

Basic Welding Metallurgy of Structural Steel

PART OF THE CWB CERTIFICATE PROGRAMS



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MODULE 9

**BASIC WELDING METALLURGY
OF
STRUCTURAL STEELS**

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Basic Welding Metallurgy of Structural Steels

MODULE 9

BASIC WELDING METALLURGY OF STRUCTURAL STEELS

Introduction

The heat from welding may have a dramatic effect on the properties of the metal adjacent to the weld. In some cases this can lead to cracks or other detrimental effects, particularly in the case of steels which undergo metallurgical transformations when heated and cooled. To ensure that welds can be made successfully without cracking and having adequate properties, *welding procedures* are developed. Those involved in developing or applying welding procedures should, therefore, have a clear appreciation of the metallurgical principles involved. These are described in detail in this module.

Objectives

Specifically the following topics will be covered:

- Heat flow and cooling rates
- Zones in a weld
- Hydrogen effects
- Avoiding hydrogen cracking
- Metallurgical transformations
- Cracking tests
- Lamellar tearing
- Weld metal reactions
- Solidification cracking
- Properties of welds

Most of the discussion centres on the welding of steels that are used for construction purposes (e.g., bridges, pressure vessels, etc.) and specific welding problems associated with other metals are not covered. In particular, this module will provide a basis for understanding the welding procedure requirements contained in many of the structural welding codes such as AWS D1.1 and CSA W59.

HEAT FLOW

Almost all welding involves heating and cooling of the metal being welded, and in arc welding sufficient heat is applied to melt the metal. Adjacent to the melted metal (the weld metal) is a zone that reaches high temperatures, but does not melt. This region is known as the *heat affected zone* (HAZ). There are two major effects of the heating and cooling cycle.

- Metallurgical transformations may occur in the weld metal and HAZ.
- Stresses and strains may be induced leading to distortion and possible cracking

In order to understand the effects that welding may have on a metal, it is necessary to know how much heat the welding process supplies to the metal, what temperatures are experienced in the HAZ, and how rapidly the metal cools.

Consider for a start, the electric lamp shown in Fig. 1. The rate at which the lamp converts electrical energy into heat and light is given by *the current times the voltage*. In the example, the rate of conversion is:

$$1.5 \text{ amps} \times 100 \text{ volts} = 150 \text{ joules per second (or watts)}$$

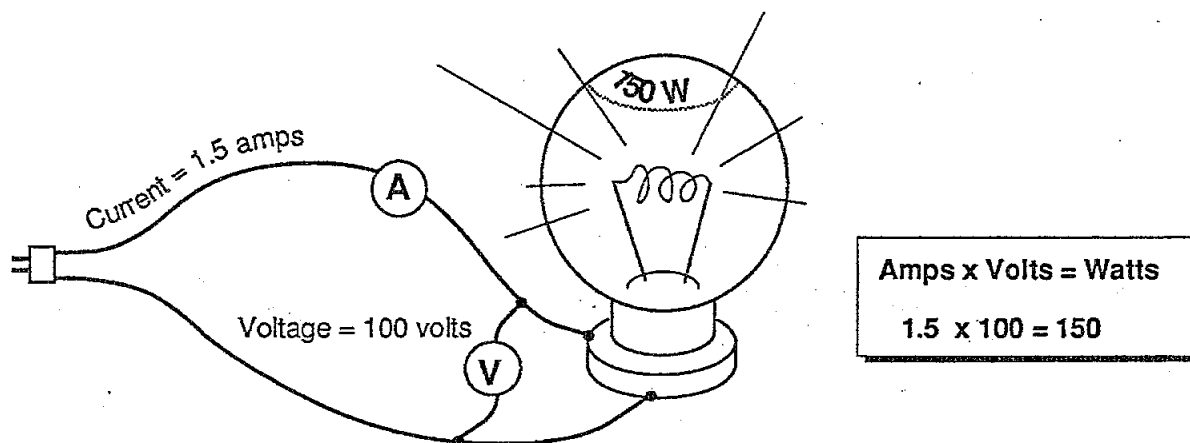
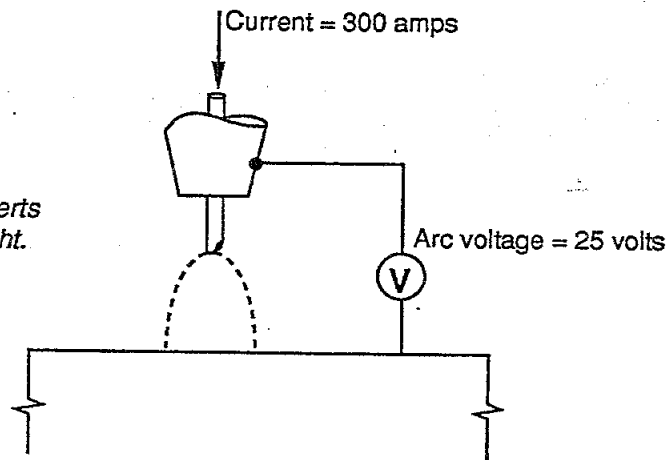


Figure 1. The electric lamp converts electrical energy to heat and light.

In a similar manner, an electric arc converts electrical energy into heat and light and the rate is calculated in the same way (Fig. 2). In the example, an arc of 300 amps with an arc voltage of 25 volts would be producing heat and light at the rate of $300 \times 25 = 7500$ joules per second.

Figure 2. The electric arc converts electrical energy to heat and light.



Rate at which heat and light are produced is $300 \times 25 = 7500$ joules per second

The proportion of total energy that is converted into heat that eventually enters the plate is known as the *efficiency* and varies with the process. Table 1 shows the values of efficiency that have been measured in experiments. In some processes it depends on technique (e.g., arc length) and precise values cannot be given.

Table 1. Heat efficiency of welding processes.

Process	Efficiency %
Submerged Arc Welding	90 - 99
Gas Metal Arc Welding	65 - 85
Flux Cored Arc Welding	65 - 85
Shielded Metal Arc Welding	50 - 85
Gas Tungsten Arc Welding	20 - 50

Energy input

In most arc welding, the arc is moved along the workpiece at a steady speed in order to produce a uniform weld. Under these conditions, a very important parameter is the energy input per unit length of weld. Suppose, for example, the arc shown in Fig. 2 is moving at a speed of 5 mm per second. The total energy per second is 7500 joules and therefore the energy per unit length of weld will be:

$$\text{Energy input} = \frac{7500}{5} = 1500 \text{ joules per mm} \\ \text{or } 1.5 \text{ kilojoules per mm}$$

$$\text{i.e., Energy input} = \frac{\text{volts} \times \text{amps}}{\text{speed}}$$

If the speed were measured in mm per minute, the calculation of energy input becomes:

$$\text{Energy input} = \frac{\text{volts} \times \text{amps} \times 60}{\text{Speed in mm per minute} \times 1000} \\ = \text{kilojoules per mm}$$

When Imperial units are used:

$$\text{Energy input} = \frac{\text{volts} \times \text{amps} \times 60}{\text{Speed in in. per minute} \times 1000} \\ = \text{kilojoules per in.}$$

To obtain the true *heat input* this would have to be multiplied by the efficiency of the process.

The energy input can vary widely depending on the process and welding conditions and some typical values are given in Table 2. The energy input is an important parameter since it relates to the size of the weld, the width of the HAZ, and the cooling rate. In general, the higher the energy input (or more correctly the heat input), the larger the weld, the wider the HAZ, and the slower the cooling rate. Fig. 3 shows a relationship between fillet weld size and energy input for submerged arc welds and Fig. 4 shows a similar relationship for shielded metal arc welds.

