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SSC-262

PREVENTING DELAYED CRACKS IN SHIP WELDS

Part II

SHIP STRUCTURE COMMITTEE
1976

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SR 210

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Delayed cracking is a matter of serious concern in some ship weldments.

The Ship Structure Committee undertook a project to prepare a shipyard guide to aid in preventing such cracks. SSC-261 contains that guide. It explains in simple and condensed form the causes of delayed cracking and means of prevention. It is intended to be useful for shipyard personnel who do not have a technical background. For this reason detailed technical explanations are avoided.

This report contains the technical background which was developed to support the recommendations in SSC-261.

W. M. Benkert
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-262

Final Report

on

Project SR-210, "Delayed Cracking Phenomena"

PREVENTING DELAYED CRACKS IN SHIP WELDS

PART II

by

H. W. Mishler

Battelle Memorial Institute

under
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Washington, D.C.
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ABSTRACT

This report discusses the causes of delayed cracking in ship steel welds and presents the steps necessary to prevent delayed cracking. Three factors, acting together, are responsible for the formation of delayed cracks: hydrogen dissolved in the weld, a hard microstructure in the weld or heat-affected zone, and high stresses in the weld joint. Each step that is taken to prevent delayed cracks has the purpose of eliminating or significantly reducing at least one of these factors.

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NOTES

A QUICK GUIDE TO DELAYED CRACKING

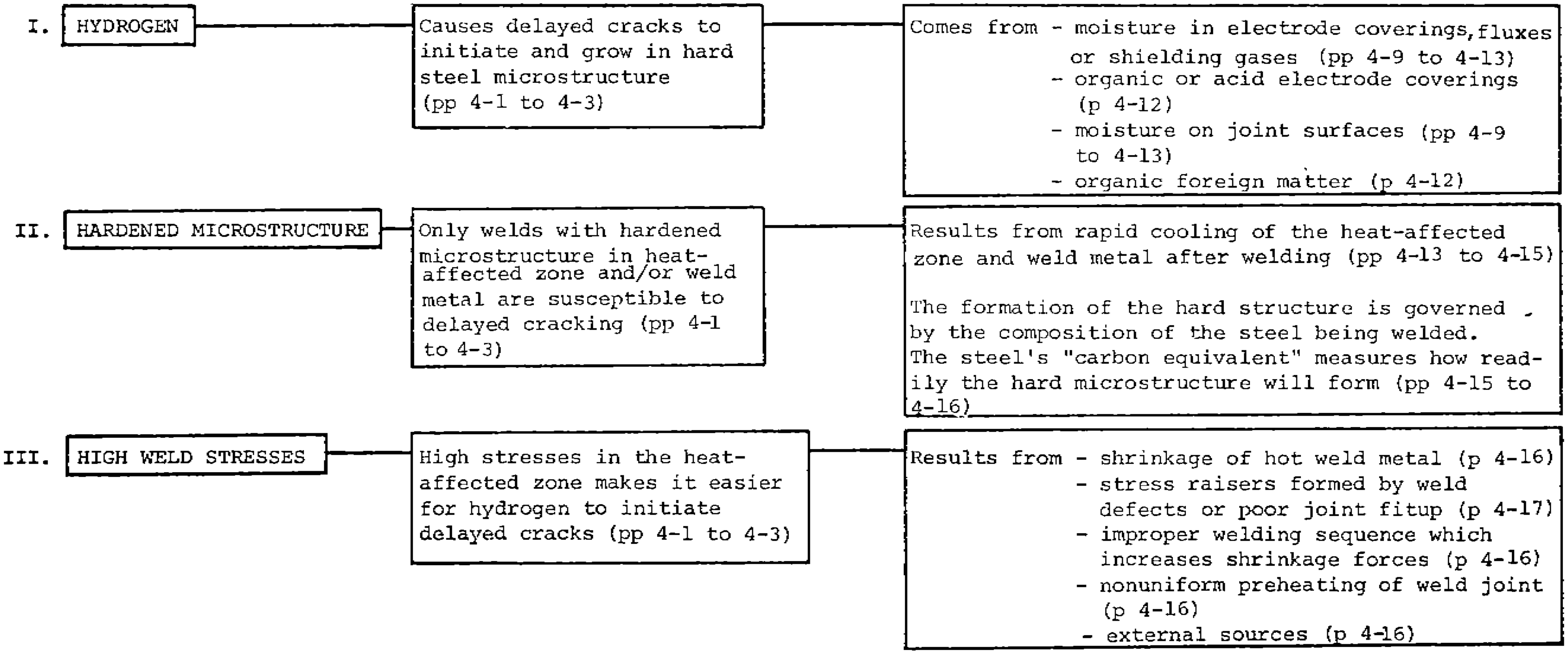
This guide provides both a synopsis of and a rapid reference to the causes of delayed cracking and the steps necessary to prevent delayed cracking. Figures 1 and 2 are "at a glance" summaries of the causes and preventive measures. The items listed in these two summaries are discussed in detail in the body of the manual. These details include items such as preheating temperatures, procedures of baking and handling covered electrodes, how to calculate carbon equivalents, etc. The pages on which these details may be found are noted in parentheses.

The methods of preventing delayed cracking are not unusual nor are they difficult to follow. The main thing is that the procedures must be executed thoroughly and with the full cooperation of everyone connected with the welding operation.

Three factors, acting together, are responsible for the formation of delayed cracks: hydrogen dissolved in the weld, a hard microstructure in the weld metal or heat-affected zone, and high stresses within the weld joint. Each step that is taken to prevent delayed cracks has the purpose of eliminating or significantly reducing at least one of these factors. If the steel being welded is susceptible to delayed cracking, the first and easiest step is to keep hydrogen from entering the weld metal. One of the major sources of hydrogen can be the welding electrode. This source is removed by using low-hydrogen type electrodes that have been properly baked and stored or by using gas-shielded or submerged-arc welding. The other major source of hydrogen, condensed moisture on the weld joint, is removed by preheating.

Preheating and maintaining a minimum interpass temperature also help to prevent the formation of a hard microstructure in the weld metal and heat-affected zone. Preheating, keeping a specified minimum interpass temperature, and increasing welding heat input slows down the cooling rate of the joint so that the heat-affected zone has a soft microstructure. Special precautions are required if quenched-and-tempered steels are being welded. The heat-affected-zone microstructure of these steels must not be changed or a serious loss of toughness will occur. Maximum limits have been set on preheat and interpass temperature and welding heat input for quenched-and-tempered steels.

There will always be some stresses in a weld joint due to shrinkage of the weld metal as it cools. However, these stresses can be kept low if the proper steps are taken. Avoid overwelding and use good joint fitup. This keeps the volume of weld metal low so there is less metal to shrink and create these stresses. Prevent or remove weld defects that act to concentrate these stresses in localized areas. "Sharp" weld defects such



I. HYDROGEN

Causes delayed cracks to initiate and grow in hard steel microstructure (pp 4-1 to 4-3)

Comes from
- moisture in electrode coverings, fluxes or shielding gases (pp 4-9 to 4-13)
- organic or acid electrode coverings (p 4-12)
- moisture on joint surfaces (pp 4-9 to 4-13)
- organic foreign matter (p 4-12)

II. HARDENED MICROSTRUCTURE

Only welds with hardened microstructure in heat-affected zone and/or weld metal are susceptible to delayed cracking (pp 4-1 to 4-3)

Results from rapid cooling of the heat-affected zone and weld metal after welding (pp 4-13 to 4-15)

The formation of the hard structure is governed by the composition of the steel being welded. The steel's "carbon equivalent" measures how readily the hard microstructure will form (pp 4-15 to 4-16)

III. HIGH WELD STRESSES

High stresses in the heat-affected zone makes it easier for hydrogen to initiate delayed cracks (pp 4-1 to 4-3)

Results from
- shrinkage of hot weld metal (p 4-16)
- stress raisers formed by weld defects or poor joint fitup (p 4-17)
- improper welding sequence which increases shrinkage forces (p 4-16)
- nonuniform preheating of weld joint (p 4-16)
- external sources (p 4-16)

FIGURE 1. THE THREE FACTORS RESPONSIBLE FOR DELAYED CRACKING

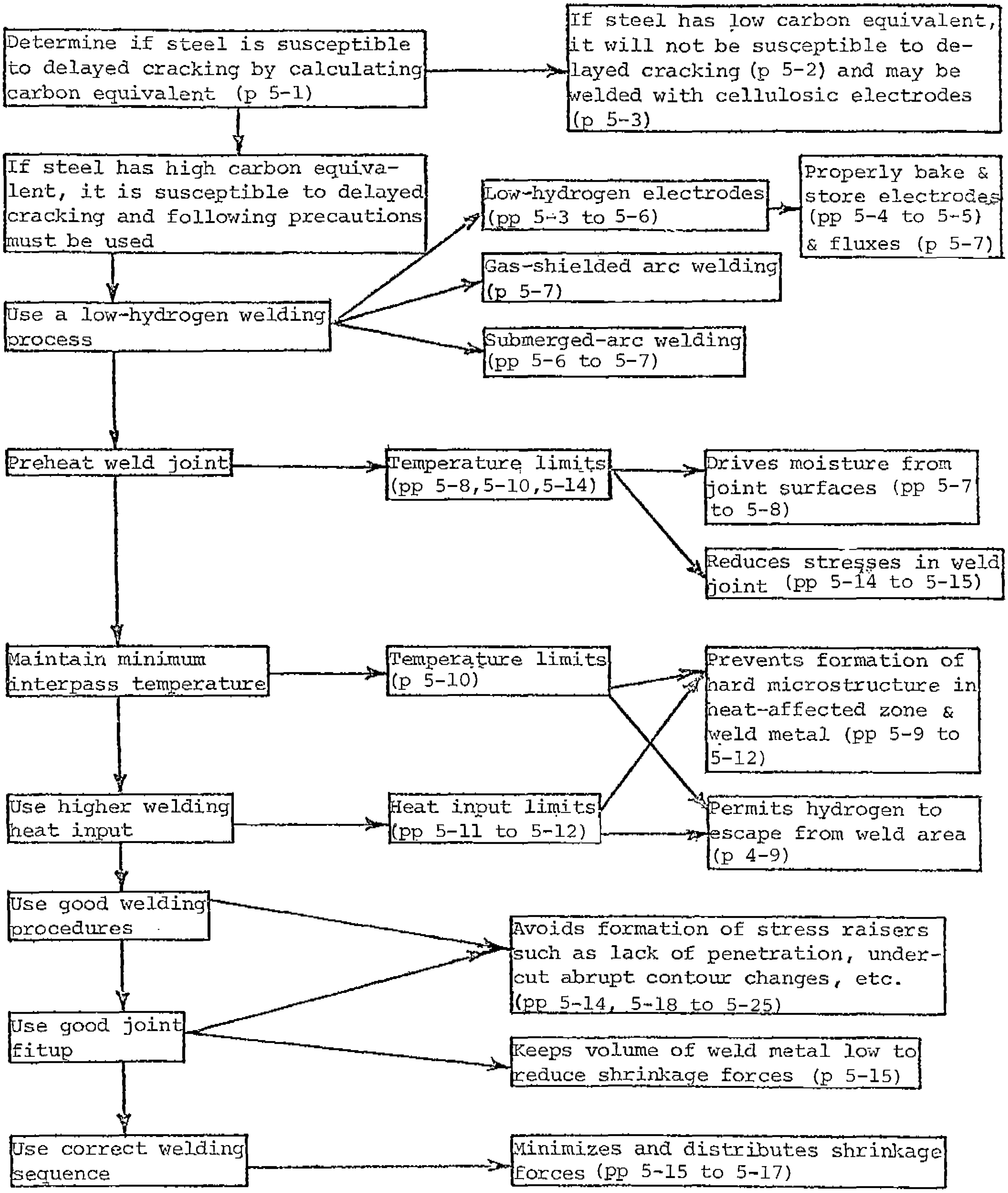


FIGURE 2. STEPS REQUIRED TO PREVENT DELAYED CRACKING

as undercut or lack of penetration and abrupt changes in weld contour can raise stresses to the point where a delayed crack will be triggered. Preheating provides still another beneficial effect by also reducing shrinkage forces.

INTRODUCTION

Delayed cracking in weld joints is a particularly nasty problem in the fabrication of welded structures, vessels, etc., from carbon and low-alloy steels. These cracks usually occur in the heat-affected zone of the weld joint although occasionally they will be found in the weld metal. The cracks develop over a period of time after welding is completed (thus the name "delayed cracking") and frequently will not be open to the surface. Since the cracks may not be apparent and since they take time to develop (several hours to several days), the cracks may go undetected and cause the weldment to fail in service. These failures are generally costly and may endanger life.

Although delayed cracks may be difficult to detect, they can be prevented with proper care. Precautions and procedures have been developed that will prevent delayed cracking, but they must be followed closely. The problem arises in obtaining close compliance with these procedures. Since the presence of delayed cracks is not obvious, it is easy to slacken off on these procedures and not see any adverse results. By the time any delayed cracks that have occurred are detected, it is hard to relate the occurrence with noncompliance to the specified procedures.

The initial portion of this manual is devoted to a discussion of how delayed cracks form and the factors related to the welding operation that cause delayed cracking. This background is intended to provide an appreciation of the delayed cracking problem and of the need for closely following the recommended procedures. The second portion of the manual describes the procedures to be followed to prevent delayed cracking in various ship steels. Close adherence to these procedures should provide the fabricator and welder with the ability to produce welds consistently that are free from delayed cracks.

NOTES

DELAYED CRACKS - WHAT ARE THEY AND WHY ARE THEY BAD?

Delayed cracks in a weld joint get their name because they do not appear until some time after the weld is completed. This time delay may be a matter of hours or even days. After a sequence of certain events takes place, the crack initiates on a microscale. If conditions are right, this microcrack slowly grows until it is large enough to be seen either visually or by means of various nondestructive inspection techniques. By this time, though, the damage has been done and the cracked portion of the weld joint must be removed and rewelded. If allowed to remain, this delayed crack could trigger a catastrophic failure during service. Delayed cracks usually take several hours to develop. Under normal conditions, a delayed crack will be fully developed within 48 hours.

Delayed cracks can appear in several locations in a weld joint. These locations are illustrated in Figure 3 along with the designations of these locations. The first three types of delayed cracks are by far the most common. The transverse weld metal cracks are less frequently encountered as the weld metals usually have lower carbon content and upon cooling are less apt to form a microstructure susceptible to delayed cracking. One characteristic common to the three usual types of delayed cracks is that they occur in the heat-affected zone of the weld joint. These cracks will initiate very close to the fusion line and may propagate deeper into the heat-affected zone as they grow.

Underbead cracks are longitudinal and lie roughly parallel to the fusion line. A typical underbead crack is shown in Figure 4. Except for the extreme lower end, this crack lies entirely in the heat-affected zone. (Toe and root cracks have the same appearance except that they are in a different location.) They usually do not propagate to the surface so this means that they cannot be detected by any of the surface inspection methods (magnetic particle or dye penetrant). Ultrasonic inspection is the only reliable method of detecting underbead cracks. Root cracks also are longitudinal initiating at the weld root and growing into the heat-affected zone and/or weld metal. Root cracks in fillet welds cannot be detected by any practical means. Sophisticated ultrasonic inspection techniques have been used successfully but these are not usable under shop or production conditions. Root cracks in butt welds, though, can be detected reliably by ultrasonic inspection. Toe cracks occur along the edge of the weld and are open to the surface. Magnetic-particle and dye-penetrant inspection as well as ultrasonic inspection can be used to detect toe cracks. Delayed cracks usually are very tight so they are extremely difficult to detect visually. For this reason, visual inspection is not a reliable technique.

Figure 3 shows a toe crack that is located well below the surface of the joint (3A). A toe crack can occur in this location if the weld joint is only partially filled and returns to ambient temperature and a time period long enough for the crack to develop elapses before the weld is completed.

