

N74 30948

SUBMERGED ARC WELDING OF HEAVY PLATE

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It has become apparent that the size and complexity of weldments has increased in the last few years.

The list of these weldments is endless but include buildings, bridges, ships, steel mills and chemical processing equipment, as well as pressure vessels and piping of all kinds.

In almost every case this increase in weldment size has been accomplished by a common denominator -- heavier plate.

The submerged arc process is particularly suitable for heavy plate welding because of its ability to combine very high deposit rates along with excellent quality. It does these things without the smoke and spatter often accompanying other processes.

It is available today in several forms that are pointed to the fabricators of heavy sections with long, short or round about welds.

Tandem arc full automatic equipment is particularly suitable for those long heavy welds where speed and deposit rate are of the first order. An attachment called long stick-out which makes use of the IR drop on long electrode extensions can be included on this equipment to increase deposition rates 50% or more.

In addition, the long familiar DC single arc automatic head represents the least investment and greatest flexibility in full automatic equipment.

For the fabricator who has short heavy welds to make, semi-automatic submerged arc equipment is available to do a wide variety of jobs with great freedom of mobility. Attachments and travel mechanisms are sold for this equipment to extend its use even further into the full automatic range for the heavier plate thicknesses.

Although heavy plates have been welded in some industries for a long time, most of us are really neophytes when 2 inch, 4 inch, 6 inch and heavier plates start to appear on the drawing boards.

What are these differences that require such careful consideration with heavy plates even though the general specifications appear to be similar to those we have been welding successfully for years in lesser thicknesses?

The first and most serious mistake anyone can make is to assume that, since the chemistry and physicals are similar to material used before, the welding is also similar, and that the only difference is the time it will take to make larger welds. This is a serious under-estimation and can lead to all kinds of problems including failure or at the least, costly repairs.

Let's take a look at the characteristics of heavy plates with respect to their effect on the welding process.

#### A. Thickness and Mass:

Just thickness or size alone can present special problems which have a direct bearing on the welding operations. These heavy plates are more difficult to:

- |                             |                 |
|-----------------------------|-----------------|
| 1. handle                   | 4. fit and tack |
| 2. work on                  | 5. position     |
| 3. bend or form             | 6. preheat      |
| 7. Cut and bevel accurately |                 |

Mistakes or lack of equipment in the above areas can add many problems that must be corrected later on. Let's take a good look at some of the possibilities.

Flame cutting and beveling accuracy are much more important in heavy plates since the volume of weld metal added has a direct bearing on shrinkage and cracking tendencies. On fillets for example, the amount of weld metal goes up as the square of the leg side and the potential for shrinkage increases proportionately.

In the case of butt welds the 60° included angle preparation so often seen on lighter plates is certainly out of the question since it requires excessively large quantities of weld metal with its attendant shrinkage. The type of plate preparation we would like to have on these heavy butt welds are U's or double U's. However this type of plate preparation is difficult and costly. The next best situation are joints with small included angles (9-11°) with sufficient width at the bottom to provide access for the first passes.

Since the heavier plates are harder to bend or form, designed joints are harder to realize for the fitters. This results in joints normally that have greater variations than we would normally like to see.

Tacking is extremely important on heavy plates. Days of work may be lost or costly straightening might be required when tacks break on heavy weldments. Occasionally it may be necessary to locally preheat the areas where tacking is required. In all cases these tacks must have sufficient throat to resist the shrinkage of the main welding operations until sufficient weld metal has been deposited to hold the parts in alignment. For submerged arc welding, these tacks may take the form of welds 4 to 5 inches long and three or more layers deep with tapered or cascaded ends. On heavy plate these tacks should always be made with low hydrogen electrode.

B. Thickness and Plate Chemistry:

In the steel mill, all steel plates and rolled sections undergo a rather slow rate of cooling after being rolled while red hot. The red hot thick sections, because of their greater mass, cool more slowly than thin sections. For a given carbon and alloy content, slower cooling from the critical temperature results in a slightly lower strength.

For the normal thicknesses, the mill has no difficulty in meeting the minimum yield strength required. However, in extremely thick mill sections, because of their slower cooling, the carbon or alloy content might have to be increased slightly in order to meet the required yield strength. Examples of how the mills correct for this problem are shown in the ASTM specifications shown here (Figure 1) for two common steels.