TEST
QUESTION

Table 2. Comparison of energy input for three processes (typical).

	Electroslag		Submerged Arc		Shielded Metal Arc	
Current (amps)	800		600		200	
Voltage	34		28		23	
Welding Speed, mm/sec (ipm)	0.32	(0.75)	5.1	(12)	3.4	(8)
Energy Input, kJ/mm (kJ/in.)	88	(2176)	3.3	(84)	1.4	(34.5)
Cross-Section Area of Weld, sq mm (sq in.)	5600	(8.7)	71	(0.11)	39	(0.06)
Width of HAZ, mm (in.)	17.8	(0.7)	3.1	(0.12)	2.0	(0.08)

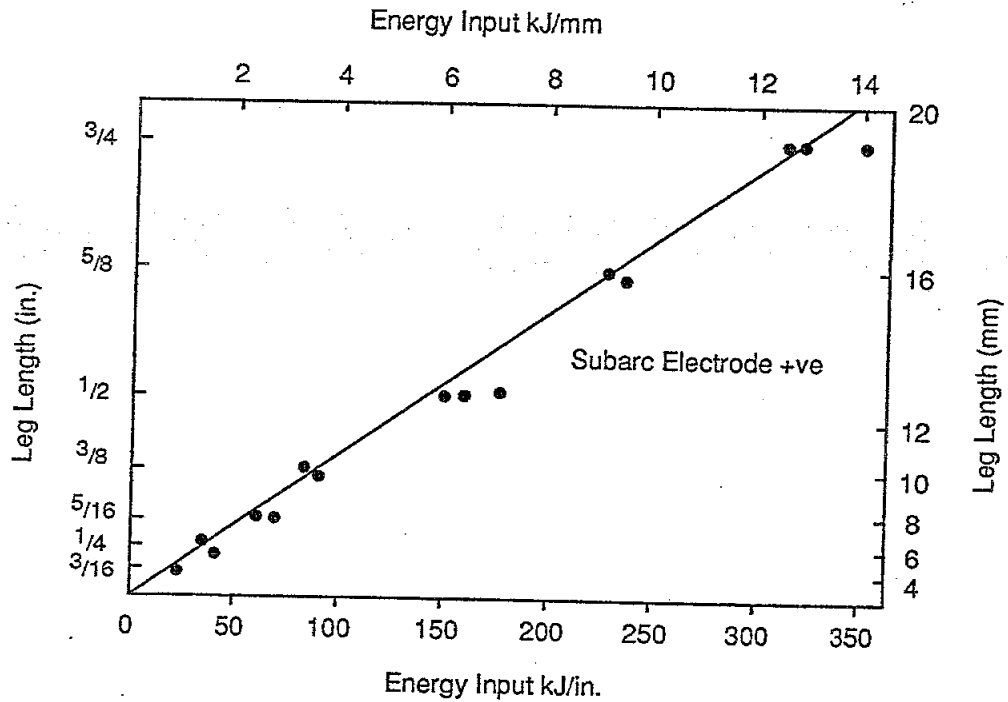


Figure 3. Relation between fillet size and energy input for submerged arc welding.

It is important to recognize that the same energy input may be achieved with various combinations of welding current and speed. Fig. 5 shows how increasing the current and speed in proportion keeps the energy input and fillet weld size constant, but increases the penetration.

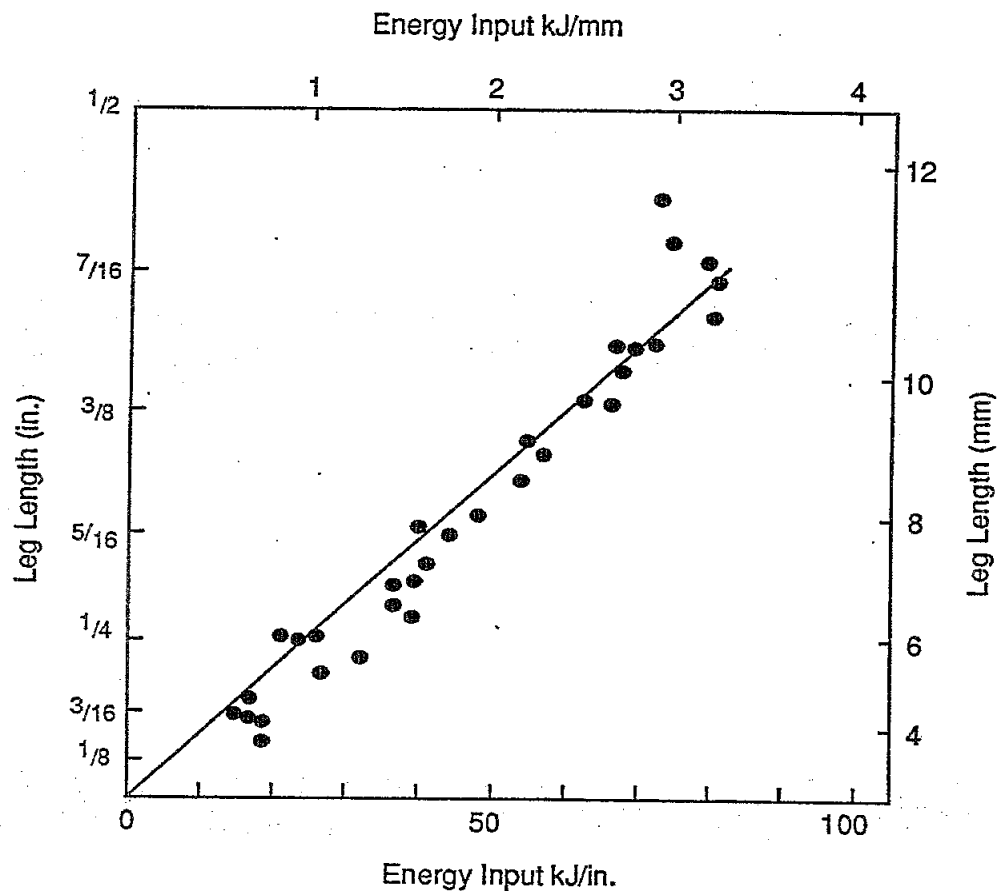


Figure 4. Relation between fillet size and energy input for shielded metal arc welding.

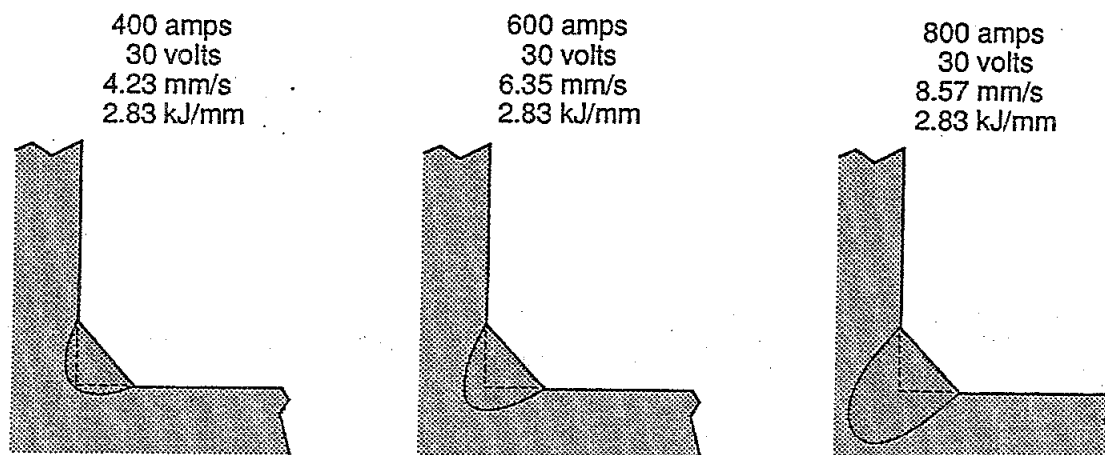


Figure 5. Effect of increasing current and speed, keeping energy input constant.