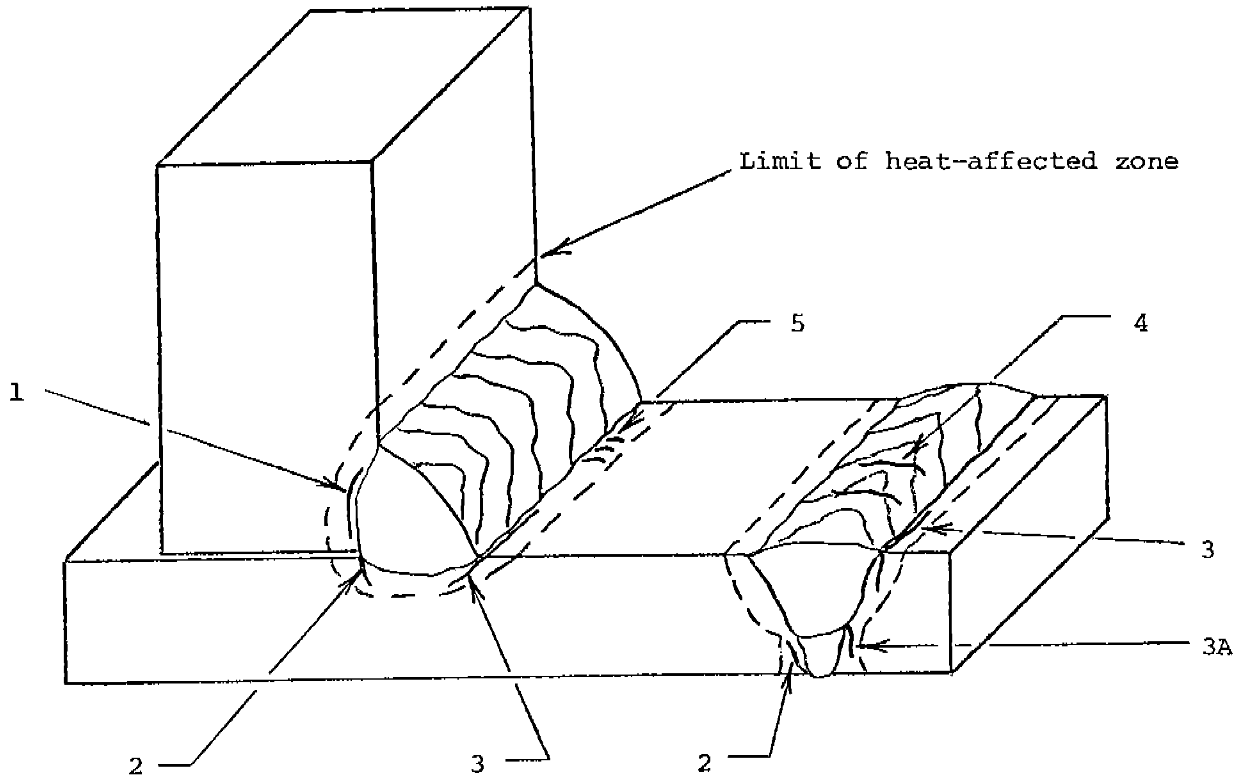


FIGURE 3. LOCATIONS AND DESIGNATIONS OF DELAYED CRACKS

1. Underbead crack
2. Root crack
3 & 3A. Toe crack
4. Transverse weld-metal crack
5. Transverse heat-affected zone crack

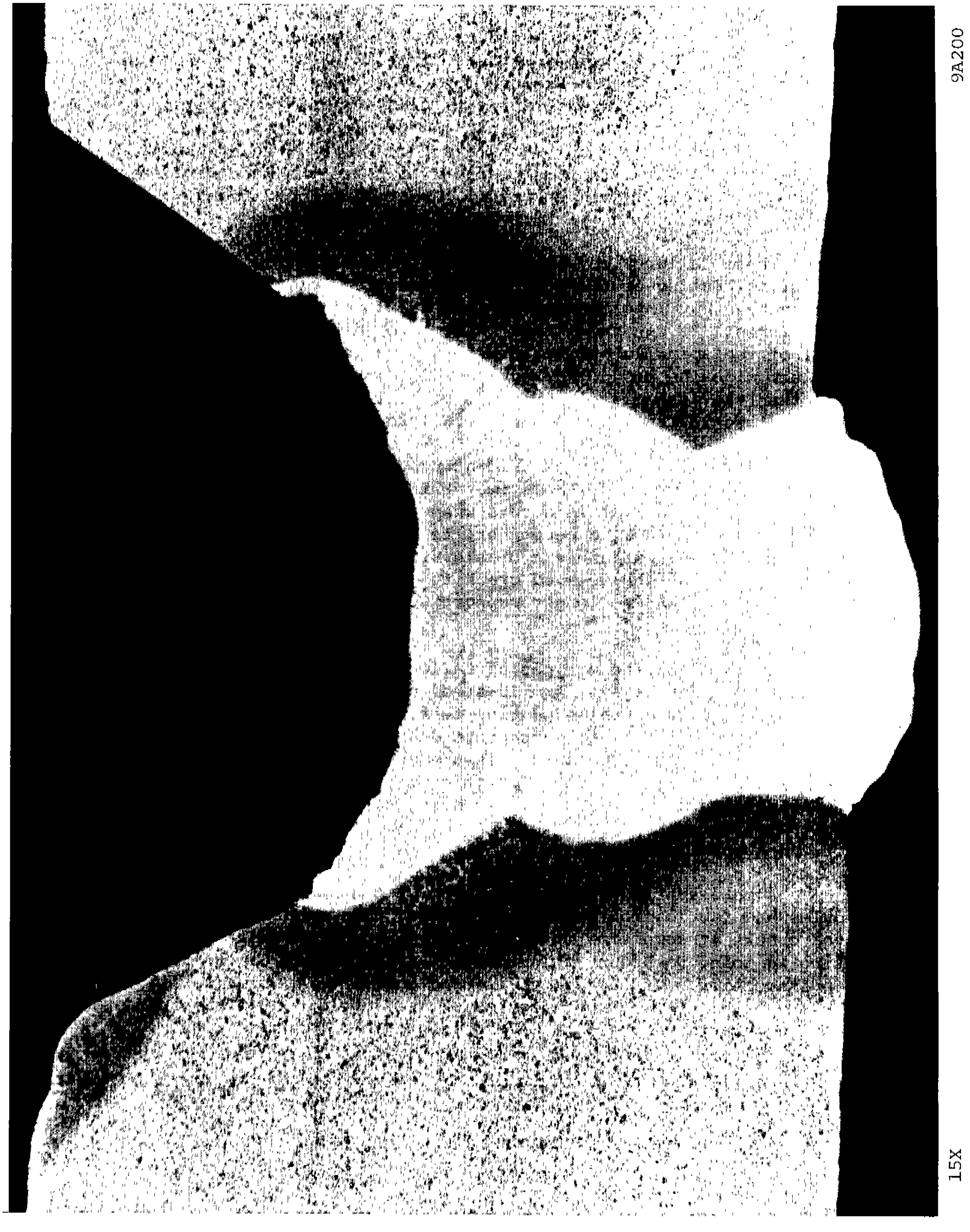


FIGURE 4. AN EXAMPLE OF AN UNDERBEAD CRACK

Obviously, there must be something bad about delayed cracks since people are so anxious to avoid them. The reason is simple - delayed cracks can cause welded parts to fail under service stresses. Root and toe cracks probably are the most serious as the welded joints usually experience some bending loads so the surfaces are stressed higher than the interior of the joint. Also, root and toe cracks frequently are associated with other weld surface defects such as undercutting or incomplete penetration. These surface defects increase the concentration of stresses in the vicinity of the crack. Under these conditions, the delayed crack is even more apt to initiate failure of the joint.

These failures may happen while the parts still are being fabricated, during testing of the parts before service, or, worse yet, after the parts have been put into service. Financial loss can be considerable in these failures. It can range from the cost of making a simple repair to the cost of replacing an entire structure plus loss of revenue that the welded item might be producing and possible liability penalties. Of more concern than the financial loss is the possible personal injury or loss of life that could result from such a failure.

Delayed cracks act as initiating points for fracture when the part is loaded or stressed. Sometimes this is a brittle fracture that occurs rapidly. Usually this occurs when the operating temperature drops low enough for the steel to become brittle. Delayed cracks can start fatigue failures even at ambient or elevated temperatures. Repeated cycles of stress will cause the delayed crack to grow gradually until it is so big that the structure can no longer support its operating load. Failure then occurs.

Examples of these types of failures come from the chemical and bridge building industries. A mild-steel heavy wall heat exchanger for a chemical installation failed during testing (Figure 5).(1)* Delayed toe cracks triggered a brittle fracture during pressure testing. The temperature of the water used to pressure the heat exchanger was 40 F, well below the temperature at which this steel became brittle. In 1962, the newly constructed Kings Bridge in Melbourne, Australia, collapsed due to the development of fractures from delayed toe cracks in welds in one of the supporting spans.(2)

A more subtle effect of delayed cracks is the effect on production schedules and fabrication costs. The usual procedure is to inspect for delayed cracks at some time interval after a weld is completed. If delayed cracking is going to occur, this time interval permits the cracks to develop before inspection. If inspection is done immediately after welding, the cracks may occur after inspection has okayed a weld. USCG requirements call for a delay of seven days before inspection. This delay extends total production times, and requires space for storing welded components while awaiting inspection. If delayed cracks do occur, considerable time and expense is

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* References are given in Section 6.

required to remove the cracks, make repair welds, wait again for seven days, and reinspect. If delayed cracks could be prevented with certainty, this delay time could be significantly reduced or perhaps even eliminated.

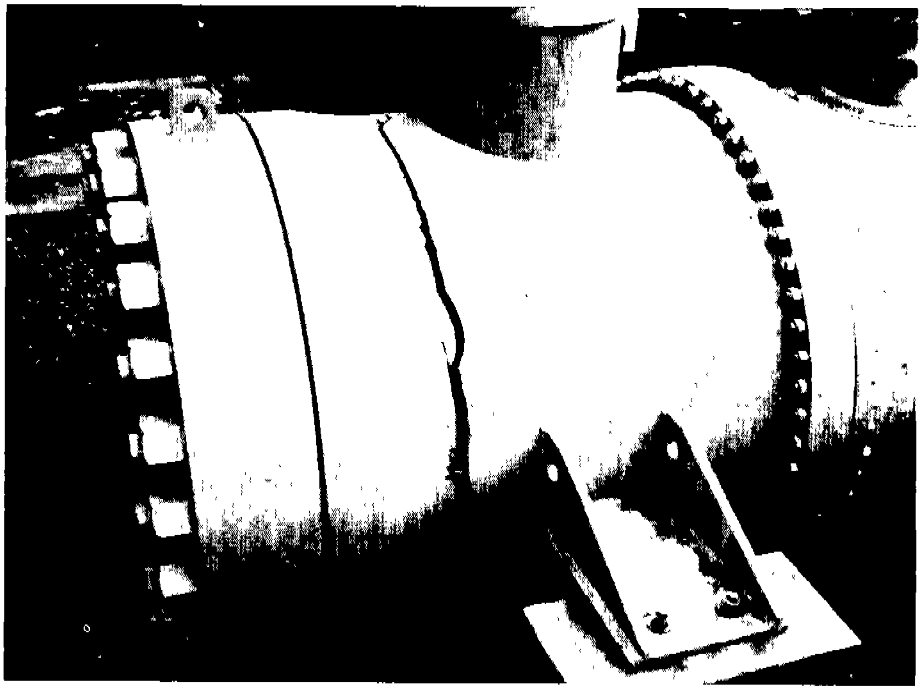


FIGURE 5. FRACTURE IN HEAT EXCHANGER THAT STARTED AT A DELAYED TOE CRACK

NOTES

CAUSES OF DELAYED CRACKS

Three conditions are required for delayed cracking to occur in a weld joint:

- Hydrogen must be present.
- The heat-affected zone and/or weld metal must have a hardened microstructure.
- The weld joint must have significant internal stresses.

These three conditions must act in combination to cause delayed cracking. The formation or absence of the hardened microstructure will determine whether or not delayed cracking can occur. If the steel is susceptible to delayed cracking, the amount of hydrogen present and the level of stresses in the joint providing both are above a threshold level determine how quickly the crack will develop. Some steels are very susceptible to delayed cracking; cracks in these steels will develop at low internal stress levels and at a low concentration of hydrogen. Steels that are less susceptible will tolerate high levels of hydrogen and/or higher internal stresses.

Delayed cracking susceptibility of a steel is governed by its composition. This is because the degree to which the joint heat-affected zone hardens as it cools after welding depends on the steel's composition. Low-carbon steels do not harden readily and, thus, have low susceptibility to delayed cracking. Higher carbon and low-alloy steels harden more readily and are more prone to delayed cracking. In certain hardenable steels, the degree of hardening can be decreased through control of welding heat input, cooling rate, and other procedural factors.

Hydrogen is introduced into the weld joint from the gas envelope that surrounds the welding arc. The welding arc breaks down any hydrogen bearing compounds that it encounters, a process which provides free hydrogen that can be dissolved by the weld metal. Typical sources of hydrogen compounds include damp electrode coverings, moisture on weld joint surfaces, or electrodes with organic or titania coverings. The use of electrodes with basic coverings, the use of a gas-shielded process or submerged-arc welding, or the elimination of moisture will reduce the risk of hydrogen pickup.

Stresses build up in a weld joint as it cools and shrinks after welding. The magnitude of these stresses are influenced by the joint design, plate thickness, and welding procedure. These stresses can be controlled to a degree through welding procedures that reduce or more evenly distribute the amount of shrinkage that occurs.

Mechanism of Delayed Cracking

No one really knows what the exact mechanism of delayed cracking really is, but a variety of theories have been proposed to explain what is happening. Three of these have been generally accepted, but at different times. The planar pressure theory was the first; it was superceded by the adsorption theory; currently, the triaxial stress theory seems to offer the best explanation.

The planar pressure theory suggests that as hydrogen atoms diffuse through the steel, they congregate in microvoids and other microscopic and submicroscopic defects. The hydrogen atoms recombine into hydrogen molecules in these microvoids. This formation of hydrogen molecules builds up very high hydrostatic pressures which trigger the initiation of a microscopic fracture or crack. As more hydrogen diffuses into this microcrack, further pressure buildup occurs and the crack grows. Ultimately, the crack reaches a macroscopic scale where it can be seen or detected by various inspection techniques.

Several variations of the planar pressure theory have been developed. As an example, one of these suggests that the hydrogen in the microdefect helps to supply the energy needed to propagate the crack. As the crack or microvoid enlarges, the hydrogen gas within the void expands, an expanding gas releases energy. This energy release lowers the applied stress needed to propagate the crack. Continued crack growth requires a continued supply of hydrogen gas. Thus, the crack growth is time dependent as time is required for more gas to diffuse into the void from the surrounding steel.

A second major theory is the adsorption theory. It suggests that when diffusing hydrogen reaches a microvoid it is adsorbed on the surfaces of the microvoid. When this happens, the amount of energy required to propagate the microvoid is lowered. In a high stress field, these microvoids then will grow into major cracks. Again, the amount of hydrogen required to continue propagation must be supplied by diffusion.

Both of these theories fall down when trying to explain some of the other aspects of delayed cracking. For example, both theories require the existence of microvoids and explain how these microvoids propagate into cracks. They fail to deal with the initiation of cracks in the absence of microvoids. Also, heating will reduce the effects of hydrogen by speeding up the diffusion of hydrogen through the steel to outside surfaces where it will escape. To diffuse through metal, hydrogen must be in the atomic form. Molecular hydrogen in microvoids will not be broken down into atomic hydrogen by this heating. These theories fail to resolve this point. The triaxial stress theory fills these gaps.