Figure 1      See page 4

Figure 1

## B. Thickness and Plate Chemistry (Cont'd.)

How carbon changes with plate thickness:

## A 516

Grade 55		C	Mn
< 1/2"		.18	.60 to .90
1/2 to 2		.20	
2 - 4		.22	.60 to .120
4 - 8		.24	
8 - 12"		.26	

## A 515

Grade 55		C	Mn
< 1"		.20	.90
1 - 2		.22	
2 - 4		.24	
4 - 8		.26	
8 - 12"		.28	

Since a weld cools faster on a thick plate than on a thinner plate, and since the thicker plate will probably have a slightly higher carbon or alloy content, welds on thick plate, because of admixture and fast cooling, will have higher strengths, but lower ductility than those made on thinner plate. Special welding procedures may be required for joining thick plate (especially for the first or root pass), and pre-heating probably will be necessary. The object is to decrease the weld's rate of cooling so as to increase its ductility. More will be said about this later.

## C. Shrinkage and Stress

On thick plates with large welds, if there is metal-to-metal contact prior to welding, there is no possibility of plate movement. As the welds cool and contract, all the shrinkage stress must be taken up in the weld, (Figure 2(a)). In cases of severe restraint, this may cause the weld to crack, especially in the first pass on either side of the plate.

### C. Shrinkage and Stress (Continued)

By allowing a small gap between the plates, the plates can "move in" slightly as the weld shrinks. This reduces the transverse stresses in the weld. See Figures 2(b) and 2(c). Heavy plates should always have a minimum of 1/32 inch gap between them and if possible 1/16 inch.

This small gap can be obtained by means of the following:

1. Insertion of spacers, made of soft steel wire between the plates. The soft wire will flatten out as the weld shrinks. If copper wire is used, care should be taken that it does not mix with the weld metal.
2. A deliberately rough flame-cut edge. The small peaks of the cut edge keeps the plates apart, yet can squash out as the weld shrinks.

Figure 2

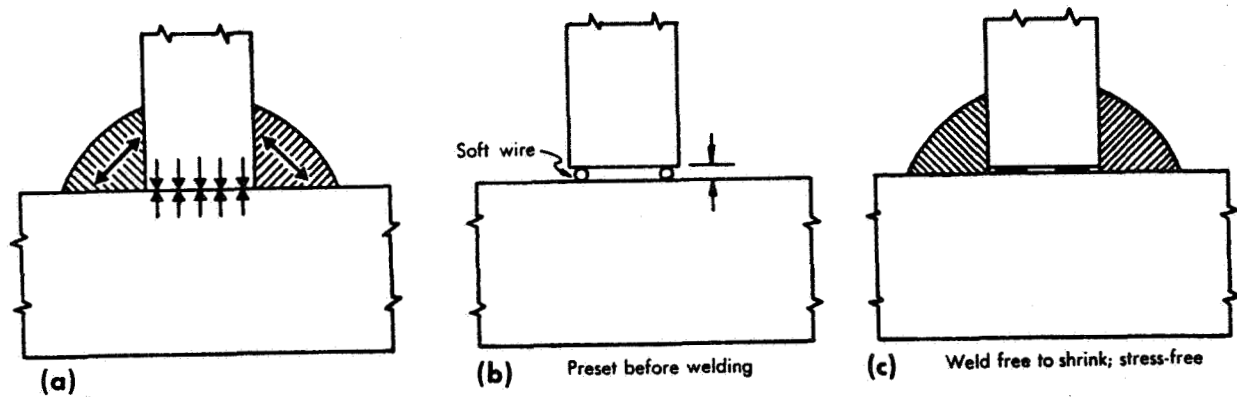
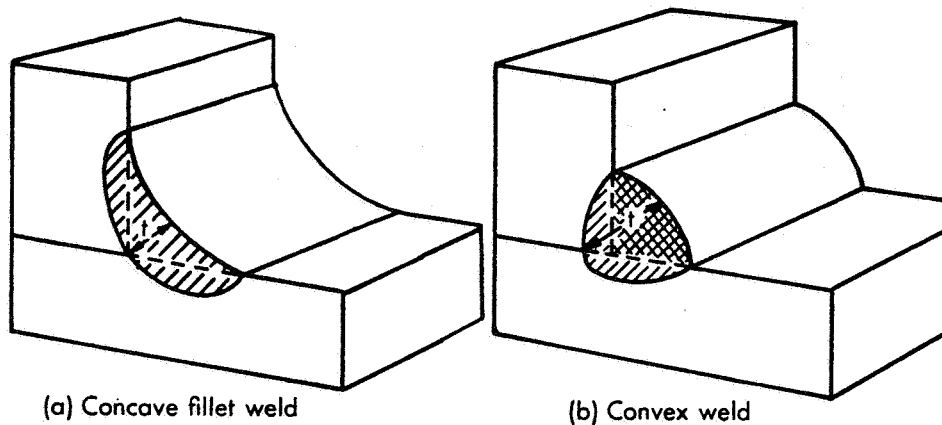