Cooling rates

With manual welding, the technique will influence the energy input. Depositing stringer beads using a small diameter electrode involves a low energy input, whereas a *weaving technique results in a higher energy input*.

When a weld is made, the heat is rapidly conducted away from the weld zone into the surrounding plate after the arc has passed. The rate at which the weld zone cools has an important effect on its structure, properties and risk of cracking. The rate of cooling in a given material will depend on three major factors:

- The heat input to the weld (i.e., the energy input times the efficiency)
- The plate thickness
- The initial temperature of the plates (i.e., the preheat or interpass temperature)

PLATE CHEMISTRY.

Increasing the heat input will reduce the cooling rate (i.e., the weld will take longer to cool). For thick plates, the cooling rate is inversely proportional to the heat input. For example, doubling the heat input will halve the cooling rate. On thin plate, the cooling rate is more sensitive to heat input and doubling the heat input will reduce the cooling rate four times.

For a given heat input the cooling rate increases as the thickness increases, as shown in Fig. 6. Beyond a certain thickness, the cooling

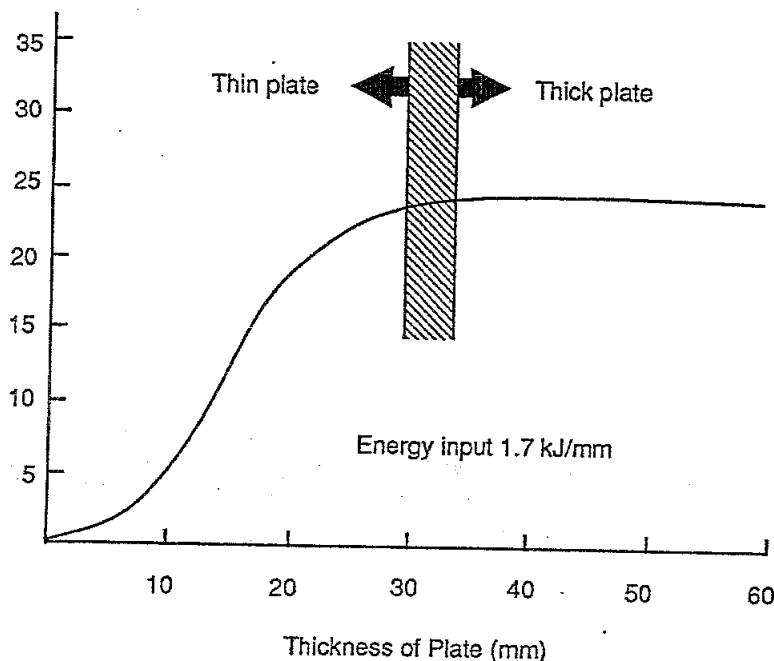


Figure 6. Increase of cooling rate with thickness.

rate becomes virtually independent of the thickness and any plate in this range may be considered as "thick". For example, the cooling rate for an energy input of 1.7 kJ/mm weld on a 100 mm plate will be the same as that on a 50 mm plate. In the range where the plate is considered thin, the cooling rate depends on the square of the thickness. For example, at 1.7 kJ/mm heat input a 12 mm plate will cool four times as quickly as a 6 mm plate.

Fortunately, the relationships among heat input, thickness, and cooling rate can be expressed graphically, making it far easier to estimate cooling rates. In Fig. 7 a cooling rate diagram is presented for the case of bead on plate welds using the submerged arc process. The diagram includes the effect of preheat which also tends to reduce the cooling rate. Notice that the bottom left scale is *energy input* for submerged arc and is simply calculated from volts, amps, and speed. The efficiency factor is already built into the curves. The cooling rate is measured at 540°C and is expressed in °C per second.

The following example illustrates how the diagram is used.

Example:

A weld is made with submerged arc on 12 mm plate using the following conditions:

Current	350 amps
Arc voltage	29 volts
Speed	508 mm per minute
Preheat	None (initial plate temperature is 20°C)

The energy input is:

$$\frac{350 \times 29 \times 60}{508 \times 1000} = 1.2 \text{ kJ/mm}$$

Enter the diagram at 1.2 kJ/in. and go up to the 12 mm line; then go across to the right hand part to intersect the line marked 20°C for preheat; then go up to read off the cooling rate, about 16°C/s.

If the plate had been 50 mm thick, then going up the 1.2 kJ/mm line would have indicated that anything thicker than 19 mm is "thick" and the line marked "thick plate" would be used.