The triaxial stress theory says that hydrogen will diffuse through steel to regions of high triaxial stresses.(3,4) Such regions always are present on a microscale in a martensitic microstructure. If a critical stress level exists and a critical amount of hydrogen is present in this area, a microcrack will initiate. As the crack appears, the region ahead of the crack is subject to increased triaxial stresses and further diffusion of hydrogen to this region occurs. The concentration of hydrogen again builds up until it reaches a critical level and the crack propagates a little bit further. This type of propagation continues until the crack reaches a macroscale and it then is called a delayed crack.

From a practical standpoint, the development of different theories does not change the procedures that are used to prevent delayed cracking. Delayed cracking is caused by a combination of hydrogen, susceptible microstructure, and internal stresses. All theories recognize and agree on this fact. Prevention is simply the removal of at least one of these contributing factors. Since this manual is dealing with the practical aspects of preventing delayed cracking, the theories are not discussed further.

Tests for Delayed Cracking Susceptibility

Various tests have been used for evaluating steels for their susceptibility to delayed cracking and for use in developing procedures to prevent delayed cracking. None of these tests are ideal. They all have shortcomings in that they may be only qualitative (a go-no go type of test) or they may not reproduce exactly the stress or thermal conditions of a production weld. However, they have been useful in laboratory studies. They are described briefly here to help provide a more complete understanding of the delayed cracking phenomena. More details of the application of these tests and the interpretation of the results can be found in the references.

The main feature of all of these tests is that they are designed to impose a high degree of restraint on the base metal pieces which make up the specimen. This restraint generates high stresses in the weld area and tests the ability of the system (base metal, welding procedure) to resist the stress without cracking. Each test, though, uses a different method for achieving the restraint.

The three delayed cracking tests discussed in the following sections have been widely used. The first two are simple to perform, use only a small amount of material, and can be used both in a production shop and in laboratory studies. The third test is an example of a test that can be used only in laboratory studies.

Controlled Thermal Severity (CTS) Test

This test is used to evaluate the susceptibility of a steel to underbead, root, or toe delayed cracking.(5-7) The specimen used is shown in Figure 6. The mating surfaces of the two parts may be in contact to simulate good joint fitup, or may be spaced with shims to evaluate effects of poor joint fitup. The bolt is used to hold the parts together while the two anchor welds are made. The test welds are made with the specimen at room temperature. The bithermal test weld is made first, the specimen is cooled to room temperature, and then the trithermal test weld is made. After a waiting period of 24 hours, the test welds are sectioned and examined to determine if delayed cracking has occurred. The thermal severity or cooling rate can be varied by changing the thickness of the parts. A thermal severity number (TSN) is obtained from:

$TSN = 4\ (t+b)$ for bithermal weld
$TSN = 4\ (t+2b)$ for trithermal weld

where, t and b are respectively the thicknesses of the upper and lower pieces of the test specimen. By using several specimens with varying thermal severity numbers, the effects of various cooling rates of the weld joint on delayed cracking can be determined.

Battelle Underbead Cracking Test

The Battelle test(8-11) is one of the simplest, quickest, and cheapest cracking susceptibility tests available. The specimen, Figure 7, is a small piece of the metal being evaluated. A short bead, about 1-1/4 inches long is deposited on the piece using a standard set of welding conditions, electrodes, and preheat. The specimens are stored 24 hours at room temperature after welding and then are tempered or normalized to stop any further cracking that might occur. After cooling, the specimen is cut longitudinally and one cut surface is examined for underbead cracks by magnetic particle inspection. A cracking index is obtained by dividing the total underbead crack length by the length of the weld bead. Usually, ten specimens are used with the index calculation using the total crack and weld lengths for the ten specimens. Using at least ten specimens insures that the results are statistically reliable. These specimens may be used to evaluate the effectiveness of actual production welding procedures in preventing underbead cracks. In this case, the welding conditions, electrodes, and preheat (if any) of the intended production application are used.

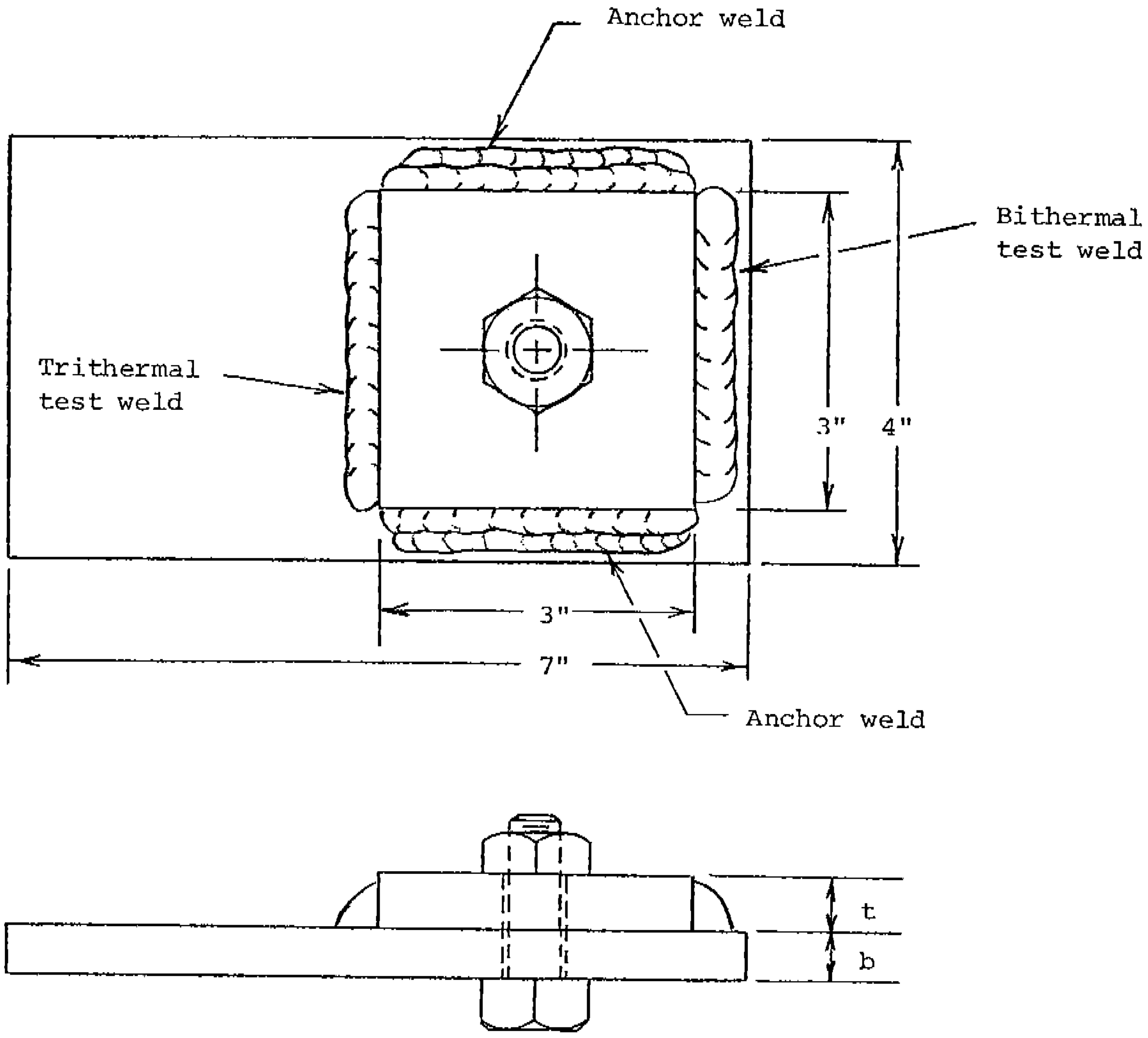
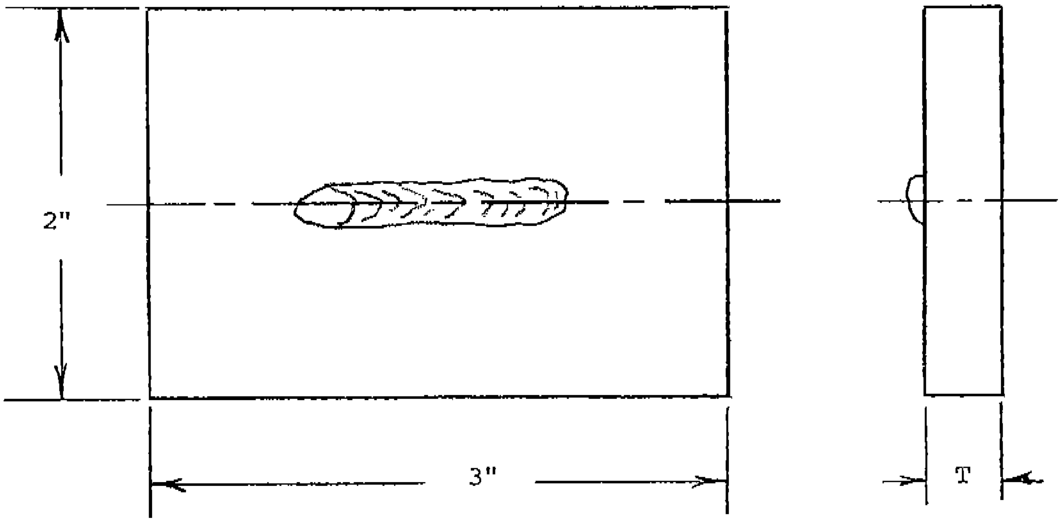


FIGURE 6. CONTROLLED THERMAL SEVERITY TEST SPECIMEN



Note: Specimen is sectioned along longitudinal centerline for examination for delayed cracks.

FIGURE 7. BATTELLE UNDERBEAD CRACKING-TEST SPECIMEN

Tensile Restraint Cracking (TRC) Test

The TRC test[12,13] is more elaborate than the CTS or Battelle test. The test requires a large specimen and special specimen loading equipment. It has the advantage, though, that the test weld can be a duplicate of a production weld; the same plate thickness, joint design, welding process, welding procedures, etc., can be used in the test as will be used in production.

The test specimen is shown in Figure 8. The two parts of the test specimen are first attached to the test apparatus by the fitup welds. The test weld then is made using the welding procedures that are being examined. As soon as the test weld is completed, a sustained tensile load is applied to the specimen by the test apparatus. This load is maintained for an extended time period (100 hours for example). The test weld is examined periodically by dye-penetrant or X-ray inspection to detect the development of delayed cracks.

For a given material and set of welding procedures, a series of specimens are tested with each specimen having a different sustained load. A minimum critical load will be obtained above which delayed cracking will occur. By comparing these minimum critical loads, the effect of different steel compositions or welding procedures on delayed cracking can be determined.

The Role of Hydrogen

The primary sources of hydrogen in arc welding are the organic material in cellulosic electrode coverings, the flux in submerged-arc welding, the shielding gas in gas metal-arc welding, and moisture. Hydrogen also may be picked up from foreign organic material, but this is not encountered as frequently as the primary sources.

Method by Which Hydrogen Enters the Weld Joint

When moisture or an organic material is in the vicinity of the welding arc, the energy or heat of the arc dissociates these materials. Moisture will break down into atomic hydrogen and oxygen; an organic material will break down into atomic hydrogen and whatever other elements make up the compound. Atomic hydrogen readily dissolves in molten iron so the weld puddle rapidly picks up any hydrogen that may be generated in the arc atmosphere. (It is important to remember that only atomic hydrogen will dissolve - molecular hydrogen will not. Thus, hydrogen gas

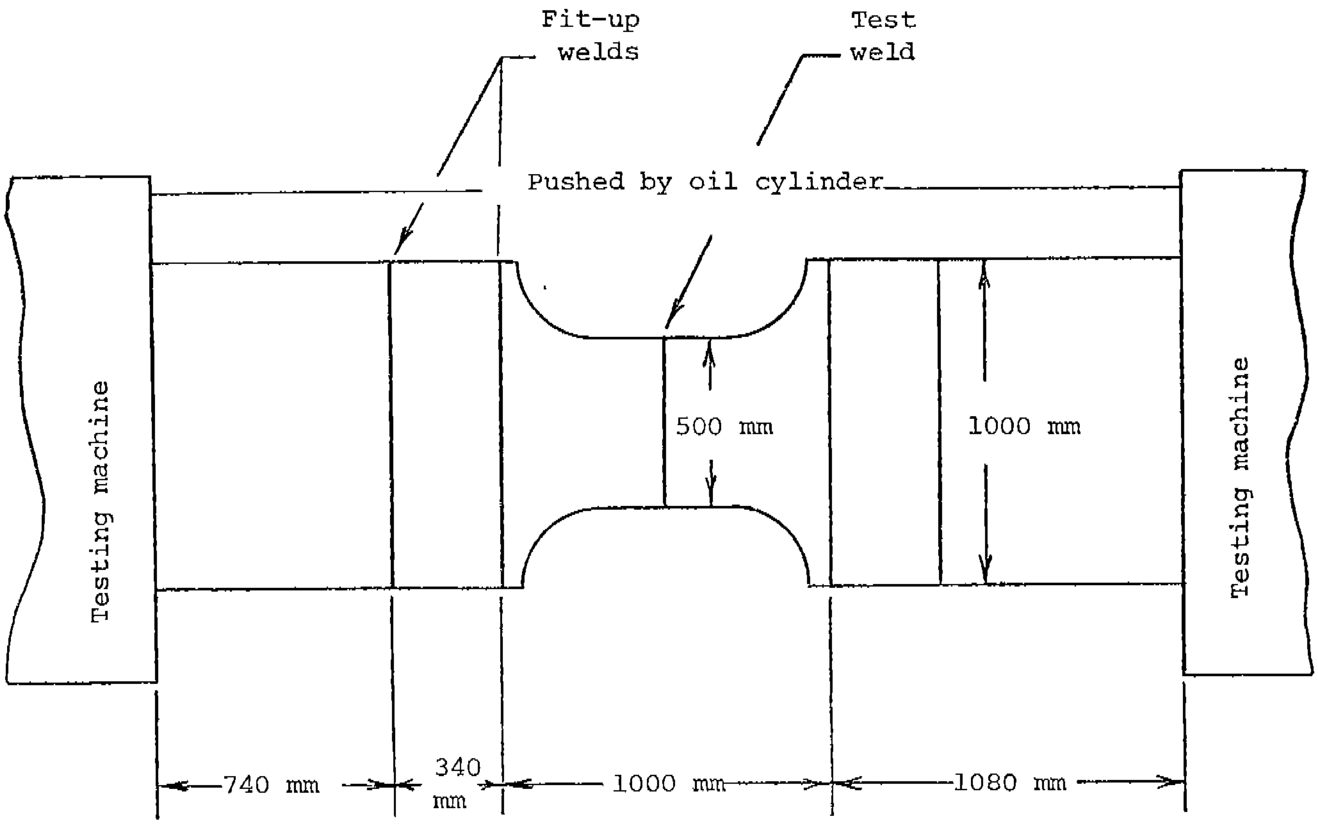


FIGURE 8. TENSILE-RESTRAINT CRACKING TEST SPECIMEN

will not dissolve in molten iron. It must first be dissociated into atomic hydrogen before solution will occur.) The amount of hydrogen that can be dissolved by molten iron or steel is shown by the graph in Figure 9. The hydrogen remains in solution in the molten weld puddle until the weld metal freezes. At this point, just below 2800 F in Figure 9, the solubility of hydrogen in iron drops drastically. As the metal continues to cool, the solubility of hydrogen drops even further. The jogs in the curve below 2800 F correspond to phase changes in the steel that occur as it cools.

Since the solidified and cooling weld metal has a relatively low solubility for hydrogen, the hydrogen must go somewhere. As long as the weld still is hot, the hydrogen will diffuse rather rapidly through the steel. Some of the hydrogen reaches the surface of the weld and escapes into the air. A significant amount diffuses from the weld metal into the hot heat-affected zone (Figure 10).