Figure 3



(a) Concave fillet weld

(b) Convex weld

#### D. Bead Shape and Cracking

Bead shape is another important factor that affects fillet weld cracking. Freezing of the molten weld due to the quenching effect of the plates commences along the sides of the joint where the cold mass of the heavy plate instantly draws the heat out of the molten weld metal and progresses uniformly inward until the weld is completely solid. Notice that the last material to freeze lies along the centerline of the weld.

To all external appearances, the concave weld (a) in Figure 3 would seem to be larger than the convex weld (b). However, a check of the cross section may show the concave weld to have less penetration and a smaller throat ( $t$ ) than first thought; therefore, the convex weld may actually be stronger even though it may have less deposited metal (darker cross section).

Designers originally favored the concave fillet weld because it seemed to offer a smoother path for the flow of stress. However, experience has shown that single-pass fillet welds of this shape have a greater tendency to crack upon cooling, which unfortunately usually outweighs the effect of improved stress distribution. This is especially true with steels that require special welding procedures.

#### D. Bead Shape and Cracking (Continued)

When a concave fillet weld cools and shrinks, its outer face is stressed in tension, Figure 4(a).  
if a

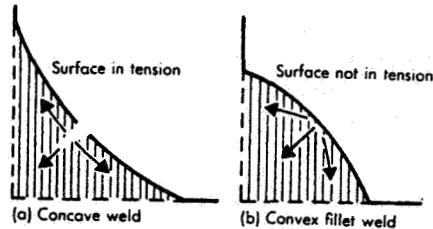


Figure 4

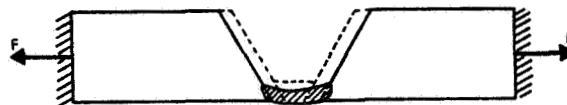
surface shrinkage crack should occur, it can usually be avoided by changing to a convex fillet (b). Here the weld can shrink, while cooling, without stressing the outer face in tension and should not crack. For multiple-pass fillet welds, the convex bead shape usually applied only to the first pass.

For this reason, when concave welds are desired for special design considerations, such as stress flow, they should be made in two or more passes -- the first slightly convex, and the other passes built up to form a concave fillet weld.

#### Groove Welds

On heavy plate, it is usually the first (or root) pass of a groove weld that requires special precautions. This is especially true of the root weld on the back side of a double Vee joint because of the added restraint from the weld on the front side. The weld tends to shrink in all directions as it cools, but is restrained by the plate. Not only are tensile shrinkage stresses set up within the weld, but the weld frequently undergoes plastic yielding to accommodate this shrinkage.

Figure 5

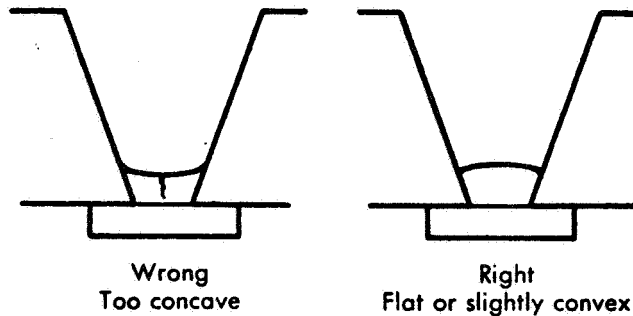


#### D. Bead Shape and Cracking (Continued)

Some idea of the possible locked-in stress and plastic flow of the weld may be seen in Figure 5. Imagine the plate to be cut near the joint, allowing the weld to freely shrink (dotted lines). Then pull the plates back to the original rigid position that they would normally be in during and after welding (solid lines). This necessitates a stretching of the weld.