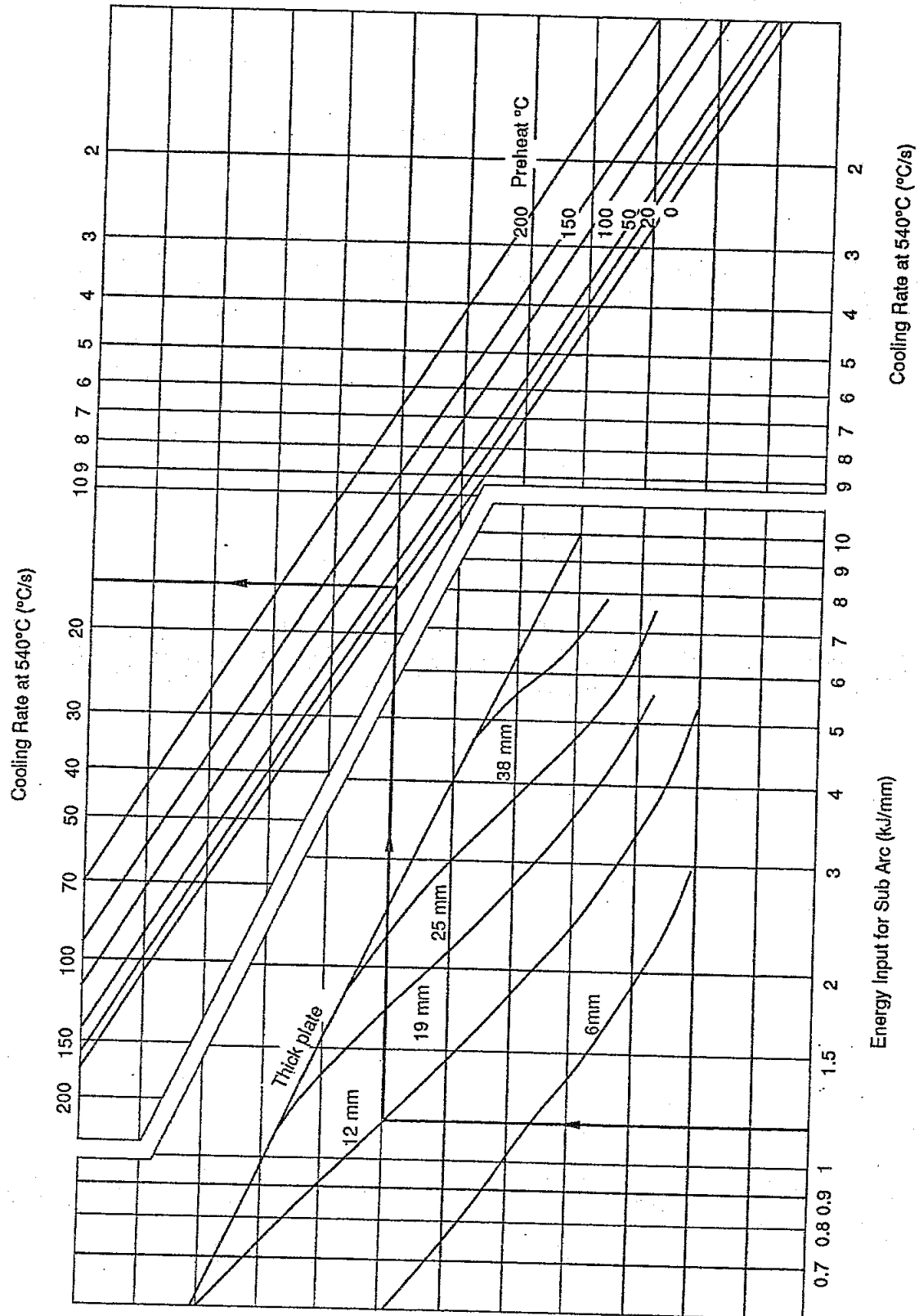


Figure 7. Graph to determine cooling rate in a bead-on-plate for submerged arc process.

Zones in a weld

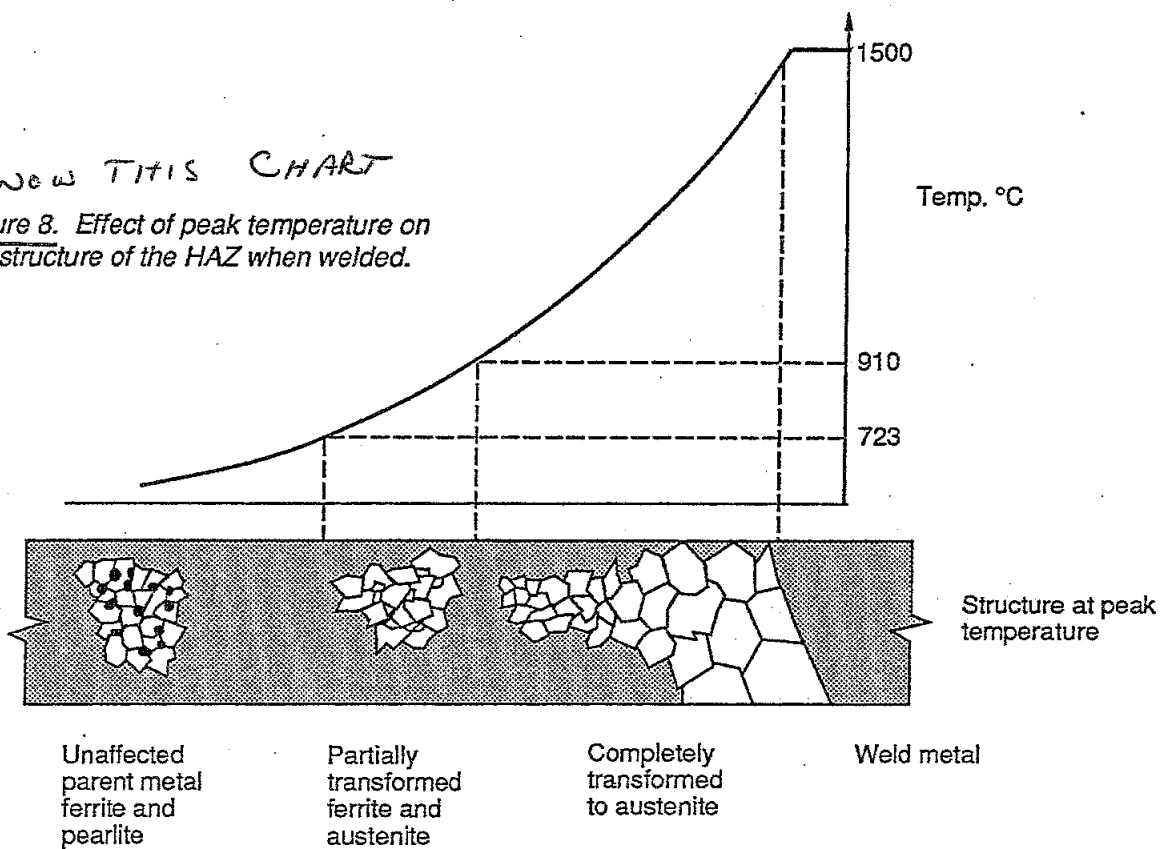
Although designed for bead-on-plate situations, the diagram can be used for groove welds if the plates are not too thick. It can also be used for fillet welds by taking 2/3 of the energy input. For example, a fillet weld of 2.4 kJ/mm will cool at the same rate as a bead-on-plate of 1.6 kJ/mm if the plate thicknesses are the same.

Adjacent to the weld pool, the metal will be rapidly heated to some peak temperature followed by cooling. The peak temperature reached will determine what metallurgical changes will occur. For steel, regions exceeding 723°C will partially transform to austenite on heating. Above 910°C complete transformation to austenite occurs. On cooling, the austenite may transform to structures quite different from the original parent plate. Regions that do not exceed 723°C will not be transformed although other minor changes may occur. Fig. 8 shows, diagrammatically, the effect of peak temperature.

Regions that are close to the fusion boundary can experience temperatures sufficiently high that growth of the austenite grains occurs. The extent to which they grow and the width of the grain coarsened zone depends on the energy input. Even in quite low energy

KNOW THIS CHART

Figure 8. Effect of peak temperature on the structure of the HAZ when welded.



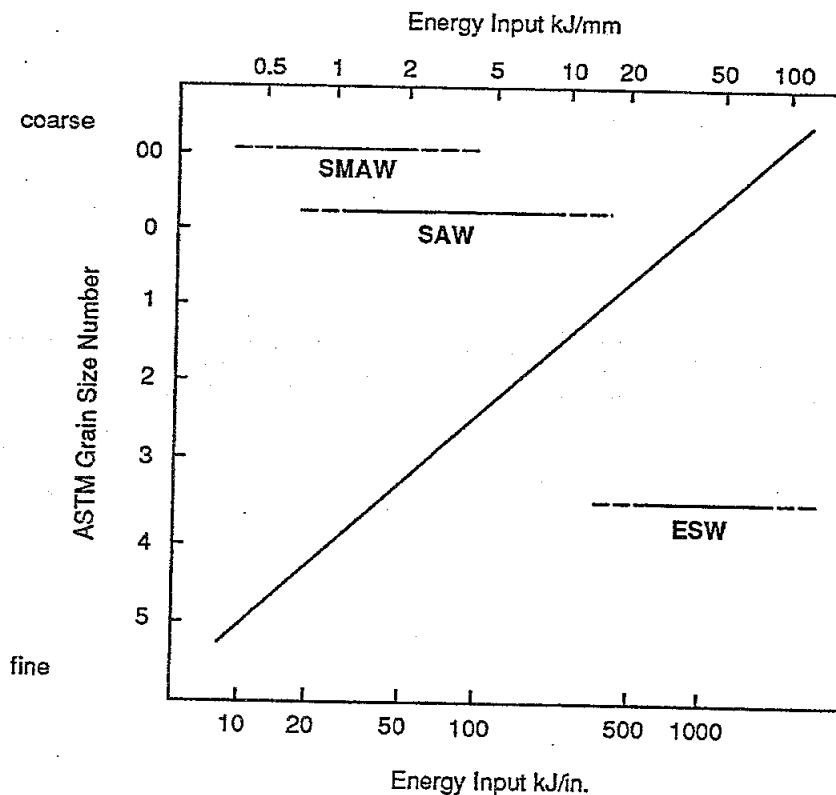


Figure 9. Effect of energy input on the maximum austenite grain size in the heat affected zone of a steel.

input welds, the austenitic grain size close to the fusion boundary may substantially exceed the original austenite grain size of the parent metal. Fine grain steels will exhibit a much narrower coarse grain zone because higher temperatures are required to cause grain growth. Fig. 9 shows the maximum austenite grain size as a function of energy input. A large ASTM number (≥ 5) indicates a fine grain.