As the weld and heat-affected zone continue to cool, the rate of diffusion of hydrogen decreases. If the weld joint remained hot, all of the hydrogen would reach the surface and escape into the air in a few hours. However, high postheating treatments usually are not used on ship steels so the weld will cool to room temperature in a rather short time. This means that hydrogen still remains in the weld joint, but it is continuing to diffuse through the steel but at a greatly reduced rate. This slowly diffusing hydrogen is responsible for delayed cracking.

Sources of Hydrogen

The question now arises - where do the moisture and organic compounds that supply the hydrogen come from? Moisture can reach the welding arc in several ways. Some of these are pretty obvious, while others are rather subtle. Typically, moisture may come from:

- Water of crystallization in electrode coverings
- Moisture absorbed in hydroscopic electrode coverings or fluxes
- Moisture on the surface of electrode coverings, fluxes, or bare electrodes
- Water vapor in shielding gases
- Moisture adsorbed or condensed on the surface of the weld joint.

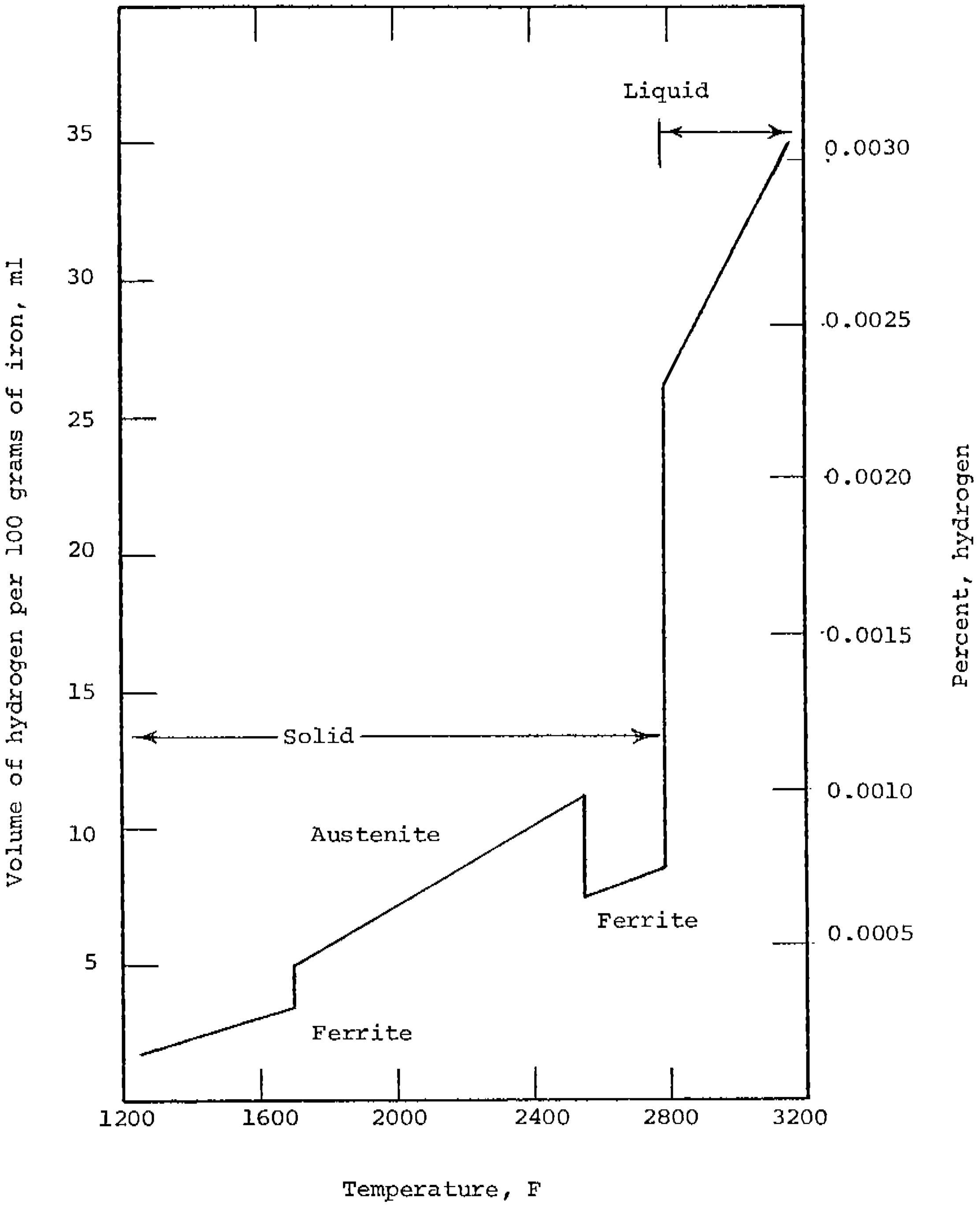


FIGURE 9. SOLUBILITY OF HYDROGEN IN IRON(14)

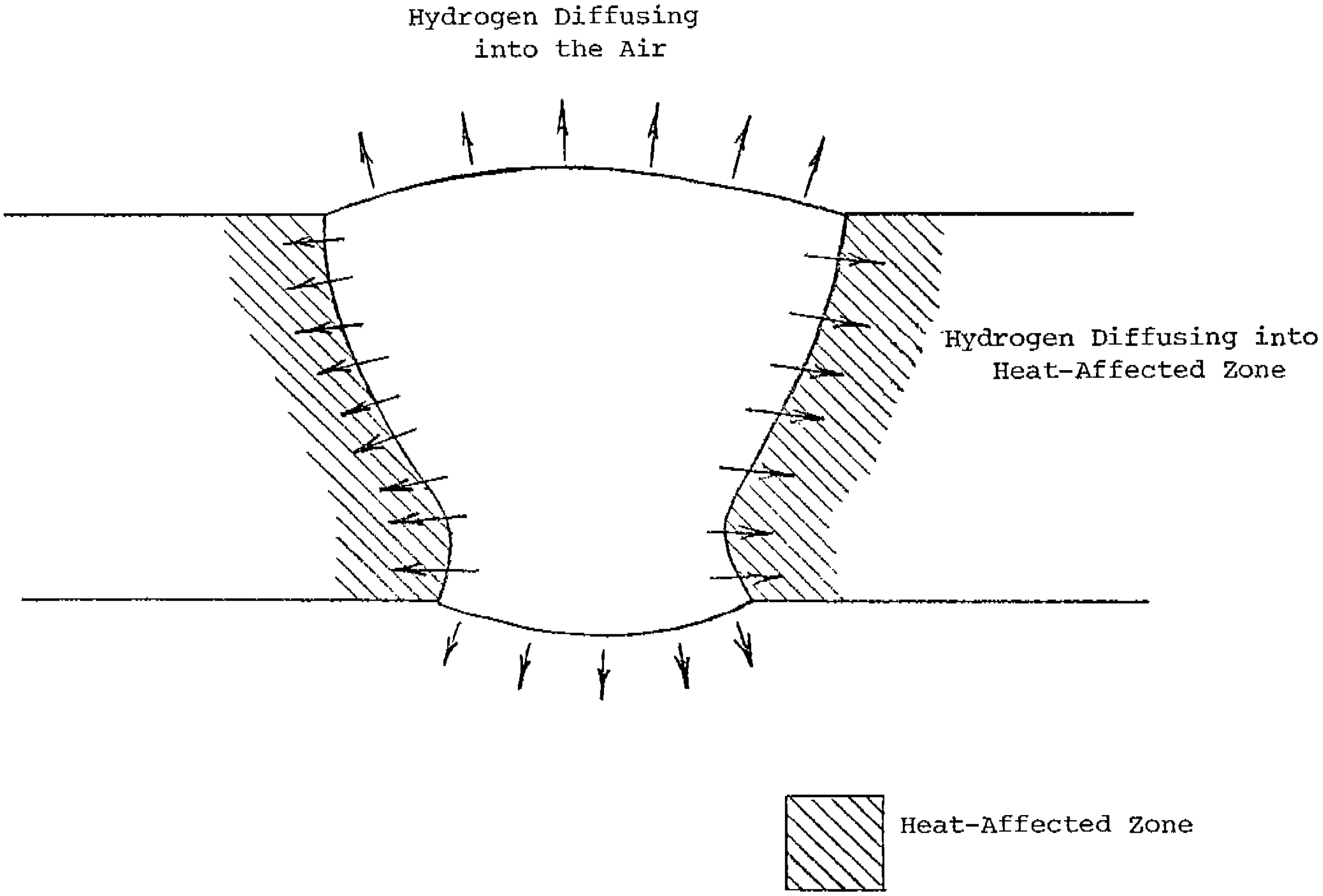


FIGURE 10. DIFFUSION OF HYDROGEN IN WELD JOINT

Organic sources of hydrogen include:

- Organic-based electrode coverings
- Grease or other foreign matter picked up on electrode
- Grease, paint, crayon markings, and other foreign matter on joint surfaces.

Most often, hydrogen in the weld metal has originated in the coverings of electrodes used in shielded metal-arc (stick electrode) welding. Both the composition of these coverings and the manner in which the electrodes are cared for can affect the amount of hydrogen that will be produced.

Consider first the covering composition. Most classes of electrodes have coverings that contain various quantities of cellulosic compounds. These are hydrocarbons that generate hydrogen when they dissociate. Whenever these classes of electrodes are used, hydrogen automatically will be present in the arc atmosphere. Four classes of electrodes (EXX15, EXX16, EXX18, and EXX28), however, do not contain cellulosic compounds but instead have lime-based coverings. These coverings were developed deliberately to reduce hydrogen in the arc atmosphere. Thus, these four classes have become known as "low-hydrogen" electrodes.

Even low-hydrogen electrodes can produce hydrogen, however with this hydrogen coming from moisture in the covering binders. Sodium and potassium silicate is the binder in all covered electrodes. These two compounds hold water in the form of water of crystallization. Low-hydrogen electrodes are baked during manufacture to drive off most of this water of crystallization, but if baking is not done properly, enough water of crystallization will remain and be a source of hydrogen.

Improper care of covered electrodes can turn even a low-hydrogen electrode into a high-hydrogen electrode. The coverings on low-hydrogen electrodes are highly hygroscopic, that is, they readily absorb moisture from the air. If low-hydrogen electrodes are carelessly exposed to the air, particularly in areas of high humidity, they quickly will absorb enough moisture to render them useless as low-hydrogen electrodes. Going back to the example of the Kings Bridge failure described earlier,(2) low-hydrogen electrodes were used but they still had sufficient moisture to create delayed toe cracks. The electrodes had not been cared for properly and moisture pickup had turned them into "high hydrogen" electrodes. (Details of correct handling are given in the section Controlling Hydrogen.) Moisture also will be picked up by allowing the electrodes to contact water or perspiration from a welder's hands or clothes.

Hydrogen pickup is less apt to occur in submerged-arc or gas-shielded metal-arc welding as the primary source of hydrogen, i.e., electrode coverings, does not exist in these processes. The granular fluxes used in submerged-arc welding can pick up moisture from the air but this can be prevented by keeping these fluxes in heated containers. Unmelted flux that is reused can collect oil or dirt which would be a source of hydrogen. Hydrogen seldom is picked up by the weld in gas-shielded arc welding unless cooling water leaks from the welding torch or the electrode wire has picked up foreign matter through careless handling or if moisture laden air is aspirated into the shielding gas.

Moisture on the joint surfaces can be a source of hydrogen in any of the welding processes. This moisture can come from condensation or rain if welding is done in an outside yard. Condensation might even be a problem in a large shop if the shop is open to the outside. Preheating the joints is the only successful way of drying wet joints.

Susceptible Microstructure

The hardened microstructure that is necessary for delayed cracking is called martensite. Its formation is governed by the composition of the steel or the weld metal and the rate at which it is cooled from a high temperature. The formation of a susceptible microstructure in the heat-affected zone will depend on the composition of the base steel. The composition of the weld metal will depend on the filler metal being used and on the amount of dilution from melted base steel. Since dilution depends on the welding process and conditions being used, it is not easy to predict the microstructure of the weld metal.

The effect of composition and cooling rate can be explained best by means of the transformation diagram shown in Figure 11. When a steel is heated above about 1600 F (defined as the "upper critical temperature") the steel's structure is called austenite. As the steel is cooled to room temperature, the austenitic structure will transform into either martensite, bainite, or ferrite/pearlite structures or a mixture of these. Martensite is a hard, brittle structure; carbon atoms are trapped in the atomic lattice of this structure in a manner that creates internal stresses within the lattice. Ferrite/pearlite is a soft, ductile structure. Bainite is harder than ferrite/pearlite but both bainite and ferrite generally are considered as soft, ductile structures. Neither ferrite nor bainite have the high internal stresses inherent in martensite.

The transformation diagram in Figure 11 is a sort of map which shows what types of structures form when the steel is cooled at different rates. Each steel alloy has its own transformation diagram. The one in Figure 11 is not exact, as it is intended for illustrative purposes. However, the transformation diagram for a ship steel would be somewhat similar to this one.

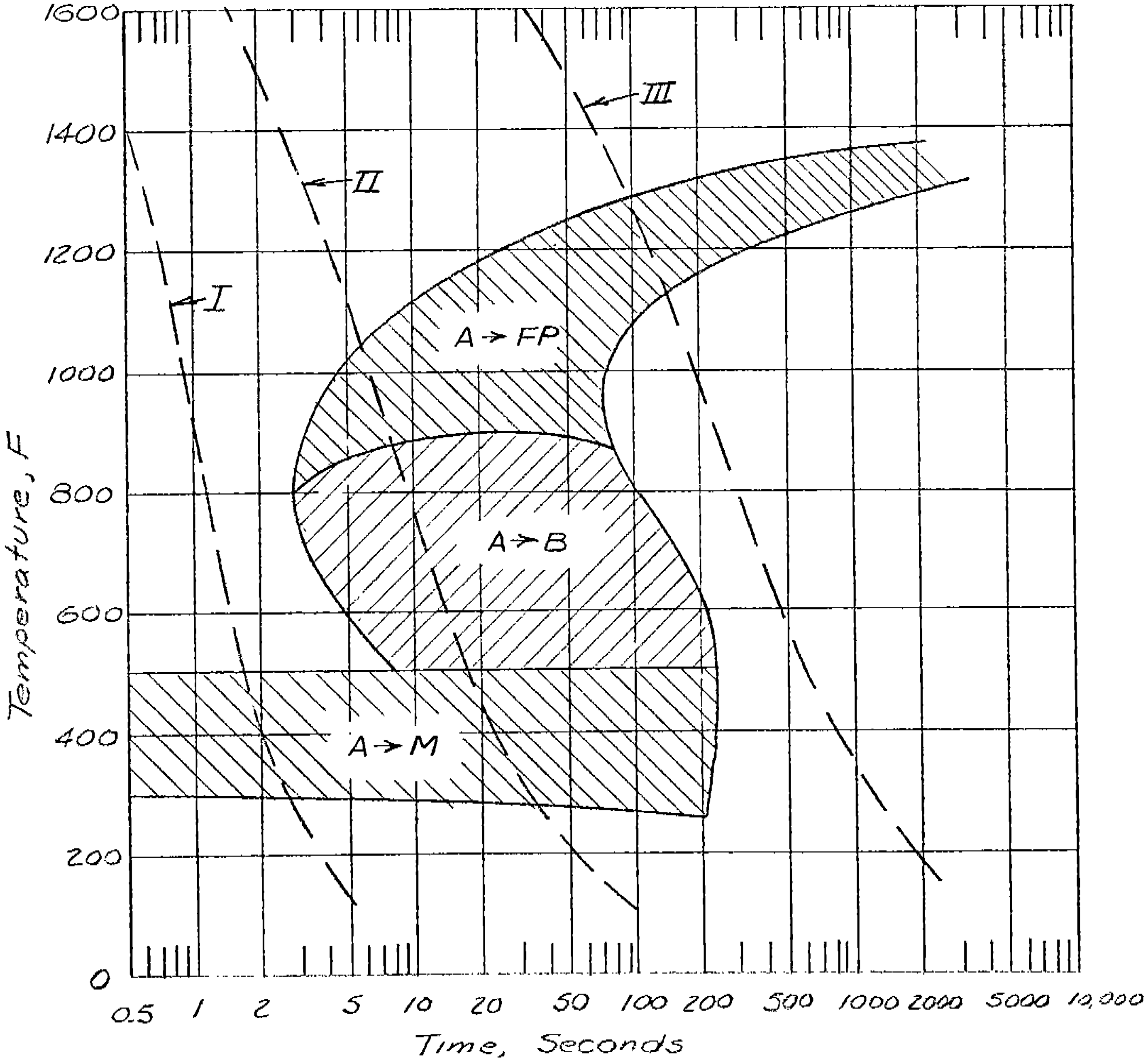


FIGURE 11. ILLUSTRATIVE TRANSFORMATION DIAGRAM

The three designated zones of this diagram indicate the type of structural change that is occurring in this area:

A → FP is austenite changing to ferrite/pearlite
A → B is austenite changing to bainite
A → M is austenite changing to martensite.