In actual practice all of this stretch or yielding can occur only in the weld, since the plate cannot move and the weld has the least thickness of the joint. Most of this yielding takes place while the weld is hot and has lower strength and ductility. If, at this time, the internal stress exceeds the physical properties of the weld, a crack occurs which is usually down the centerline of the weld.

Figure 6



The problem is enhanced by the fact that the first (or root) bead usually picks up additional carbon or alloy by admixture with the base metal. The root bead thus is less ductile than subsequent beads.

A concave bead surface in a groove weld creates the same tendency for surface cracking as described for fillet welds, Figure 6. This tendency is further increased with lower ductility.

Increasing the throat dimension of the root pass will help to prevent cracking -- use electrodes or procedures that develop a convex bead shape. Low hydrogen welding materials are useful and preheat can be specified.



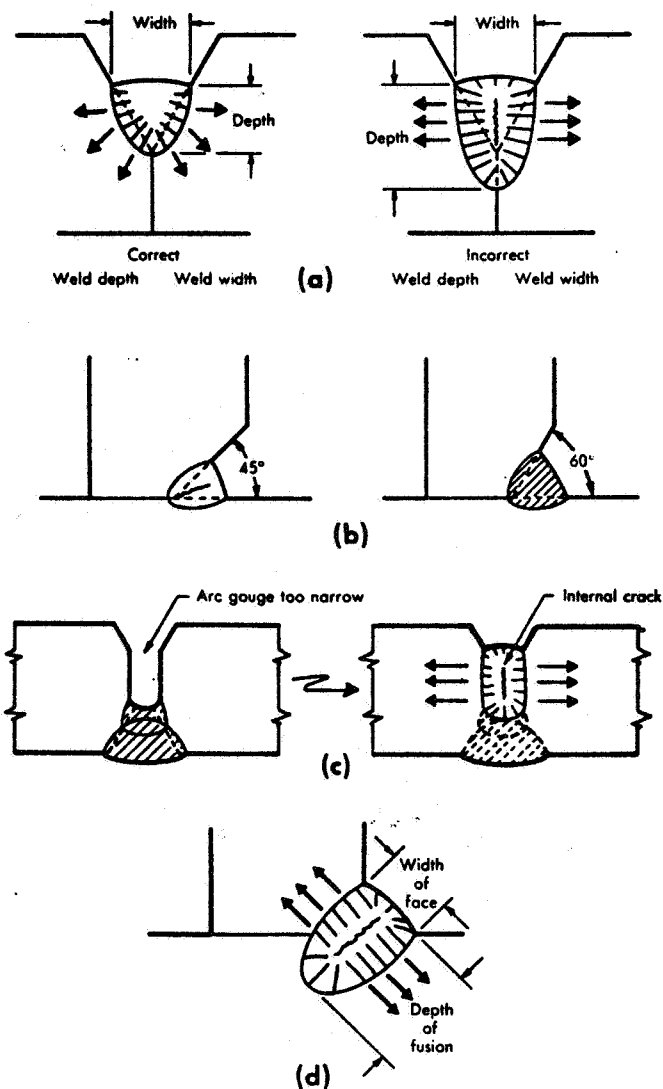


A small bevel on the second pass side of the double-V-groove weld, Figure 8(c), and arc gouging a groove too deep for its width led to the internal crack illustrated.

Internal cracks can also occur on fillet welds if the depth of fusion is sufficiently greater than the face width of the bead, Figure 8(d).

Although internal cracks are most serious since they cannot be detected with visual inspection methods, a few preventative measures can assure their elimination. Limiting the penetration and the volume of weld metal deposited per pass through speed and amperage control and using a joint design which sets reasonable depth of fusion requirements are both steps in the right direction.