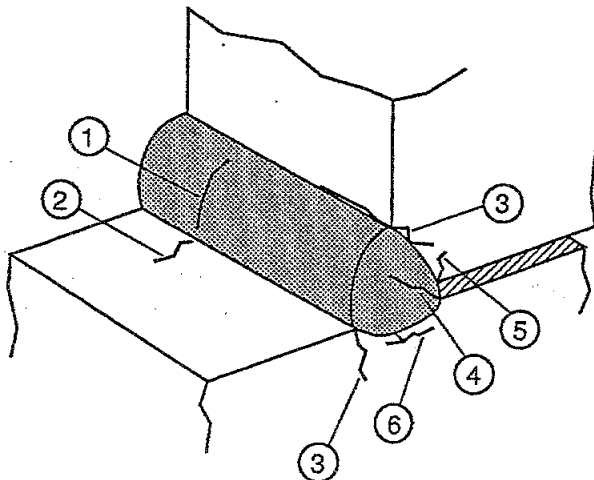
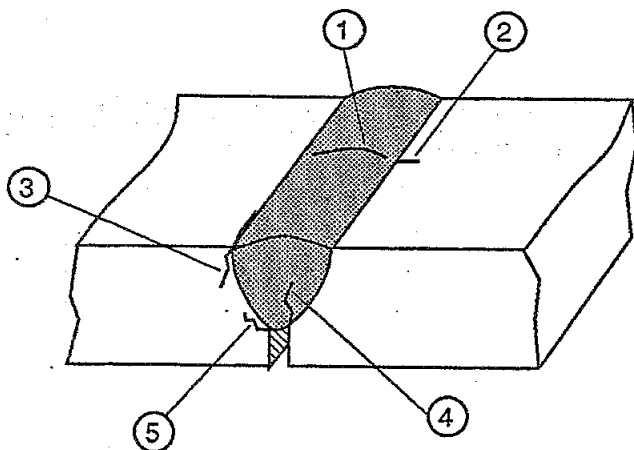
When the weld cools, the parts of the HAZ that have formed austenite will transform back again. The structure that is finally produced will depend on the cooling rate. In low energy input welds on thick plate the cooling rate will be as fast as a quench and a hard martensitic structure may be produced. With higher energy, thinner plates, or preheat, a slower cooling rate will be experienced and a softer microstructure may result. It is most important for those involved in welding to understand the type of HAZ structure likely to be produced in the steel being welded. If a hard martensitic structure is formed it may be susceptible to cracking. On the other hand, in some steels, a very slow cooling rate may produce a soft, but coarse grain structure with very low toughness. Later in this module, the effects of steel composition on the HAZ structure will be discussed more fully, but first the general problem of hydrogen cracking will be described.

HYDROGEN CRACKING

General features

One of the major problems encountered in welding steels is *hydrogen cracking*. The term "hydrogen cracking" is used for a broad class of cracks since hydrogen is nearly always involved. It need not, however, always be the most important factor and several other factors can contribute to the problem. It is also known as *cold cracking* since it only occurs *after the weld has cooled down*.

These cracks can occur in many locations in the weld and some commonly observed locations are shown in Fig. 10. They may occur in



KNOW THESE TERMS.

- ① Transverse crack in weld metal
- ② Transverse crack in heat affected zone
- ③ Toe crack
- ④ Weld metal crack
- ⑤ Root crack
- ⑥ Underbead crack

Figure 10. Commonly observed positions of hydrogen cracks (cold cracks) in groove and fillet welds.

the weld metal or in the heat affected zone, and in various orientations. One feature of hydrogen cracking is that it may exhibit a delay phenomenon. Even after the weld has cooled to room temperature, there may be a further lapse of time before cracking occurs. Under most conditions if cracking is to occur it will do so within a day of welding. This is one of the reasons that codes often call for a waiting period between welding and inspection.

The major factors that influence hydrogen cracking are:

- The susceptibility of the weld metal or HAZ to hydrogen embrittlement, which is related to the chemical composition and microstructure
- The hydrogen content
- The stress or strain level at the point of crack initiation
- Temperature—cracking can only occur after the weld has cooled below about 100°C

Hydrogen

Hydrogen is a gas that is often present in the atmosphere surrounding the arc. The hydrogen comes from the breakdown of water or organic material and can dissolve in the molten pool as shown in Fig. 11. If the weld cools quickly significant quantities of hydrogen may be trapped in the weld and heat affected zone as shown in Fig. 12.

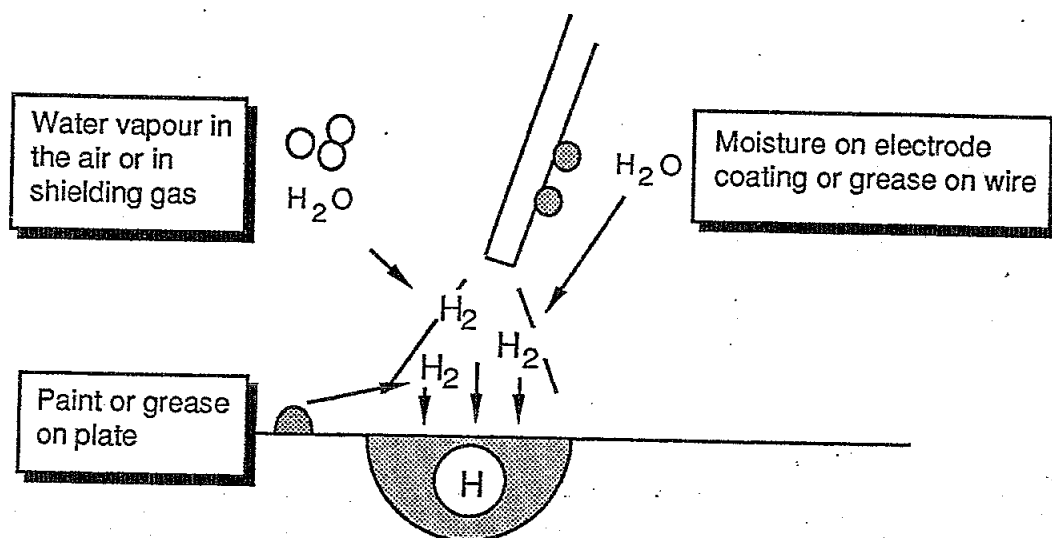


Figure 11. Possible sources of hydrogen.