Three cooling curves also are drawn on this diagram. The fastest cooling rate is shown by Curve I. As the steel cools at this rate, no structural changes occur until a temperature of about 500 F is reached whereupon the austenite changes entirely to hard martensite. This cooling rate would correspond to a drastic water quench. The curve of the slowest cooling rate, Curve III, passes through the A → FP zone so all of the austenite transforms to ferrite/pearlite. This curve corresponds to the cooling rate of the heat-affected zone of a preheated weld joint. The intermediate Curve II would be that of the heat-affected zone of a weld joint that is not preheated. This curve passes through all three zones so some of the austenite transforms to ferrite/pearlite, some to bainite, and some to martensite. This illustrates how preheating can be used to prevent the formation of martensite, the structure that is necessary for the formation of a delayed crack.

The addition of carbon or other alloying elements to a steel will act to shift the A → FP and A → B zones to the right. It will take longer for the austenite to ferrite/pearlite and bainite transformations to occur and a larger amount of austenite will transform to martensite. The zones may even be shifted far enough to the right that the cooling Curve II may entirely miss the A → FP or A → B zones in which case the heat-affected zone will be entirely martensite. This is the case for some of the quenched and tempered steels used in shipbuilding.

Carbon Equivalents

The relative ease with which martensite will form in a steel can be estimated by use of "carbon equivalents". It was mentioned above that increasing carbon and other alloying elements in a steel will make it easier to form martensite. A steel that is more apt to form martensite in the heat-affected zone will be more susceptible to underbead cracking. Thus, the carbon equivalent of a steel can be used to estimate the delayed cracking susceptibility of the steel. Carbon equivalent does not give an exact measure of cracking susceptibility as there are too many other factors involved, but it is good for estimating purposes.

Carbon equivalent is a number that expresses in a simple manner the hardening susceptibility of the steel. It is made up by adding to the percentage of carbon present in a steel, a factor for each important alloying element present. This factor is determined by dividing the percentage of the alloying element by a number that relates to the influence of the alloying element. Referring back to the transformation diagrams, this influence is the effect of the alloying element on shifting the zones of the diagram to the right.

A variety of carbon equivalent formulas have been developed. Some of these formulas use only carbon and manganese while others include a variety of alloying elements. One of the more accurate formulas that is being used more and more is:(15)

$$\text{Carbon equivalent}=\text{C.E.}= \%\text{C} + \frac{\%\text{Mn}}{4} + \frac{\%\text{Cr}}{10} + \frac{\%\text{Ni}}{20} - \frac{\%\text{Mo}}{50} - \frac{\%\text{V}}{10} + \frac{\%\text{Cu}}{40}$$

The carbon equivalents calculated by this formula are pretty good estimating ratings of the delayed cracking susceptibility of steels. When the carbon equivalent is known, it can be used as a basis for selecting the precautions that must be taken to prevent delayed cracking.

The delayed cracking susceptibility of the weld metal cannot be directly predicted from carbon equivalents because of dilution effects. Usually, the filler metal has a lower carbon equivalent than that of the steel being welded. Therefore, precautions based on base steel carbon equivalent should be satisfactory for preventing delayed cracking in weld metals.

Weld Stresses

Stresses in a weld joint are made up of "local stresses" and "external stresses". The local stresses are caused by the welding operation itself. The base plate expands and contracts as it heats and cools during and after welding. The weld metal shrinks as it cools after solidifying. Multiple passes cause repeated heating and cooling. Welding variations along the joint mean that heating and cooling will not be uniform along the joint. All of these act together to create internal stresses in the joint after the weld is completed. External sources are not related to the welding process but will add to the internal local stresses. External sources come from forcing parts into alignment, the weight of the parts being welded, shrinkage of other welds, lifting and moving the welded part, etc.

Unlike the other two factors which are required for delayed cracking, weld stresses cannot be completely eliminated in a practical manner. Welding stresses can be removed by annealing a welded part but this is not feasible for welded ship structures. Procedures can be used to keep these stresses at a relatively low level but the weld joint always will have some stresses. Although the joint stresses may be kept low by using appropriate procedures, an abrupt change in the shape of the weld or a weld defect will cause a buildup of stresses at the point of the shape change or defect. These are called stress raisers. Stress raisers can be external or internal, caused by poor design, poor joint fitup, poor workmanship, or improper welding technique.

From the standpoint of delayed cracking,* stress raisers are of concern when they are located either in or close to the weld metal or heat-affected zone. In either of these positions, the field of increased stress that they create will extend into the weld metal and the heat-affected zone. This increased stress when combined with a susceptible microstructure and some hydrogen may be sufficient to start a delayed crack.

Stress raisers can be in a variety of forms. They can be inadequate weld root penetration, an abrupt change in the contour of the weld reinforcement, undercutting, lack of fusion, or an elongated slag inclusion. External stress raisers are the most critical since internal stresses usually are higher near the surface of the joint. This is because most weld joints are subjected to some bending stresses which produce high surface stresses.

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* Stress raisers should be avoided for a variety of reasons. They can initiate fatigue cracks or be the starting point for a brittle fracture in steel with low notch toughness. The delayed cracking aspect of stress raisers is only one consideration.

NOTES

METHODS FOR PREVENTING DELAYED CRACKING

The extent to which precautions are required to prevent delayed cracking depends on the strength and composition of the steel being welded. To be more accurate, one should say that these measures depend on the cracking susceptibility of the steel. However, since cracking susceptibility goes hand-in-hand with the steel composition, it is somewhat easier to use the steel composition as a rating factor. The carbon equivalent index has been discussed as a measure of delayed cracking susceptibility. Thus, the calculated carbon equivalent of a steel can be used to determine the measures needed to prevent delayed cracking.

The preventive measures that can be used fall into three categories:

(1) Control of hydrogen
(2) Control of weld-joint microstructure
(3) Reduction of stresses in the weld joint.

These categories are listed in the order in which they normally are applied. This also is the order of difficulty in applying the measures. Controlling hydrogen is the easiest and for most ship steels is sufficient to prevent delayed cracking. However, with increasing carbon equivalent, delayed cracking is harder to prevent and additional measures must be taken through controlling the microstructure and reducing welding stresses.

Specific precautions that should be taken in the welding of steels of various carbon equivalents are summarized in Table 1. These items are discussed in more detail in the following sections along with other preventive measures that fall into the simple category of good welding practices.

Control of Hydrogen

Hydrogen in the weld joint is controlled by following a simple rule: remove the source of hydrogen. If there is no hydrogen present to enter the weld in the first place, then there is no need to remove hydrogen from the weld joint. Removing hydrogen from a weld involves heating the weld for an extended period of time to allow the hydrogen to diffuse away. It is more reliable to eliminate the source of hydrogen before welding even starts. The techniques required to meet this simple rule are varied and do require precise care and control.

As discussed previously, the three sources of hydrogen are the welding electrodes, moisture on the joint surfaces, and contaminating materials on the joint surfaces. Each of these sources must be controlled to prevent picking up hydrogen in the weld metal.

TABLE 1. PRECAUTIONS FOR WELDING STEELS OF VARIOUS CARBON EQUIVALENTS

Carbon Equivalent	Preventive Measures	Minimum Preheat, F Thickness 3/4-inch or less	Minimum Preheat, F Thickness over 3/4-inch
0.50 or less	No precautions required. Can be welded with cellulosic covered electrodes without preheat		
0.50 to 0.57	Weld with low-hydrogen covered electrodes or the gas shielded or submerged-arc processes with sufficient preheat to remove moisture from the joint surfaces	75-125 (see text)	175
0.57 and over	Weld with low-hydrogen covered electrodes or the gas shielded or submerged-arc processes with medium preheat	150	250

Use of Cellulose-Covered Electrodes

Hydrogen in appreciable quantities will be present in the arc atmosphere if cellulose-covered electrodes are used. This is inherent and no supplementary precautions can remove this hydrogen. Therefore, these electrodes may be used only with low-carbon equivalent steels that are not susceptible to delayed cracking.

Use of Low-Hydrogen Electrodes

The use of low-hydrogen electrodes greatly reduces the primary source of hydrogen in shielded metal-arc welding with covered electrodes. These electrodes must be used when welding steels with higher carbon equivalents that are sensitive to delayed cracking (Table 1).

As manufactured, low-hydrogen electrodes have a very low moisture content. The maximum contents permitted by both American Welding Society and government specifications(16-18) are:

Electrodes	Maximum moisture content, percent*
E7015, E7016, E7018	0.6
E8015, E8016, E8018, E9015, E9016	0.4
E9018, E10018, E11018	0.2

These coverings, however, will absorb moisture from the air very rapidly and to an unacceptable level unless they are packaged, stored, and handled properly. Since the moisture content of the electrodes is very critical in preventing delayed cracking, it is extremely important that procedures be established by the user to guarantee proper moisture content in the electrode when it is used. These procedures should be designed both to minimize moisture pickup and to remove what moisture is absorbed.

Investigations done at United States Steel Corporation provide a good example of how critical the electrode moisture content is and how readily moisture is picked up from the air.(19) E7018 electrodes which had a moisture content of 0.2 percent were stored for 24 hours at room temperature in air that had relative humidities of 60 percent and 90 percent. The moisture content of electrodes increased to 1 percent and 1.8 percent, respectively for the 60 percent and 90 percent humidity conditions. Both of these moisture contents were sufficient to cause delayed cracking when used to weld steels with carbon equivalents of about 0.57.

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* E70XX and E80XX electrodes sometimes are used as substitutes for E90XX and E110XX electrodes for tack and root pass welding. When this substitution is made, the E70XX and E80XX electrodes should be baked to reduce the moisture content to 0.2 percent.

Another example is where penstocks were being fabricated in two locations: out of doors in a relatively dry atmosphere and inside where the humidity was nearly 100 percent.(20) Identical welding procedures were used at both locations. The welds made outside were sound while those made inside had a large number of delayed cracks. Sufficient moisture was being picked up by the electrodes in the high-humidity location to cause delayed cracking.

The first step in the control of electrode moisture is in the packaging of the electrodes. Before packaging, electrodes are baked to drive off any absorbed moisture and bring the moisture content below the limits mentioned above. The electrodes then must be packaged in a container that will protect against outside moisture during shipping and storage. The containers used are either hermetically sealed metal cans or cardboard or fiber boxes that are wax impreganted or otherwise treated to make them waterproof. The metal cans are preferred as the cardboard or fiber boxes can be easily broken or punctured by rough handling. For maximum protection, electrodes should be purchased only in the metal cans.

The next and most important step in electrode moisture control is the prevention of moisture pickup at the job site. As explained, the electrode coverings will start to pick up moisture as soon as they are removed from their sealed package. To prevent this, the electrodes should be placed in a heated oven immediately after they are removed from the package. They should stay in this oven until they are to be used. Storage in the heated oven will prevent moisture pickup. Heating in this oven serves another purpose also. Tests have shown that, even in hermetically sealed metal boxes, electrode moisture content may increase during storage. This may be a result of a poor seal on the box or residual moisture within the box. Heating the electrodes will drive off any moisture picked up in the package and restore the electrodes to their original moisture content level. Only vented heating ovens should be used so that moisture driven from the electrodes may escape from the oven.

Heating procedures have been developed by producers and users of low-hydrogen electrodes. This treatment should reduce the moisture content of the electrodes below 0.2 percent.

(1) Electrodes should be baked according to vendor instructions immediately after being removed from their package. The electrodes should be placed in the oven in a manner that will permit air circulation around the electrodes. They should be stacked no more than three layers high.

(2) Electrodes should be transferred while still hot to a holding oven maintained at 250 F - 300 F. Electrodes should be kept in this holding oven until issued for use.

(3) Welders should be issued a maximum of a four-hour supply of electrodes at any one time. If possible the holding ovens should be located close to the production area. If not, the electrodes should be issued in a closed container for transport to the welding area.

(4) It is good practice, especially if the humidity at the welding site is high, to have a heated electrode container for each welder. The welder should remove only a few electrodes at a time and use only electrodes that are still warm to the touch. Cold electrodes should not be used.

(5) If the welder does not have a heated electrode container, the electrodes should be used within the following time limits:

E70XX	4 hours
E80XX	2 hours
E90XX	1 hour
E110XX	1/2 hour.

Sometimes E70XX and E80XX electrodes are substituted for E90XX or E110XX electrodes for tack or root-pass welding. In these cases, the maximum exposure times should be reduced to 1/2 hour.

Any electrodes that are unused at the end of these time limits should be returned to a 250 F - 300 F holding oven. All electrodes remaining in a welder's heated electrode container at the end of four hours should be returned to this holding oven. These electrodes should not be reissued until they have been rebaked as specified in Rule (2).

(6) Electrodes should be rebaked only once. Electrodes that would require a second rebaking should be discarded.

(7) Any electrodes exposed to rain, snow, or any other moisture source other than atmospheric humidity should be immediately discarded.

(It should be emphasized that these procedures are meant only for low-hydrogen electrodes. Cellulosic electrodes should not be baked nor held at these temperatures as the electrode coverings will be damaged. Since cellulosic coverings are organic, baking will not remove any hydrogen anyway.)

These procedures require close monitoring to insure that electrodes are not mixed up and that the procedures are being followed. It is an advantage to have separate ovens for each operation to help avoid mixing of electrodes.

A periodic check of the moisture content of electrodes should be made once the procedures are established. During procedure setup, these checks should be made frequently. It is particularly important to check moisture content on days of high humidity or inclement weather. The procedures for measuring the moisture content of electrode coverings are described in the American Welding Society specification for low-alloy steel covered electrodes.(16)

The ovens used for baking the electrodes should have a system for circulating the air inside of the oven. Both baking and holding ovens should be maintained in good operating condition. The accuracy of thermostats should be checked periodically and any burned-out heating elements should be replaced immediately. These ovens should be used only for electrode conditioning. The heating of other items or materials in these ovens should be prohibited. These other materials could leave organic deposits that could be picked up by the electrodes.

Organic materials also can be picked up in careless handling of the electrodes. Welders and their helpers should be cautioned about handling the electrodes with greasy gloves, allowing the electrodes to come in contact with grease, oil, dirt, or other foreign matter, etc. This is particularly important if the electrodes are hot from the holding oven. A hot electrode contacting a painted surface, for example, may pick up paint which is an excellent source of hydrogen. Any electrodes that have contacted any of these substances should be discarded immediately.

Submerged-Arc Welding

The role of hydrogen should be less critical in submerged-arc welding than in covered-electrode welding. This is because higher heat inputs are used which slows down the weld cooling rate which, in turn, provides a microstructure which is not susceptible to delayed cracking. If quenched-and-tempered steels are submerged-arc welded, though, the heat input must be kept low to prevent degradation of the mechanical properties of the heat-affected zone. In this case hydrogen pickup definitely is of concern.