Figure 8



#### D. Bead Shape and Cracking (Continued)

##### Underbead Cracking

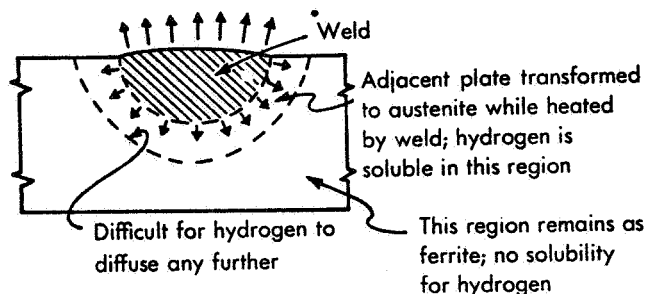
Underbead cracking is usually not a problem with the controlled analysis low carbon steels up to 1". This problem, if it occurs, is in the heat affected zone of the base metal. It can become a factor with thick plate as the carbon or alloy content of the steel increases. As an example, this can occur with the heat treatable very high strength, high carbon low alloy steels like 4140 or 6150. The construction alloy steels which have over 100,000 psi tensile strength and are heat treated before welding, also can experience underbead cracking in thick plates.

Low hydrogen processes, including submerged arc, should be used to join these materials since one cause of underbead cracking is hydrogen embrittlement in the heat affected zone. Hydrogen in the welding arc, either from the electrode coating or from wet or dirty plate surfaces and fluxes, will be carried by the droplets of weld metal being deposited and absorbed into the molten metal beneath the arc.

As the welding arc progresses along the plate, the deposited hot weld metal (which has now solidified) and the adjacent base metal heated by the weld above the transformation temperature are both austenitic at this elevated temperature, and have a high solubility for hydrogen. Fortunately, a considerable amount of hydrogen escapes through the weld's surface into the air; however, a small amount may diffuse back through the weld into the adjacent base metal. (The rate of diffusion decreases with decreasing temperature.)

Beyond the boundary of the heat affected zone, the base metal is in the form of ferrite, which has practically no solubility for hydrogen. This ferrite boundary becomes an imaginary fence, and the hydrogen tends to pile up here, going no farther. See Figure 9.

Figure 9

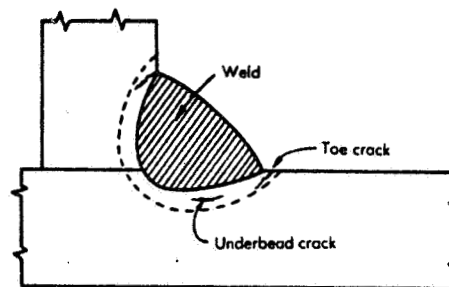


#### D. Bead Shape and Cracking (Continued)

Upon further cooling, the heat affected area transforms back to ferrite with almost no solubility for hydrogen. Any hydrogen present tends to separate out between the crystal lattice and builds up pressure. This pressure, when combined with shrinkage stresses, any hardening effect of the steel's chemistry, and quench rate may cause tiny cracks. Since weld metal is usually of a lower carbon than the base plate, this trouble occurs mainly just beyond the weld along the austenite-ferrite boundary and is called "underbead cracking". See Figure 10. If some of these cracks appear on the plate surface adjacent to the weld, they are called "toe cracks". Slower cooling by welding slower and preheating allows hydrogen to escape and helps control this problem.

The use of low-hydrogen producing welding materials eliminates the major source of hydrogen and with proper preheat usually eliminates underbead cracking on heavy plates.

Figure 10



#### E. PREHEAT IS A PREREQUISITE TO SUCCESS

Thick plates always suggest greater restraint, higher quench rates and greater hardenability, all of which aggravate the tendency for weld or base metal cracking.

From a practical standpoint, preheating is the most effective single means of minimizing the inherent difficulties in welding thick plates. From a metallurgical standpoint it is generally recognized that the need for preheat increases with the plate thickness. But it is equally true that the difficulty and the cost of preheating also increases very rapidly with the thickness and the complexity of the weldment. The weldor also is made more uncomfortable by the use of high soaking preheats. The net result is that too often either the required preheat has not been ob-

### E. Preheat is a Prerequisite to Success (Continued)

tained or the heating has been too localized and therefore ineffective. One experience with extensive field repairs usually teaches that preheating not only is a "must" but also is well worth the expense in lowering the total cost of a job.

#### WHY PREHEAT? WHAT'S ITS PURPOSE?

The basic purpose of preheating is seldom clearly understood by those who are required to do it. This in itself contributes to its being done improperly.