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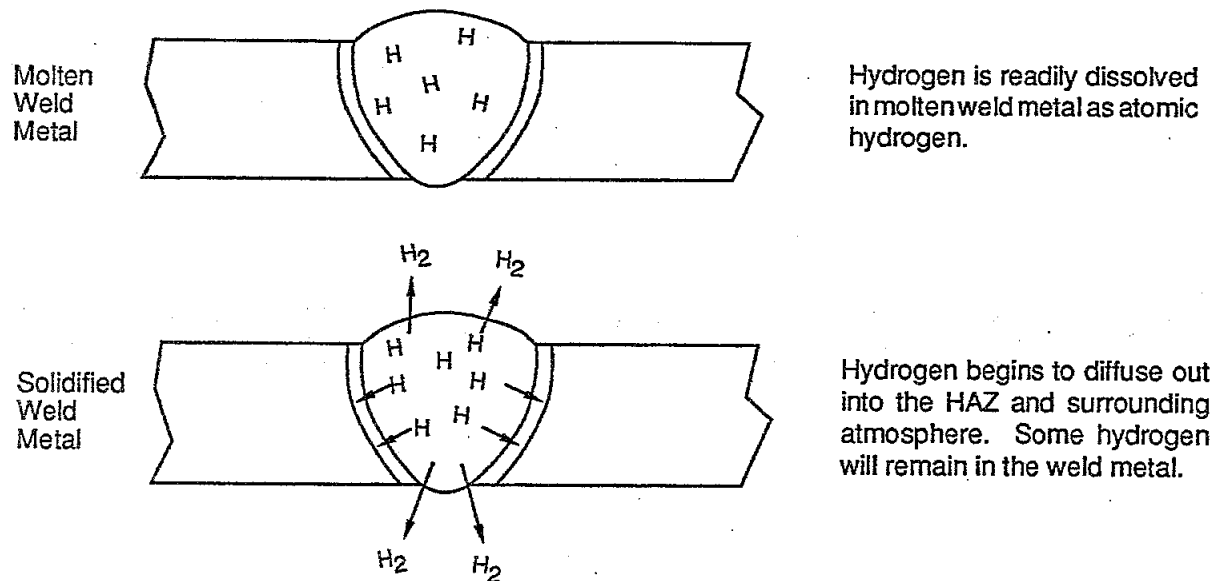
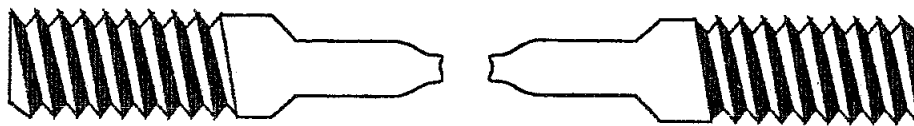


Figure 12. Trapping of hydrogen in rapidly cooled weld.

Hydrogen, trapped in steel, has the peculiar property of causing severe embrittlement. *Even small quantities of hydrogen can cause a large reduction in ductility or a drop in the fracture stress of a notched steel specimen.* Weld metal tensile specimens that contain hydrogen very often reveal "fish eyes" on the fracture surface and a loss of ductility (Fig. 13).



Tensile specimen free of hydrogen showing good ductility when tested



Tensile specimen containing hydrogen showing poor ductility when tested

Figure 13. Loss of ductility in steel due to the presence of hydrogen.

Embrittlement may be delayed and a specimen containing hydrogen may sustain a load for a period of time before breaking. This effect is illustrated in Fig. 14 where a series of specimens have been tested to plot a "load versus time to failure" curve.

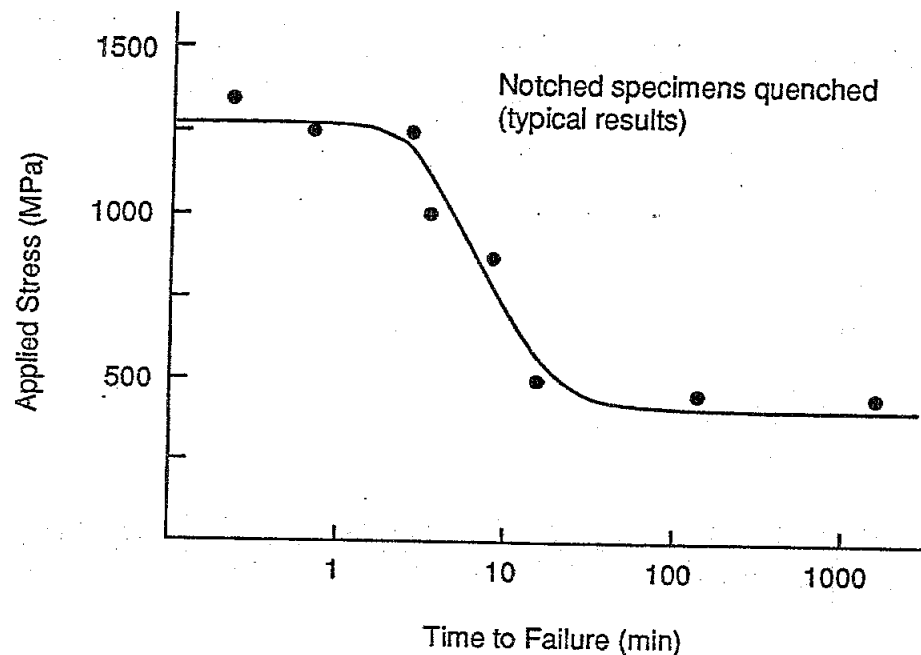


Figure 14. Plot of load against time to failure for steel specimens containing hydrogen illustrating the delayed fracture effect.

There are two other peculiar features of hydrogen embrittlement. One is that the effect diminishes with increasing temperatures and at about 150°-200°C hydrogen has no embrittling effect on steel. The second is that the effect is a maximum at very slow or steady rates of loading. Unlike other types of embrittlement the effect of hydrogen disappears at very fast or impact loading rates. The presence of hydrogen will not, therefore, affect the results of a Charpy Impact Test.

