130(T) weldments as marginal.

TABLE 25. COMPOSITION AND PROPERTIES OF 2-INCH-THICK PLATES FROM WHICH EXPLOSION-BULGE WELDMENTS WERE FABRICATED(66)

Steel	Heat	Plate Chemical Composition, percent: C	Mn	P	S	Si	Ni	Cr	Mo	V
HY-80	66U438	0.17	0.38	0.018	0.016	0.18	2.58	1.56	0.30	
HY-130(T)	5P0323	0.12	0.68	0.004	0.006	0.28	4.85	0.54	0.40	0.05
HY-130(T)	3P0365	0.12	0.75	0.003	0.004	0.28	4.95	0.57	0.46	0.07
HY-130(T)	5P0540	0.12	0.79	0.004	0.005	0.35	4.96	0.57	0.41	0.06

Specimen Set	Heat	Plate	Orientation	Tensile Properties(a): Yield Strength (0.2 percent offset), ksi	Tensile Strength, ksi	Elongation in 2-Inches, percent	Reduction of Area, percent	Charpy V-Notch(a) Energy Absorption, ft-lb: +30 F	0 F
HY-80	66U438	0117727	Longitudinal	84	103	27.0	75	146	
U. S. Steel			Transverse	86	105	24.0	68	89	
HY-130(T) Steel	3P0365	0178588A	Longitudinal	133	146	20.0	65	94	92
Air Reduction			Transverse	136	147	18.0	62		58
HY-130(T) Steel	5P0540	0233631A	Longitudinal	142	152	19.0	65	90	81
Arcos			Transverse	140	150	19.0	63	74	73
HY-130(T) Steel	5P0323	0143624A	Longitudinal	137	144	19.0	64	72	71
McKay			Transverse	141	148	16.0	55	66	60

(a) Average of two tests.

TABLE 26. CONDITIONS USED TO FABRICATE 2-INCH-THICK COVERED-ELECTRODE EXPLOSION-BULGE WELDMENTS(66)

	HY-80 Steel U. S. Steel	HY-130(T) Steel Air Reduction	HY-130(T) Steel Arcos	HY-130(T) Steel McKay
Position	Vertical Up	Vertical Up	Vertical Up	Vertical Down
Electrode Diameter, inch	1/8, 5/32	5/32	5/32	5/32
Current (DCRP), amperes	120,140	150	125	190
Voltage, volts	22, 22	22	20	24
Average Travel Speed, ipm	2.9,2.6	3.9	4.7	11.5
Preheat and interpass temperature, F	200 to 300	200 to 300	225 to 275	275
Total Number of Passes	26	38	33	60
Joint Geometry	60-degree, double V	60-degree, double V	60-degree, double V	45-degree, double V
Root Opening, inch	1/8	1/8	1/8	5/32

TABLE 27. COMPOSITIONS OF WELD METALS FROM 2-INCH-THICK EXPLOSIVE -BULGE WELDMENTS(66)

Item	Specimen Set	Composition of Tension-Test Specimens, percent(a): C	Mn	P	S	Si	Ni	Cr	Mo	Al(b)	N(c)	O(d)
A	HY-80 Steel U. S. Steel	0.073	1.70	0.015	0.014	0.39	1.86	0.42	0.32	ND	0.010	324
B	HY-130(T) Steel Air Reduction	0.11	1.98	0.004	0.013	0.45	2.21	0.86	0.50	0.012	0.012	306
C	HY-130(T) Steel Arcos	0.099	1.92	0.005	0.007	0.45	3.58	0.65	0.48	0.007	0.010	226
D	HY-130(T) Steel McKay	0.062	1.80	0.005	0.006	0.52	2.10	0.78	0.41	0.009	0.017	389

(a) All analyses were obtained from the reduced section of all-weld-metal 0.505-inch-diameter tension-test specimens. ND–not determined.
(b) Total.
(c) Kjeldahl determination.
(d) Results are in ppm.

TABLE 28. MECHANICAL PROPERTIES OF WELD METALS FROM 2-INCH-THICK EXPLOSION-BULGE WELDMENTS[66]

		All-Weld-Metal Tensile Properties[a]				Charpy V-Notch Impact Properties[b]					
						Energy Absorption, ft lb			Fibrous Fracture, percent		
Item	Specimen Set	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 2 Inches, percent	Reduction of Area, percent	+30 F	0 F	-60 F	+30 F	0 F	-60 F
A	HY-80 Steel U. S. Steel	120	132	19.0	60	56	46	--	90	80	--
B	HY-130(T) Steel Air Reduction	145	153	16.8	56	53	41	34	98	85	70
C	HY-130 (T) Steel Arcos	141	158	17.1	50	35	30	21	88	50	28
D	HY-130(T) Steel McKay	141	146	14.0	43	52	47	27	80	65	35

(a) Average of four 0.505-inch-diameter specimens.
(b) Average of two specimens.