However, submerged-arc fluxes may be very susceptible to moisture pickup and thus require as careful handling as low-hydrogen covered electrodes. Submerged-arc fluxes used for welding quenched-and-tempered steels should be stored in flux holding ovens maintained at 250 F minimum to keep the flux dry. Flux exposed to moisture should be discarded as it is very difficult to bake dry. Only new flux should be used; unfused flux,unless it is controlled, that is recovered from the weld joint should not be used. Recovered flux may have picked up dirt or oil that would be a source of hydrogen.

Gas-Shielded-Arc Welding

Welds made by gas-shielded metal-arc welding generally are considered immune to hydrogen pickup. However, moisture can be carried into the welding atmosphere by the shielding gas if the gas itself is not dry. As supplied, welding gases normally have moisture contents that are low enough to be used for welding even the highest carbon equivalent ship steels. Occasionally, though, gas may be obtained that has a moisture content high enough to generate sufficient hydrogen to cause delayed cracking. Also, leaks in the system supplying gas to the welding torch may permit atmospheric moisture to be carried into the shielding gas. Instruments are available for checking the moisture content of shielding gases.

Periodic checks should be made on gases as received from the supplier and on the gas as it enters the welding torch. The shielding gas should have a dew point lower than -40 F. The gas supply system should be maintained in good condition. If the welding torches are water cooled, they should be checked frequently to be certain that cooling water is not leaking into the shielding gas or onto the weld joint. When torch-cooling water is first turned on at the start of welding operations, moisture may condense on the torch components particularly in humid weather. This moisture could drip into the weld joint or be picked up by the shielding gas. In this case, initial welds should be made on scrop pieces to heat up the torch and drive away this condensed moisture.

Moisture on Weld Joints

Moisture that may have condensed on the surfaces of weld joints must be removed before welding except when the welds are being made with cellulose-covered electrodes. Wiping is not a satisfactory way of doing this. The only acceptable method is to preheat the weld joint.

Referring to Table 1, steels with intermediate carbon equivalents (0.50 to 0.57) should be preheated to a temperature range of 75 F - 125 F. If the ambient temperature is above 75 F, no additional preheating is required. If the ambient temperature is below 75 F, however, the weld joint should be preheated to a minimum of 125 F.

Steels with high carbon equivalents (over 0.57) should always be preheated to the range of 150 F - 250 F depending on thickness (see Table 1). These higher preheat temperatures are required to reduce welding stresses, not to drive off moisture. However, the elimination of moisture is a beneficial by-product of the preheating.

These preheat temperatures are required with any of the arc-welding processes that may be used (covered electrode, gas shielded, or submerged arc). If the welding operation is interrupted before the joint is completed, the minimum interpass temperature should be maintained until such time as the welding operation can be restarted. Interrupting welding before the joint is completed is not a good practice and should be avoided.

Special precautions must be followed when using preheat on quenched-and-tempered steels, since the good tensile and impact properties of these steels are a result of their heat treatment. This heat treatment involves water quenching the steel from about 1600 F followed by tempering at 1000 F to 1200 F depending on the particular alloy. The key to this heat treatment is the rapid quench which produces a martensitic microstructure. If the steel is cooled too slowly, martensite will not form and good mechanical properties, particularly good notch toughness, cannot be achieved. This means that preheating must be controlled. If the preheat temperature is too high, the weld heat-affected zone will cool to slowly to form martensite and the heat-affected zone properties will suffer.

To avoid loss of heat-treated properties in the heat-affected zones, the maximum preheating temperature for quenched-and-tempered steels should be 300 F. For the same reasons, limits should be placed on the welding heat input and interpass temperature (discussed in subsequent sections).

Weld Joint Cleanliness

In addition to condensed moisture, the weld joint must also be kept free from organic materials that could generate hydrogen during welding. Before welding is started, all paint, dirt, oil, crayon markings, etc. should be removed from the joint faces. This should be done by wiping with a solvent. If temperature-indicating crayons are used to determine preheating temperature, the marks from these crayons should not be made on the joint faces. Instead, they should be made on the surface of the base plate slightly away from the edge of the joint.

A point of concern that may arise involves the possible pickup of hydrogen from zinc-silicate primer coatings on steel surfaces. These coatings usually are applied to steel plates before the joints are prepared for welding. Joint preparation removes the coatings from butt-joint surfaces. However, fillet joint surfaces may not be prepared so welding would occur directly on the primed surfaces. Investigations have shown that these coatings do not cause delayed cracking primarily because they are non-organic.(21) However, there still is some question that these coatings may be a source of hydrogen. They do affect the arc characteristics somewhat with an increased tendency to undercutting.

Control of Heat-Affected Zone Microstructure

If the source of hydrogen is removed or controlled, these steels should have negligible susceptibility to delayed cracking. However, added insurance is obtained in the case of as-rolled or normalized steels by controlling the microstructure of the heat-affected zone. This control involves preventing the formation of the martensitic microstructure that is susceptible to delayed cracking. By preventing the formation of martensite in the heat-affected zone, another contributing factor to delayed cracking is eliminated.

The failure of a heavy-walled heat exchanger mentioned in the first section of this manual is a good example of a delayed crack caused by a susceptible microstructure.(1) The joints in the heat exchanger were preheated but the preheating temperature was too low. Preheating temperatures of 200 F were set up using steel having a maximum carbon equivalent of 0.58. The steel used in the heat exchanger had a carbon equivalent of 0.63 and a 200 F preheat was not enough to prevent martensite from forming in the heat-affected zone. The result was a delayed toe crack that triggered a brittle fracture during pressure testing.

Preheating

Martensite formation is prevented by slowing the cooling of the heat-affected zone below a critical rate. This corresponds to moving from cooling rate II to cooling rate III of Figure 6. The hydrogen control measures involving preheating to remove condensed moisture generally will slow down the cooling rate enough to keep martensite from forming. Other methods of reducing the cooling rate also are available and are discussed in the following sections.

Remember the caution of the previous section about preheating quenched-and-tempered steels. These steels are intended to have a martensitic microstructure. Therefore, the methods of controlling the heat-affected zone microstructure discussed in the following sections should be used only with as-rolled or normalized steels.

If a weld joint is preheated, the cooling rate of the joint after welding will be retarded with the degree of retardation being dependent on the preheating temperature. As the preheating temperature is increased, the cooling rate will be decreased. The cooling rate also is dependent on the thickness of the plate being welded. Thicker plate provides a greater heat sink and welds in thicker plate will cool faster than welds in thin plate. This means that to maintain a given cooling rate, the preheating temperature must be adjusted to compensate for changes in plate thickness.

For steel grades having a carbon equivalent below about 0.57 and used in the as-rolled or normalized condition, the cooling rate generally can be controlled adequately by using the preheating temperatures needed to drive away condensed moisture. For thin material, the minimum plate temperature can be 75 F and the cooling rate still will be slow enough that martensite will not form in the heat-affected zone after welding. For thick plate, however, higher preheating temperatures are required. As a general rule, the relation between preheating temperatures and thickness is:

Plate Thickness, inch	Preheat Temperature Required to Control Heat-Affected Zone Microstructure, F
Under 1	75 minimum
1-2	125 minimum
Over 2	225 minimum

Interpass Temperature

In a multipass weld, the weld joint will cool between passes. The amount of cooling will depend on the time lag between passes. If this time lag is long, the joint can cool to a temperature below the preheating temperature. When the next pass is deposited, the situation will be analogous to making the first pass without sufficient preheat; the heat-affected zone will cool fast enough to form martensite. What this means is that in a multipass weld, the interpass temperature should always be kept within the same limits as the preheating temperature. If the weld joint has cooled below the preheating temperature between passes, it should be reheated to the preheating temperature before depositing the next pass.

Extra precautions will be required when welding under situations that promote rapid cooling, for example, in cold weather or when welding thick plate. More frequent reheating of the joint may be required in these situations. The weld joint temperature should be checked frequently with a surface pyrometer or with temperature-indicating crayons.* Cooling can be slowed down by covering the weld joint with an asbestos blanket or by erecting baffles to protect the weld site from cold drafts. If additional heating is required between passes, it can be applied in the same ways that the joints were preheated.

Control of Heat Input

Welding heat input is a term that estimates the amount of heat that is generated in a weld joint as a result of the welding operation. It is a simple number to calculate using the formula:

$$\text{Heat Input} = \frac{\text{Welding current x arc voltage x 60}}{\text{welding speed}}$$

where these terms are measured as

heat input - joules per inch
welding current - amps
arc voltage - volts
welding speed - inches per minute.

The welding heat input will affect the cooling rate of the weld joint in the same manner as preheating. As the welding heat is increased, the temperature of the area around the weld joint will be increased and the joint will cool more slowly. As the formula indicates, welding heat input can be increased by increasing the current or arc voltage or by slowing down the travel speed. Increases in current and voltage are not always practical as these parameters influence the welding characteristics of the electrode being used. If a significant increase in current is desired, a larger size electrode can be used. Slowing the welding speed is a simple method of increasing heat input. A weaving technique also increases the heat input since the linear travel speed along the weld joint is decreased.

Heat input is closely controlled in the welding of quenched-and-tempered steels, but for the purpose of maintaining good mechanical properties in the heat-affected zone. Typical maximum heat inputs for a quenched-and-tempered steel are 45,000 joules per inch for steel less than 1/2 inch thick and 55,000 joules per inch for steel over 1/2 inch thick. Such limits are not needed in the welding of as-rolled or normalized steels as the cooling rate does not have to be controlled

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* It is important to remember that marks from temperature-indicating crayons should be made on the base-plate surface only. Marks on weld-metal surfaces or joint faces will be a source of hydrogen when subsequent weld passes are deposited.

for these steels. As a general rule, the welding conditions should be those recommended by the electrode manufacturer taking care not to use excessive travel speeds. This, in combination with recommended preheat and interpass temperatures should provide a cooling rate slow enough to prevent martensite in the heat-affected zone. Consultation with the steel manufacturer also is recommended to obtain his suggestions for welding conditions for the specific steel.

Arc Strikes

An arc strike occurs when a welder (1) accidentally touches the electrode to the base plate at a location away from the weld joint or (2) strikes the arc on the surface of the base plate near the joint and then leads the arc into the joint to continue welding. In either case they are bad for a variety of reasons including delayed cracking. The appearance of an arc strike adjacent to a fillet weld is shown in Figure 12. A fracture initiated in this arc strike probably from a hot crack. Although no delayed cracks were present in this arc strike, they could have occurred as the heat-affected zone contained extremely hard martensite.

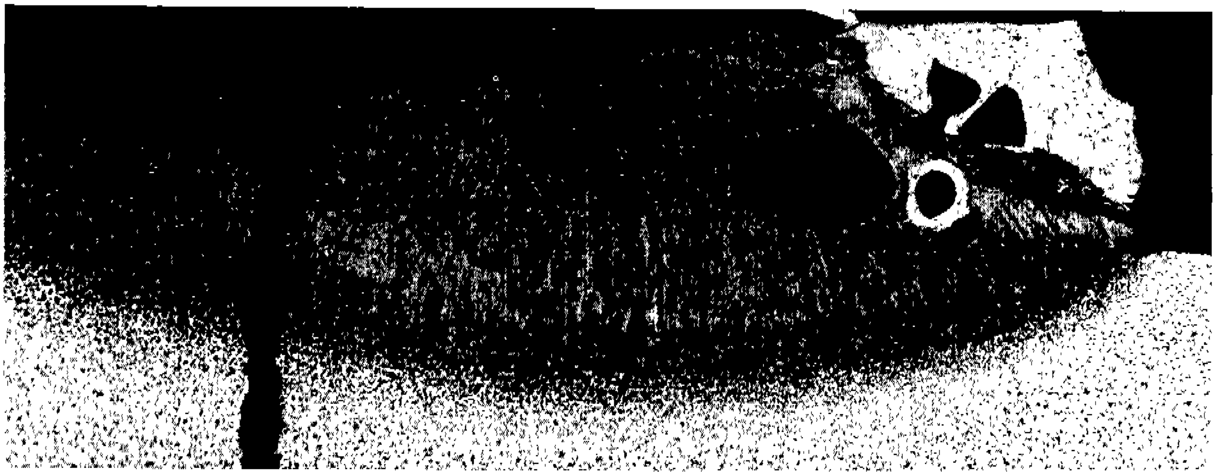
The length of time of an arc strike is very short - probably only about 1/4 second. The amount of metal melted is very small and it will cool extremely fast. This means that the heat-affected zone probably will be martensitic even in a low carbon-equivalent steel. Shrinkage stresses will be very high also because of the inherent shape of an arc strike. There is a good chance that a source of hydrogen will be present since accidental arc strikes frequently occur in an area away from the joint where the plate may be damp or dirty. Thus, an arc strike is accompanied by all of the factors that lead to delayed cracking and experience has shown that delayed cracking will occur at an arc strike.

There is only one way to prevent arc strikes: use care. Accidental arc strikes can be prevented only by the welder being careful in his handling of the electrode and electrode holder. If an accidental arc strike occurs, it should be ground off immediately. The metal should be ground down at least 1/32 inch below the plate surface to be sure that all of the heat-affected zone is removed.

An arc always should be initiated within the weld joint where a subsequent weld pass will remelt the area of the arc strike. It is best to start the arc about an inch ahead of the last deposit from the previous electrode. The arc then can be brought back to the previous deposit and the weld can be continued. The continuing weld will pass over the arc strike and remelt it.

2X 2% Nital 9D558

Location of arc strike next to fillet weld and fracture initiated by arc strike



2X 2% Nital 9D559

Magnified view of arc strike

FIGURE 12. ARC STRIKE

Reduction of Weld Joint Stresses

The need to control weld joint stresses increases as the delayed-cracking susceptibility of the steel increases and is particularly important in the welding of the quenched-and-tempered steels. Two basic methods of minimizing these stresses are available (1) through adjustments in the welding procedures that are used, and (2) through the design and fitup of the weld joints. Together, these methods are used to reduce shrinkage forces in the weld joints and to eliminate points of stress concentrations. While these practices are particularly important when quenched-and-tempered steels are used, they also should be applied to the as-rolled and normalized steels.

Reduction of Shrinkage Forces

Several methods are available for reducing the shrinkage forces that build up as the weld joint cools. These include the use of preheating, minimizing weld metal volume, and the control of welding sequence.

Preheating. Preheating reduces the magnitude of the shrinkage stresses in a weld joint. Preheating produces a relatively wide band next to the weld that will be at an elevated temperature throughout the welding cycle. Without preheating, this high-temperature band will be restricted to the narrower heat-affected zone. At elevated temperatures, a steel's ductility increases and its strength decreases. With this change in properties, the elevated temperature band will absorb some of the shrinkage that occurs as the weld cools. By distributing the shrinkage through the wide preheated band, the unit shrinkage stresses will be low. If shrinkage must be contained within the narrower band of a nonpreheated joint, unit shrinkage stresses will be high.

The amount that shrinkage stresses are reduced increases with increased preheating temperature. Preheating to the temperatures previously discussed for reducing the cooling rate to control heat-affected zone microstructure will help some to reduce shrinkage forces. A more pronounced effect would be obtained if preheating temperatures were increased to 300-400 F. For as-rolled and normalized steels, this additional stress reduction probably isn't needed if hydrogen sources are controlled. Maximum temperatures already are set for preheating the quenched-and-tempered steels. These are high enough to get some reduction in shrinkage stresses.

Care must be used in applying preheating. Preheating should be uniform and hot spots should be avoided. Hot spots result in nonuniform expansion and contraction which defeats the purpose of using preheating.

Preheating should be applied in a band extending away from the joint at least six inches in all directions. The preheating temperature should be checked at a point 3 inches away from the edge of the joint.