The main purpose of preheating is to slow down the cooling rate -- therefore it is the "volume" of heat as well as the temperature that is important. A thin surface area of high temperature is not enough if there is a mass of cold metal underneath.

Because of the heat absorption capacity of a thick plate, the heat affected zone and the weld metal may be in a highly quenched condition unless sufficient preheat is provided. It is time at temperature during the cooling period which really counts. Without adequate preheat intolerably high hardness and brittleness could occur in the weld or adjacent area.

Figure 11

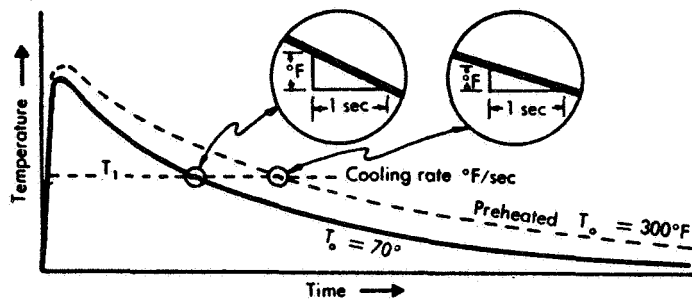


Figure 11 - This indicates the temperature in the heat affected zone as the weld arc passes by. The cooling rate ( $^{\circ}\text{F/sec}$ ) is slower when preheat is used.

When the purpose for preheating is misunderstood, it is not likely to be done properly. For example, in one instance involving a series of cracked welds, the operator insisted he had preheated to the required temperature which seemed to rule out one possible explanation for the cracks. On further checking he was asked what he did after he preheated it. His reply was, "I went to lunch."

E. Preheat is a Prerequisite to Success (Continued)

Another popular misconception is that the only purpose of preheating is to "get any moisture out of the joint." These concepts are wrong and they accomplish little or nothing when applied to massive weldments.

Preheating is used for one of the following reasons:

1. To reduce shrinkage stresses in the weld and adjacent base metal; especially important in highly restrained joints. Will eliminate tendency towards cracking and distortion.
2. To provide a slower rate of cooling through the critical temperature range (about 1600°F to 1330°F) preventing excessive hardening and lowering of ductility in both weld and heat-affected area of the base plate.
3. To provide a slower rate of cooling through the 400°F range, allowing more time for any hydrogen that is present to diffuse away from the weld and adjacent plate to avoid underbead cracking. Underbead cracking normally presents no problem when welding the lower carbon steels except on heavier plates. Preheat may be necessary to prevent its occurrence with the higher carbon steels even when low hydrogen processes are used. More often, some other problem, such as a highly restrained joint between very thick plate or high alloy content steel, is the factor that demands a higher preheat temperature to prevent weld cracks.
4. The importance of the effect of the cooling rate in heavy plate welding cannot be overemphasized. For example, the cooling rate of a 6 inch plate is over four times that of a 3/4 inch plate and about twice that of a one and a half inch plate even though the interpass temperatures (300°F) and heat input (36,000 Joules) are held the same. This cooling rate can only be reduced to the same general level by increasing the preheat and interpass temperature of the six inch plate to 500°F. The specific degree of preheat required for any application can only be determined by taking into account such factors as base metal chemistry, plate thickness, restraint,

## E. Preheat is a Prerequisite to Success (Continued)

and rigidity of the members, heat input of the process, etc. Some guide lines are available, but the best of these cannot be considered totally accurate if only because of the nebulous factor of rigidity and restraint in the assembly.

Any of these recommendations are represented as "minimum preheat recommendations" and they should be accepted as such.

The American Welding Society has set up minimum preheat and interpass temperature requirements as shown in Table 1.

**TABLE 1 – MINIMUM PREHEAT AND INTERPASS TEMPERATURE!**

This material has been compiled from the preheat data contained in the AWS Building Code D1.0-69 and AISC 1.23.6.