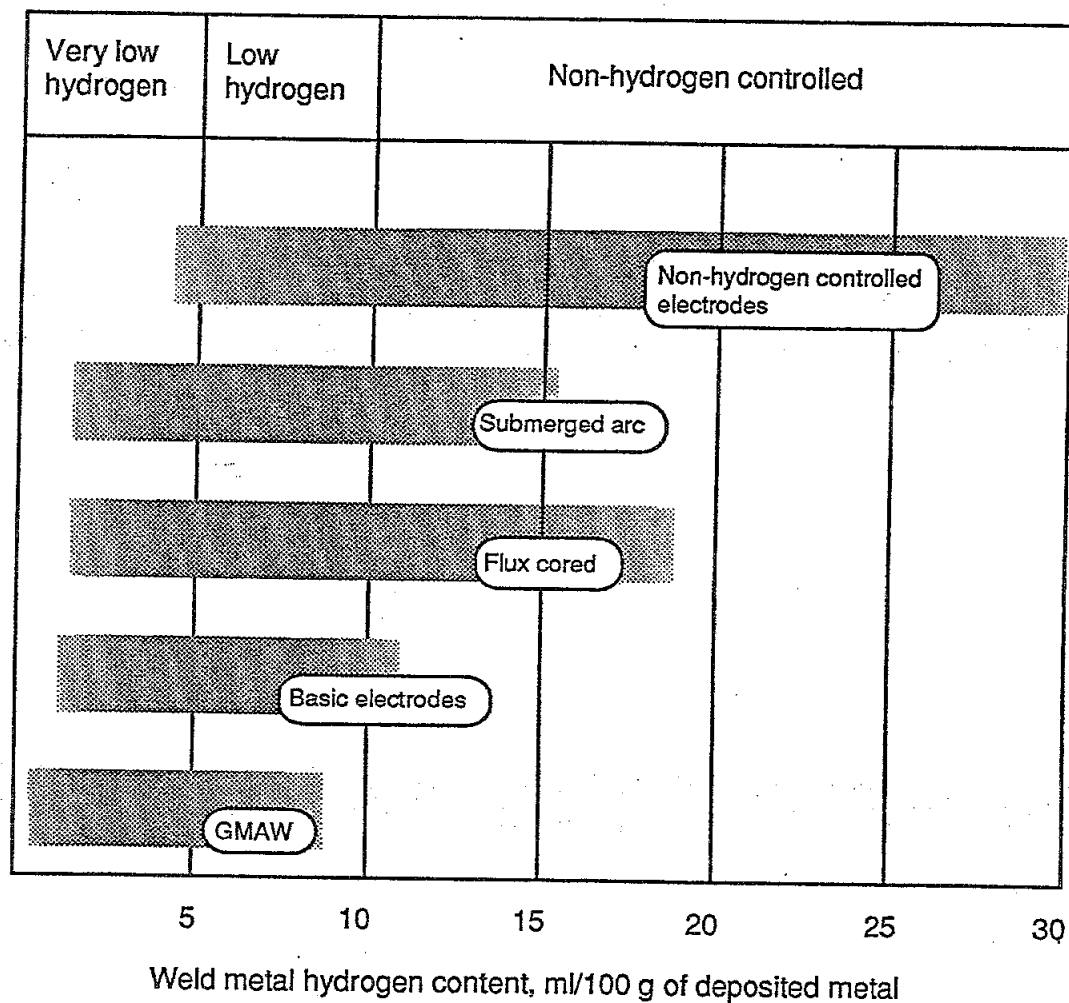


Figure 15. Effect of process and types of electrodes on potential hydrogen (after Coe).

The hydrogen content of a weld depends on the process used (see Fig. 15), the welding procedure and, in particular, the level of preheat. Some electrodes are designed to provide a low hydrogen level by special formulation of the coating. Coatings which are termed "basic", release carbon dioxide into the arc atmosphere and this lowers the amount of hydrogen gas present. These electrodes will only produce low hydrogen if they are kept dry, and proper storage and drying procedures should be followed.

Standards, such as CSA W59 and AWS D1.1, specify maximum exposure times before electrodes must be rebaked as shown in Fig. 16. AWS A4.3 provides methods for determining hydrogen content.

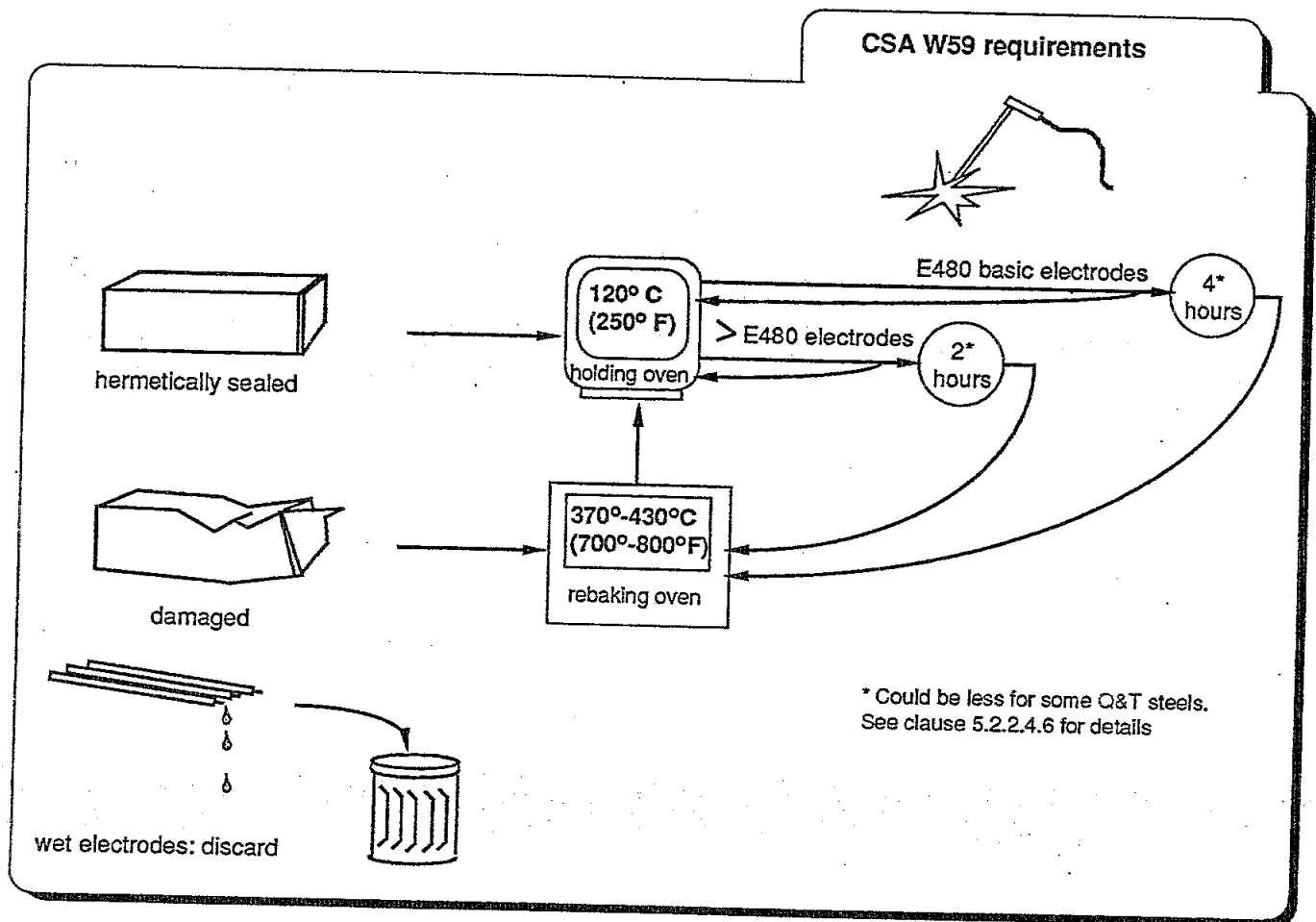


Figure 16. Summary of some CSA W59 requirements for electrodes.

Stresses

Hydrogen will not cause cracking in a weld unless there is a stress present; but due to the non-uniform heating in welding, there are always contraction stresses formed. In most cases, the exact stresses in a weld are never known and would be very difficult to measure or calculate. There are, however, two contributing factors that may sometimes be estimated, even if only qualitatively:

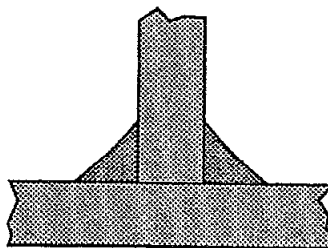
- Restraint
- Stress concentrations

The restraint is the resistance to shrinkage that is imposed on the plates being welded. Welding personnel learn from experience what types of joints are "high restraint" and what are "low restraint" and in a few cases calculations have been made. Restraint is higher in thicker plates and usually higher in groove welds than fillet welds. In Fig. 17 some examples are given.