Minimize Weld Metal Volume. The magnitude of shrinkage forces is directly dependent on the volume of weld metal that is deposited. Therefore, the size of the weld should be as small as possible but still provide the required strength. For butt welds, double V or U joints should be used instead of single V or U joints. The root opening should be kept to the minimum necessary to achieve full penetration. Fillet welds should not be overwelded. A fillet weld should be the size specified in the welding procedure or by the design drawings and no more. Nothing is gained by overwelding fillet welds except an increase in shrinkage stresses. Additional weld metal deposited in a fillet weld does not add to the strength of the weld joint.

Welding Sequence. Use of the proper sequence in which portions of the weld joint are completed will help to keep shrinkage forces low. Block welding, backstep welding, or skip welding are sequences that frequently are used.

Block welding is applied primarily with long joints in thick material. The joint is divided into several blocks; each block is fully welded before proceeding to the next block. When compared to a technique in which each pass or layer of passes is completed in sequence along the entire joint, block welding provides significant reduction in shrinkage forces.(22) A reduction of up to one-third in shrinkage forces has been achieved using the block technique instead of completing the weld in complete passes or layers. Maximum effect is achieved when block welding begins at the midpoint of the joint with subsequent blocks being completed in sequence from the midpoint to the ends of the joint (Figure 13).

Backstep welding is similar to block welding but is applied to thinner material that can be welded in one or two passes. As shown in Figure 14, welding proceeds along the joint in a series of short welds that are each made in the direction opposite to the general direction of welding. Skip welding (Figure 15) is another variation in which the short passes are spaced with the intervening gaps being completed after the initial series of short passes have been deposited. A second welder can be following along welding up the "spaces". By using a series of short passes in these sequences, localized buildup of heat is minimized which, in turn, minimizes the amount of expansion and contraction that occurs in the weld joint.

In any of these sequences, the overall direction of welding should be away from the point of highest restraint and towards the areas of lowest restraint.

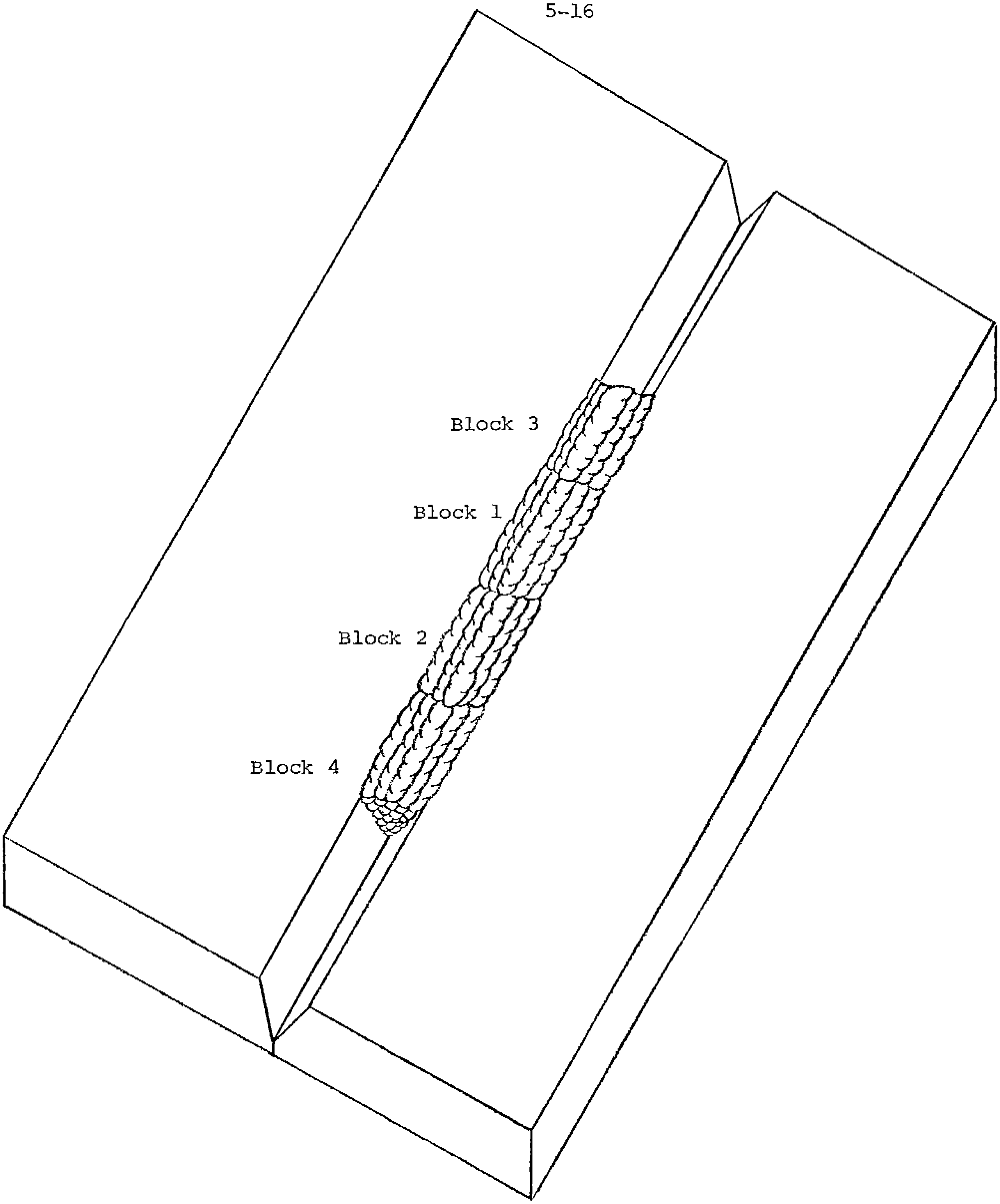


FIGURE 13. BLOCK WELDING TECHNIQUE

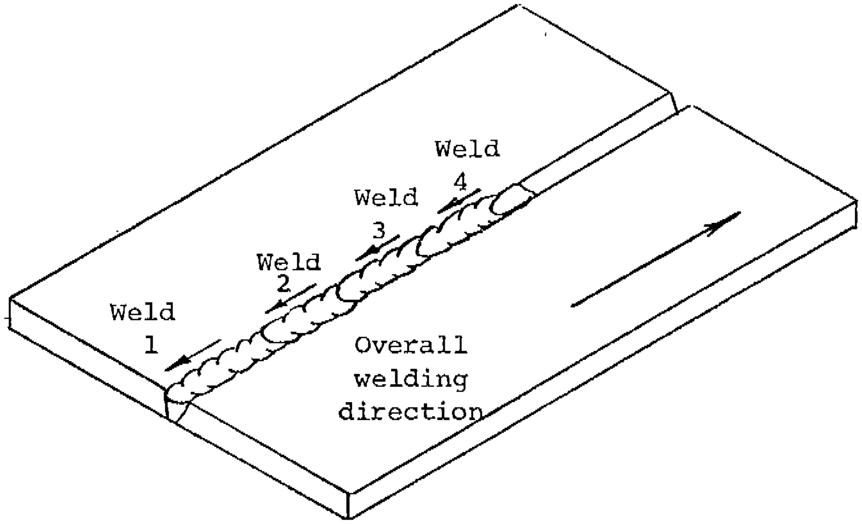


FIGURE 14. BACKSTEP WELDING

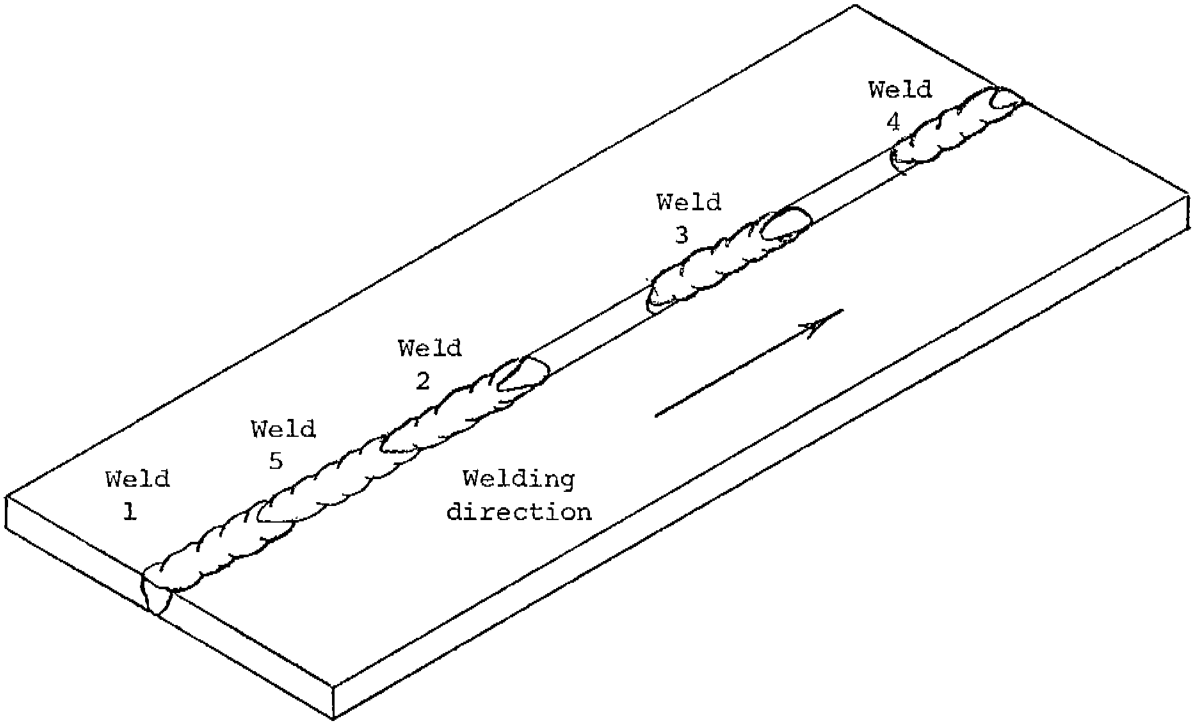


FIGURE 15. SKIP WELDING

Reduction of Stress Concentrations

Every effort should be made to avoid stress raisers in weld joints. As explained earlier, these stress raisers may cause concentrations of stresses high enough to trigger a delayed crack. Generally, preheating will reduce these stresses to a noncritical level. However, the best insurance is obtained by eliminating the stress raisers from the beginning.

Butt welds are preferred to fillet welds. Usually, there is little change in shape of the welded part at a butt joint; a fillet weld joins parts that generally are at right angles which, in itself, is an abrupt change in shape. Many fillet welds are required in a ship structure so some precautions should be taken to provide a shape change as gradual as possible. Figure 16 illustrates a desirable contour for a fillet weld. The surface of the weld should have a smooth contour that blends into the adjacent surfaces of the plate. The previous section contained a caution about avoiding overwelding of fillet welds. This caution also applies here because a fillet weld that is not overwelded is more likely to have a good contour than is one that is overwelded.

The contour of butt welds can be a problem area if the weld reinforcement has excessive buildup. The sketches in Figure 17 illustrate this condition and how a stress raiser is created. Grinding can remove this stress raiser but only if it is done properly.

Corner welds should be welded from the inside as well as the outside if possible. While the inside weld may not be required from a strength standpoint, the inside weld removes the stress raiser inherent at the toe of a corner weld (Figure 18). This is particularly important in corner welds as, even during construction, corner welds will be loaded in a manner that will cause high stresses at the toe of the weld.

Improperly fit joints will have built-in stress raisers even if welded with the best procedures. Figure 19 illustrates a failure caused by a delayed crack that occurred at a stress raiser in poorly fit joints. Had the joint been fit properly, the delayed crack probably would not have occurred.

Particular care should be given to the fitup of fillet joint. The sketch in Figure 20 shows how excessive joint gap creates a stress raiser at the weld root. When the joint gap is increased, the shape of the fusion line near the weld root is convex. In this area, the direction of the shrinkage forces and the fusion line are roughly parallel. With a wide joint opening, the shape of the fusion line becomes concave and stress raisers form at the root. Here the shrinkage force direction becomes almost perpendicular to the fusion line. This orientation of the shrinakge force and the fusion line combined with the stress raisers produces a

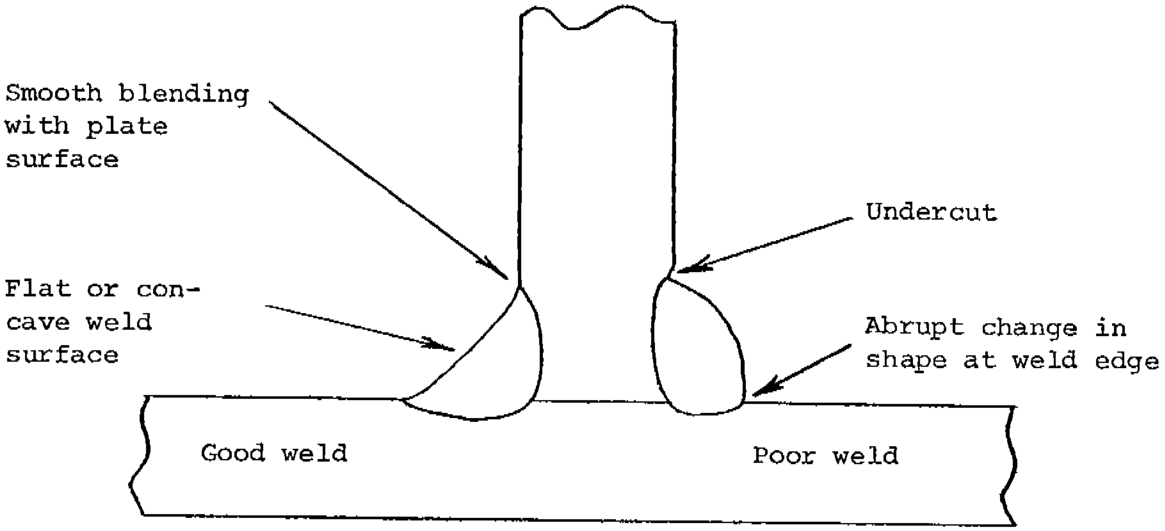
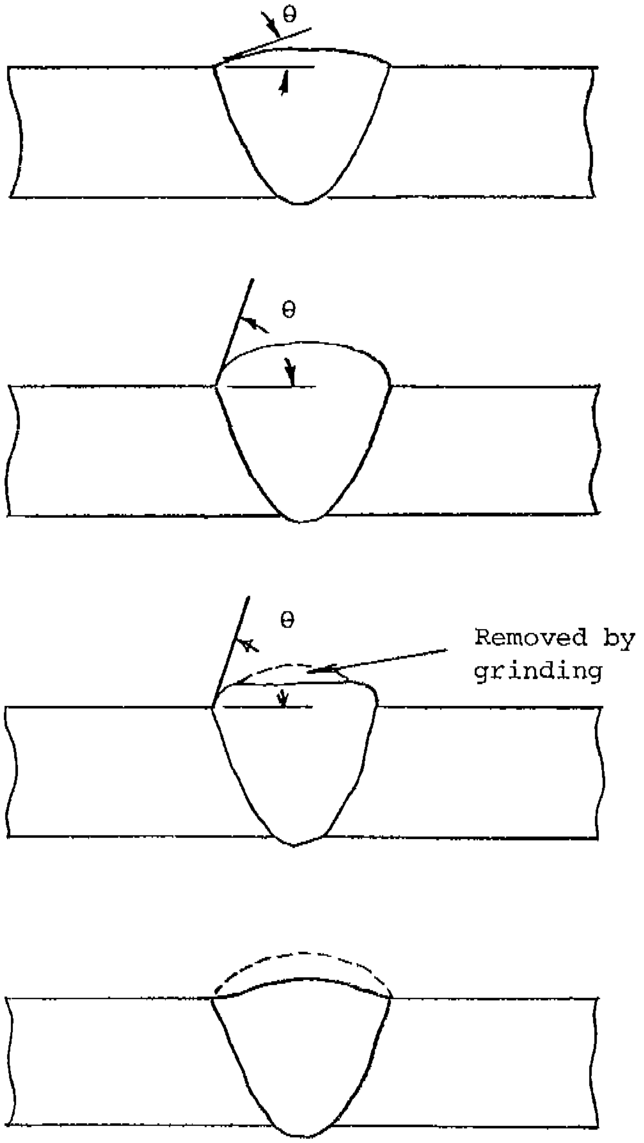