Thickness of Thickest Part at Point of Welding – Inches	Welding Process				
	Shielded Metal-Arc Welding with other than Low Hydrogen Electrodes	Shielded Metal-Arc Welding with Low Hydrogen Electrodes: Submerged Arc Welding; Gas Metal-Arc Welding; or Flux Cored Arc Welding		Shielded Metal-Arc Welding with Low Hydrogen Electrodes: Submerged Arc Welding with Carbon or Alloy Steel Wire. Neutral Flux; Gas Metal-Arc Welding; or Flux Cored Arc Welding	Submerged Arc Welding with Carbon Steel Wire. Alloy Flux
		ASTM A36; A53 Grade B; A375; A500; A501; A529; A570 Grades D and E	ASTM A36; A242 Weldable Grade; A375; A441; A529; A570 Grades D & E; A572 Grades 42, 45, and 50; A588		
To 3/4, incl.	None (2X3)	None (2X3)	70°F	50°F	50°F
Over 3/4 to 1-1/2, incl.	150°F	70°F (4)	150°F	125°F	200°F
Over 1-1/2 to 2-1/2, incl.	225°F	150°F	225°F	175°F	300°F
Over 2-1/2	300°F	225°F	300°F	225°F	400°F

1. Welding shall not be done when the ambient temperature is lower than 0°F. When the base metal is below the temperature listed for the welding process being used and the thickness of material being welded, it shall be preheated (except as otherwise provided) in such manner that the surface of the parts on which weld metal is being deposited are at or above the specified minimum temperature for a distance equal to the thickness of the part being welded, but not less than 3 inches, both laterally and in advance of the welding. Preheat and interpass temperatures must be sufficient to prevent crack formation. Temperature above the minimum shown may be required for highly restrained weld. For A514 steel the maximum preheat and interpass temperature shall not exceed 400°F for thicknesses up to 1-1/2 in., inclusive, and 450°F for greater thicknesses. Heat input when welding A514 steel shall not exceed the steel producer's recommendation.

When the base metal temperature is below 32°F, preheat the base metal to at least 70°F and maintain this minimum temperature during welding.

303 (g) Members do not have to be preheated for single pass tack welds which will later be remelted and incorporated into continuous submerged arc welds.

403 welding heat input for A514 steel should not exceed the steel producers recommendations.

415 (g) For single pass fillet welds over 3/8" made with multiple electrode submerged arc, the preheat and interpass temperature may be such that result in a hardness in the heat affected zone of less than 225 VHN for steels not exceeding specified T.S. of 60 ksi and 280 VHN for steels not exceeding T.S. of 70 ksi.

#### EFFECTIVE PREHEATING

Because of the difficulty of getting massive members up to the required preheat, human patience often runs out before the job has been done properly. However, the requirements are clearly stated (Table 1) --- and restated on page 17 of this paper.

## E. Preheat is a Prerequisite to Success (continued)

## PREHEAT AND INTERPASS TEMPERATURE

Keep it hot until job is finished or else preheat again. This is a simple rule to apply when welding heavy plate.

Since the purpose of preheating is to reduce the quench rate, it logically follows that the same slow cooling should be accorded all passes. This can only be accomplished by maintaining an interpass temperature which is at least equal to the preheat temperature. If this is not done each individual bead will be subjected to the same high quench rate as the first bead of a non-preheated assembly.

On a massive weldment it is not likely that the heat input of the welding process will be sufficient to maintain the required interpass temperature. Thus an additional source of heat will often be required as welding progresses.

When preheating large weldments, slow soaking or preheating in a uniform manner has a very desirable effect on the welding operations. It prevents cracking of tacks and welds caused by uneven local heating and shrinkage.

When is preheat needed?

1. When mass or plate size is sufficient to cause excessive cooling rates
2. When weldment is at a low temperature
3. When ambient surrounding temperature is low
4. When weldment has complex shape or large variation in size of adjacent parts
5. When carbon manganese or alloy contents have been increased to levels that indicate possible problems.

HOW MUCH PREHEAT IS REQUIRED?

Welding in low ambient temperatures or shop welding on steel brought in from outside storage on cold winter days greatly increases the need for proper preheat. Footnote 1 of the AWS Table 1 shown on page 15 states as follows:



E. Preheat is a Prerequisite to Success (continued)  
Footnote 1 -- Table 1

"Welding shall not be done when the ambient temperature is lower than 0°F. When the base metal is below the temperature listed for the welding process being used and the thickness of material being welded, it shall be preheated (except as otherwise provided) in such manner that the surface of the parts on which weld metal is being deposited are at or above the specified minimum temperature for a distance equal to the thickness of the part being welded, but not less than three inches, both laterally and in advance of the welding. Preheat and interpass temperatures must be sufficient to prevent crack formation. Temperature above the minimum shown may be required for highly restrained weld. For A514 steel the maximum preheat and interpass temperature shall not exceed 400°F for thicknesses up to 1-1/2 in., inclusive, and 450°F for greater thicknesses. Heat input when welding A514 steel shall not exceed the steel producer's recommendation."