TABLE 29. SUMMARY OF RESULTS OF EXPLOSION-BULGE TESTS OF COVERED-ELECTRODE WELDMENTS[66]

		Explosive Loads and Thickness Reduction Associated With Extensive Crack Propagation						
		HY-80 Steel Weldment	HY130(T) Steel Weldments					
		Item A	Item B		Item C		Item D	
Specimen Geometry	Test Measurement	Vertical	Flat[a]	Vertical	Flat[a]	Vertical	Flat[a]	Vertical
With reinforcement	Number of Shots	4	3	2	2	2	3	2
	Thickness reduction, percent	14.9	10.3	6.2	6.7	4.7	14.1	4.8
Without reinforcement	Number of Shots	6	4	3	4	3	4	3
	Thickness reduction, percent	28.0	17.6	12.7	18.3	11.6	19.3	8.3

(a) Data obtained from previous explosion-bulge tests.

Hydrogen Content of HY-130 Weld Metal

As previously mentioned, HY-130 does not appear to be proportionately more difficult to weld than HY-80. In fact, the heat-affected-zone cracking that has been a problem with HY-80 does not appear to be severe with HY-130, probably because of its different transformation kinetics.[10, 67] Like any high-yield-strength steel, however, HY-130 is more sensitive than is HY-80 to contamination from gases and such elements as carbon, sulfur, and phosphorus. The presence of excessive amounts of one or more of these elements can cause weld-metal cracking of the type sometimes reported in HY-130 welds. Because of this sensitivity, carbon is purposely kept as low as is consistent with attaining the desired yield strength; sulfur and phosphorus are kept as low as possible; and every effort is made to exclude moisture, hydrogen, oxygen, and nitrogen from the electrodes and coatings. Figure 30 shows the possible effects of exceeding the allowable hydrogen content of GMA electrode wire and SMA electrode coatings on weld-metal cracking in HY-130 weldments.[42]

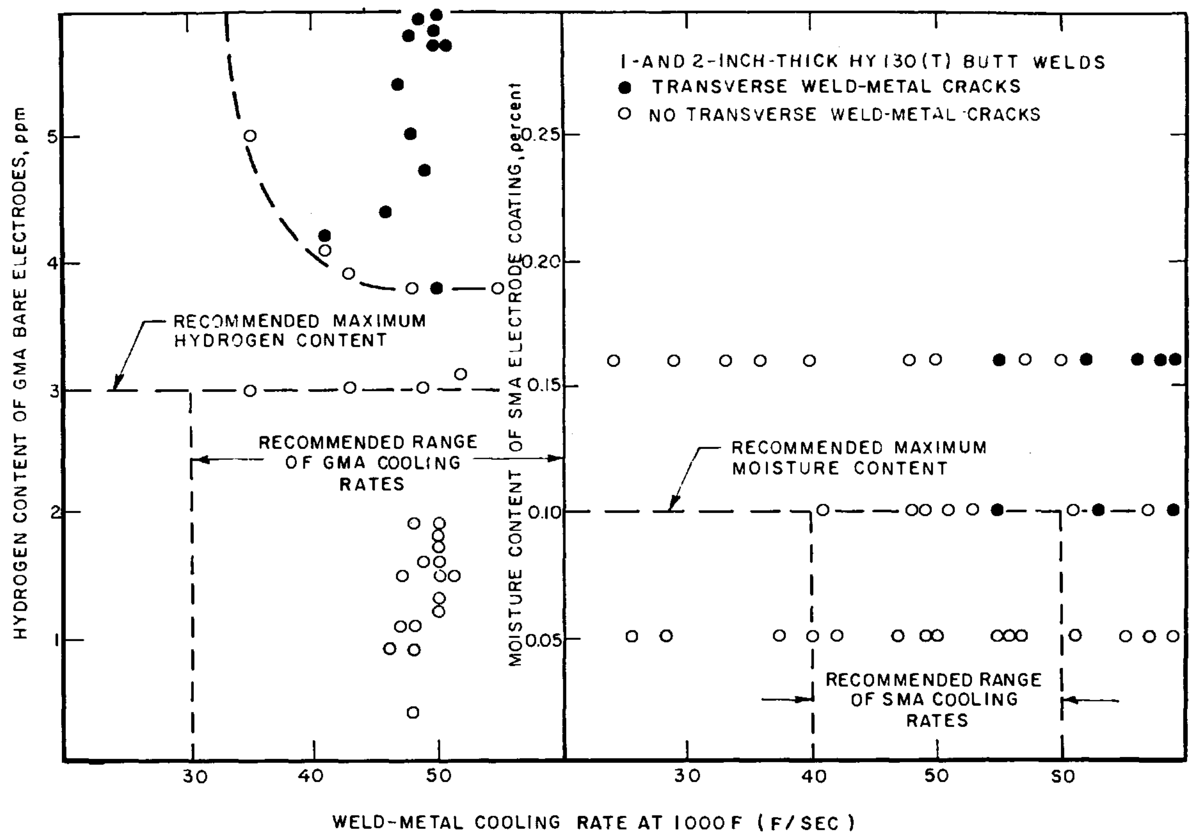


FIGURE 30. EFFECT OF HYDROGEN IN GAS METAL-ARC (GMA) BARE ELECTRODES AND MOISTURE IN SHIELDED METAL-ARC (SMA) ELECTRODE COATINGS ON WELD-METAL CRACKING.(42)

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