FIGURE 16. FILLET WELD CONTOURS



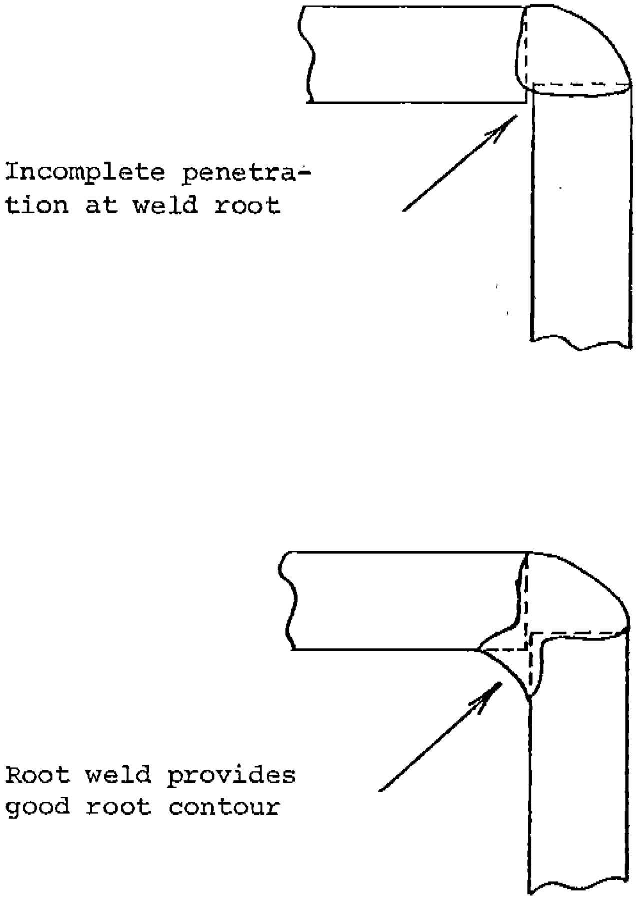
Desirable reinforcement contour
Gradual change in contour at weld edge
Angle θ is low

Undesirable reinforcement contour
Abrupt change in contour at weld
edge produces stress raiser
Angle θ is high

Improper grinding
Stress raiser at weld edge still present

Correct grinding to remove stress
raiser at weld edge

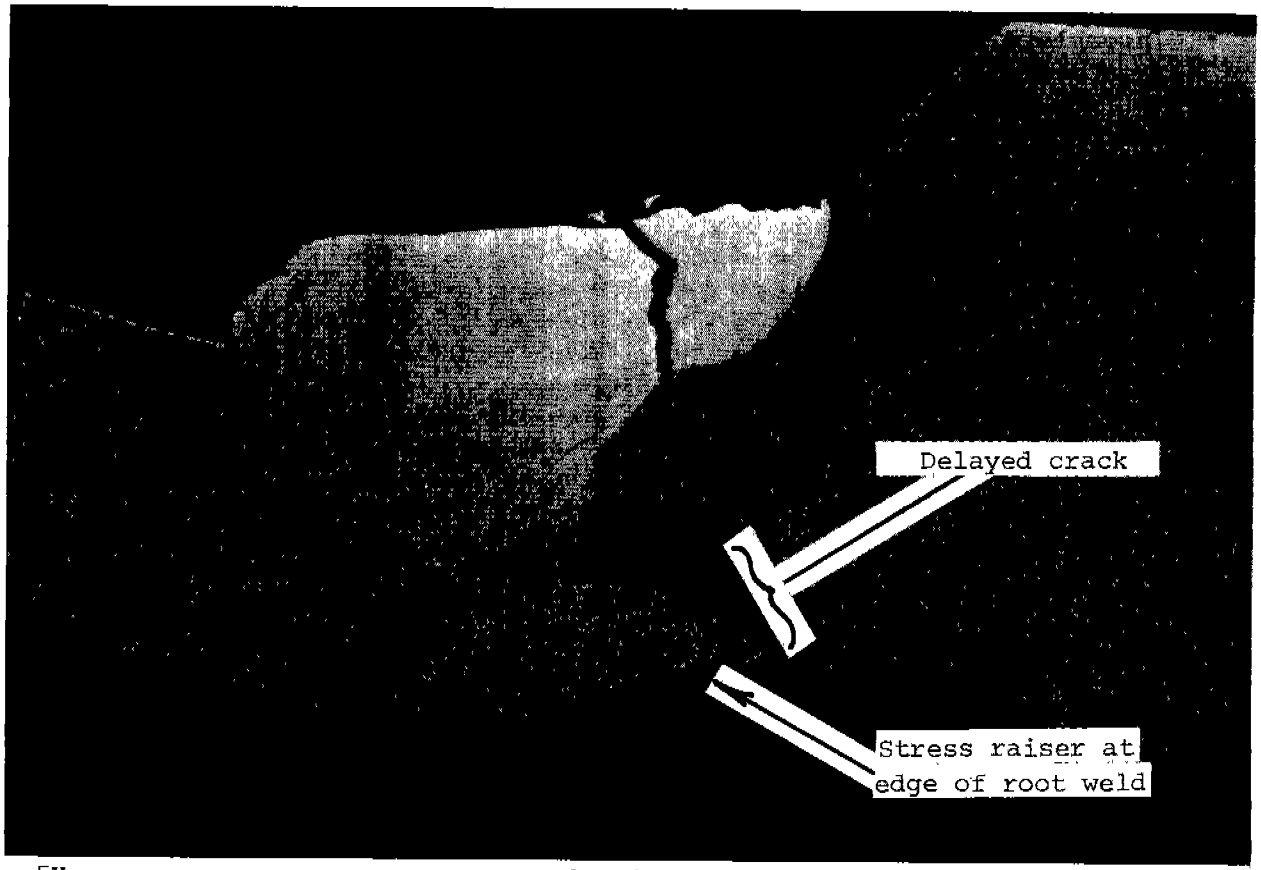
FIGURE 17. PROPER GRINDING TO REMOVE EXCESS REINFORCEMENT IN BUTT WELD



Incomplete penetration at weld root

Root weld provides good root contour

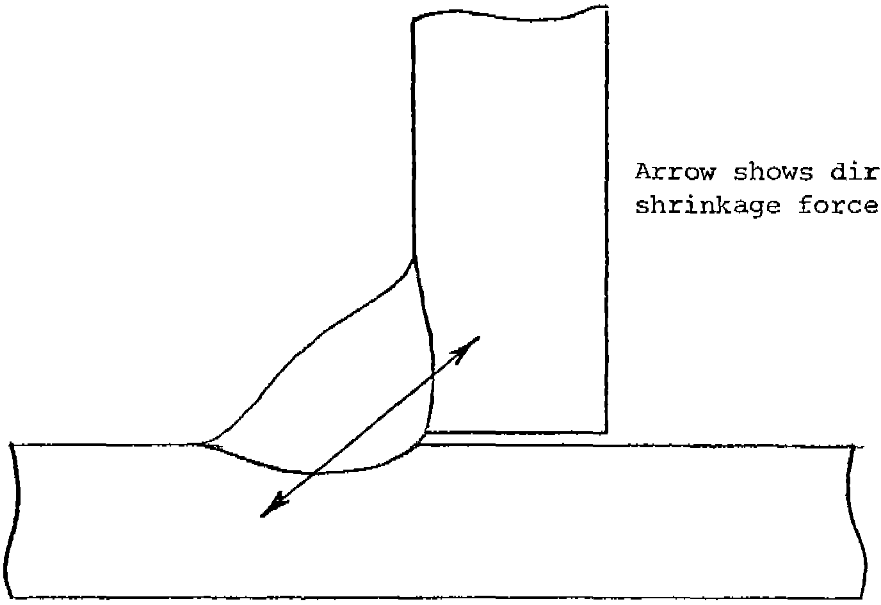
FIGURE 18. CORNER WELD CONTOURS



5X 2% Nital 2D800

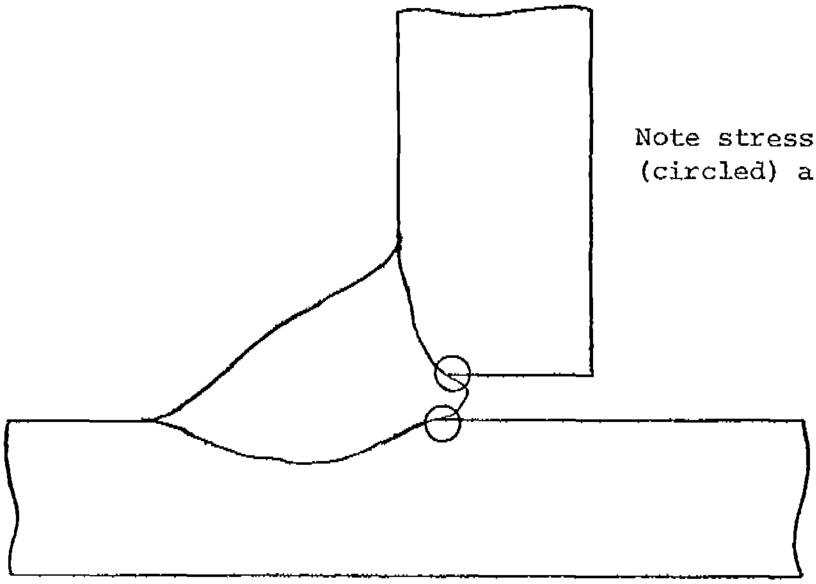
FIGURE 19. FAILURE CAUSED BY A DELAYED CRACK IN A POORLY FIT JOINT

With good fitup, the surface of the root weld would have had a flat contour that would have avoided the stress raiser.



Arrow shows direction of shrinkage forces

Joint with good fitup



Note stress raisers (circled) at weld root

Joint with excessive root gap

FIGURE 20. FILLET WELDS WITH VARYING JOINT GAP

significant increase in tensile stresses at the weld root - a condition conducive to delayed cracking at the weld root. Some investigations have been made to see how the joint gap in fillet welds affects the occurrence of delayed cracking.(23) Fillet welds were made in a steel having a carbon equivalent of about 0.62 so this steel was quite susceptible to delayed cracking. Low-hydrogen electrodes were used; stresses on the weld joint were entirely due to weld shrinkage. Without preheat, delayed cracks developed at the weld root with a joint gap of as little as 1/64 inch. Preheating to 200-300 F was necessary to prevent delayed cracks. Although these were quite severe tests, they serve to illustrate how poor joint fitup can result in delayed cracking.

Various weld defects are stress raisers and can cause delayed cracking if they are located near the fusion line. Proximity to the fusion line is necessary so that the field of concentrated stress will extend into the heat-affected zone. The most troublesome defects are undercutting, lack of penetration, lack of fusion, and slag inclusions.

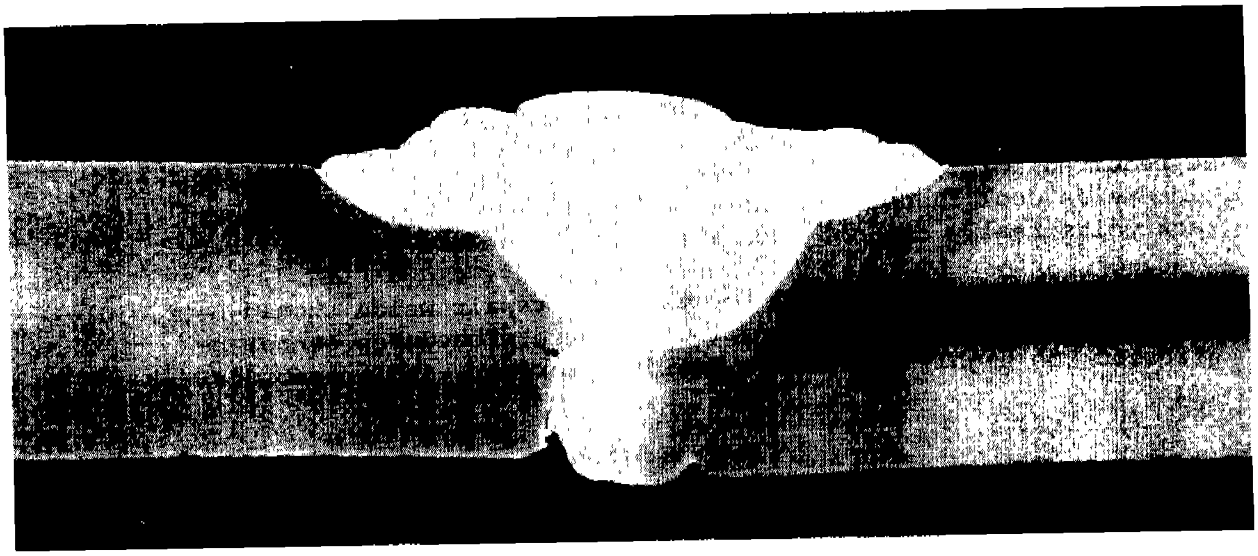
Undercutting occurs on the surfaces of the joint where tensile shrinkage stresses are highest. It is hardest to prevent in the root of welds made from one side only. The undercutting in Figure 21 has caused a small delayed crack on the left side of the weld. If at all possible, butt welds should be made from both sides to avoid this type of defect. Undercutting in butt welds made from both sides and in fillet welds can be prevented through use of proper welding technique.

Lack of penetration in butt welds made from one side is even more serious than root pass undercutting because a much sharper stress raiser is formed. Again, correct welding procedures or welding from both sides can avoid this defect.

Lack of fusion and slag inclusions are less serious because they occur below the surface where shrinkage stresses are lower in magnitude. Slag inclusions are bad only if they are elongated and form a sharp notch. Both of these defects can create high stress concentrations if the weld is highly restrained or if external loads are applied during welding. External loads can be created if force is needed to hold the parts in alignment for welding.

Tack and Repair Welds

Tack welds and welds made to repair weld defects must always be considered in the same manner as a constructional weld. This means that all of the precautions used in making the constructional weld must be used in making tack and repair welds. Delayed cracking can accompany both of these welds if proper procedures are not followed.



20X 2% Nital Etch 8D750

FIGURE 21. ROOT BEAD UNDERCUTTING

The characteristics of both tack and repair welds favor delayed cracking. Tack welds are short, single-pass welds that will cool rapidly. They may be highly stressed if the parts that the tack weld is holding in alignment have been bent or deformed to achieve proper fitup. Repair welds may be of any size; small repair welds will cool fast like tack welds. Most repair welds will be highly restrained by the surrounding plate and weld metal so shrinkage stresses will be high. What this means is that tack and repair welds must have at least as much if not more care than the primary or constructional weld. Tack and repair welds must be made with the same procedures as used with the constructional weld. This includes the same preheat, the same electrodes, the same joint cleaning procedures, etc. In addition, a minimum length should be required for tack welds; three inches is recommended. Shorter tack welds cool faster and are more highly stressed. Very short tack welds really are not much more than large arc strikes.

These requirements for tack and repair welds should be rigidly enforced; the importance of following these procedures cannot be stressed too highly to welders, welding foremen, and inspectors.

Inspection

Inspection procedures that can be used to detect delayed cracks are discussed in Report SSC-245, "A Guide for Inspection of High-Strength Steel Weldments". (To be published)

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FURTHER READING

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This report discusses the causes of delayed cracking in ship steel welds and presents the necessary steps necessary to prevent delayed cracking. Three factors, acting together, are responsible for the formation of delayed cracks: hydrogen dissolved in the weld, a hard microstructure in the weld or heat-affected zone, and high stresses within the weld joint. Each step that is taken to prevent delayed cracks has the purpose of eliminating or significantly reducing at least one of these factors.

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