When the recommendations given in Table 1 are conscientiously applied to massive members it sometimes becomes apparent that the old concept of a man with a single preheating torch in his hand is not going to get the job done. Large weldments may require more heat and the application of heat over a wider area than a single torch can provide. Other methods which have been used are thermostatically controlled electric strip heaters, multiple jet and infra-red gas heaters built to fit the contour of the weldment; also, electrical resistance heating systems which are designed primarily for stress relieving have been used for this purpose.

When adequate preheat is not provided it may be an easy matter to give reasons (or excuses) why it was not done, but this will not remove the problem. Weld metal or base metal cracks are the inevitable result of inadequate preheat which in turn results in very expensive cut outs and repairs.

F. WELD CHEMISTRY

One area we have not mentioned is the tendency in submerged arc welding for the manganese and silicon contents to build up in heavy multipass welds. This means that proper procedures and wire-flux combinations should be chosen not only for the plate chemistry but for the thicknesses involved. There frequently is a tendency in heavy plate welding to "over match" or make the weld stronger than it should be. This should not be done since it will reduce the ductility and increase shrinkage stresses that may cause cracks in the plate itself.

## CONCLUSION

Heavy plate welding with submerged arc or any other process presents additional problems to the fabricator which are critical if good welds are to be made. The following list of variables must be controlled:

## A. Joint Design and Preparation

Design for minimum amount of weld to reduce shrinkage forces and retain accessibility for welding equipment. If possible, design the joint and prepare the steel so that the lamellar pattern (direction of rolling) will be parallel with the weld shrinkage forces. Laminations are known to exist at the weld location (this can be determined ultrasonically), remove the questionable material and butter it with low hydrogen weld metal.

## B. Fit-Up

Control fit-up as closely as possible to reduce weld time and shrinkage forces. Allow slight gaps for shrinkage of heavy sections.

## C. Tacking

Tack with low hydrogen electrodes and make sure the tacks are of sufficient size to hold parts in alignment until sufficient weld has been deposited. Preheating may be necessary for tacking in some instances.

## D. Positioning and accessibility

Position job properly to make the most efficient use of the process.

## E. Preheating and Interpass Temperatures

Uniform preheating and interpass temperatures are extremely important in heavy plate welding. Do not assume that the heat input from the arc will be sufficient to maintain interpass temperatures at the proper level after preheating. Outside heat may have to be applied even as welding progresses. Slow, uniform cooling is desirable especially in low ambient temperatures. This would be especially true if either the weld metal or the base metal is hardenable because of alloy or carbon content.

#### F. Welding Procedures and Sequence

Welding procedures should be carefully chosen beforehand to assure the quality required. Welding sequence is of great important in helping to control distortion. Bead shape and location in multipass welding should be anticipated to prevent cracking or slag inclusions. Do not over match base metal with weld metal as this can cause excessive shrinkage forces and cracking. The susceptibility to delayed cracking is proportional to the hydrogen content of the welding atmosphere and greater crack sensitivity is exhibited by high chemistry base metal and by heavier plate thicknesses.

In general, cracking will initiate in the heat affected zone of the base metal, except in cases where the weld metal is of higher hardness.

Do not make concave bead shapes or single pass beads that are deeper than they are wide.

Tandem and long stickout procedures can be extremely helpful in giving maximum deposit rates on heavy plate welding.

#### G. Choice of Submerged Arc Equipment

Highest Deposit Rate - Full automatic tandem arc DC-AC or DC-AC-AC for long, heavy welds.

Most Flexibility - Full automatic single arc DC.

Most versatile for short, heavy welds - Semiautomatic DC with and without travel mechanisms.

Long stick-out attachments - Suitable for all sub-arc equipment to increase deposition rates or decrease heat inputs on quenched and tempered steels.