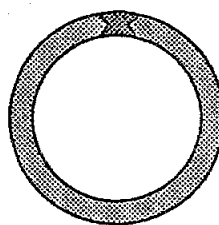
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WELDS USUALLY LOW RESTRAINT

Most fillet welds
e.g., web to flange welds

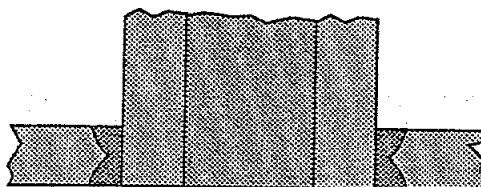


Groove welds in thin material
Longitudinal seam in a vessel

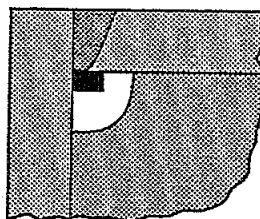


WELDS OFTEN HIGH RESTRAINT

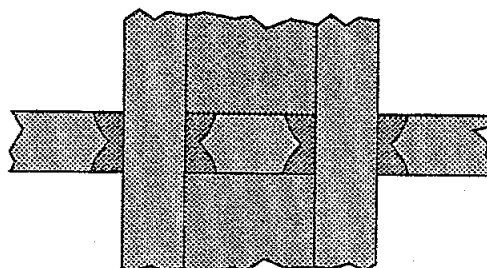
Set through nozzles in
thick plate



Corner joints restrained
by diaphragm



Tee joints on both sides
of a member



Repair welds

Figure 17. Some examples of low and high restraint welds.

Stress concentrations are more easily recognized and in some cases they can be avoided, but in others they cannot. A gap between parts being fillet welded will cause a stress concentration at the root and increase the risk of cracking. Another situation that may promote a crack is where a gap exists between sections of a backing bar. Welding over this gap may produce a transverse crack in the weld metal. In this case the sections of the backing bar should be welded together first so that no gap exists. A few examples of stress concentrations are shown in Fig. 18.

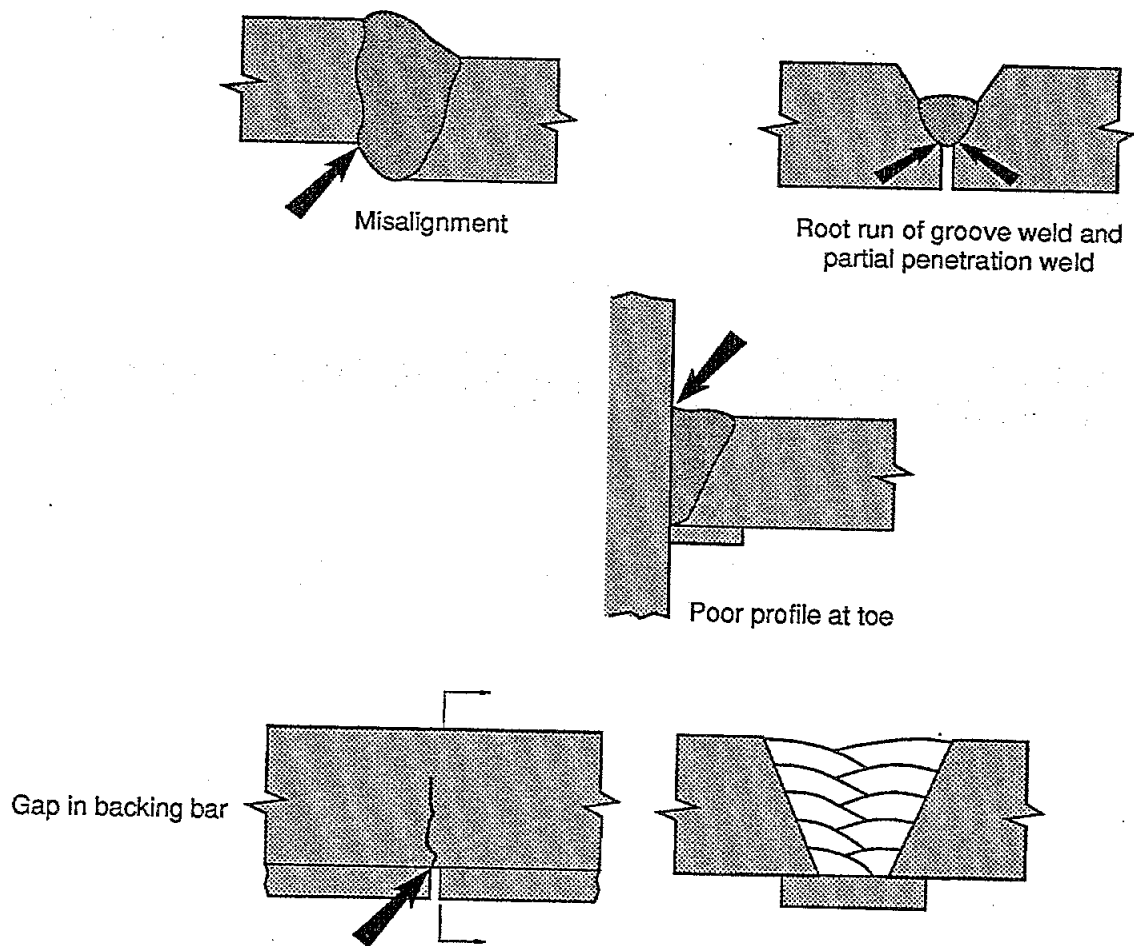


Figure 18. Some examples where stress concentrations increase the risk of cracking.

Avoiding cracking

Steels can be welded without cracking if procedures are used that control one or more of the primary factors responsible. The procedure must, therefore, control one or more of the following:

- The stress
- The microstructure (hardness of the HAZ)
- The hydrogen content
- Temperature

In most cases the stress cannot be controlled and the procedure must be aimed at controlling the HAZ microstructure (hardness) and the hydrogen content. Guidelines on controlling cracking are given in CSA W59-M1989 Appendix P and AWS D1.1 Appendix XI.

The type of microstructure, its hardness and susceptibility to cracking, that forms in the heat affected zone depends on:

- the hardenability of the steel (alloy content)
- the weld cooling rate

If the HAZ hardness of a carbon steel is measured as a function of the cooling rate, a curve such as that in Fig. 19 will be obtained. At fast cooling rates, a hard martensitic structure will form, whereas at slower cooling rates, a softer HAZ will be produced.

Increasing the carbon content of the steel raises the hardness of the martensite and also allows it to form at a slower cooling rates. The hard

Heat affected zone structure

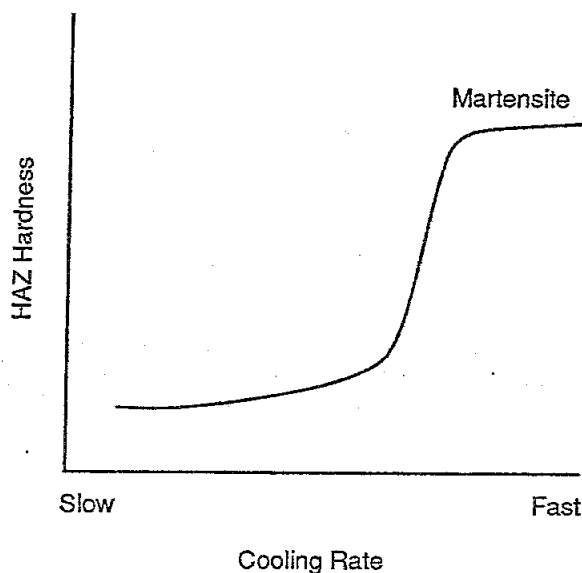


Figure 19. HAZ hardness plotted against cooling rate for a carbon steel.

Softer { pearlite
& ferrite

martensite is very susceptible to cracking but the softer structures are not. Such a steel could be welded without cracking by ensuring that the cooling rate was sufficiently slow to prevent martensite formation.

If the steel contains alloying elements, its hardenability would be higher and the HAZ hardness curve would change as shown in Fig. 20. The cooling rate at which martensite forms now decreases. A useful index of the hardenability of the steel is the carbon equivalent which indicates the net effect that alloy elements will have in shifting the curve in Fig. 19 to one like Fig. 20.

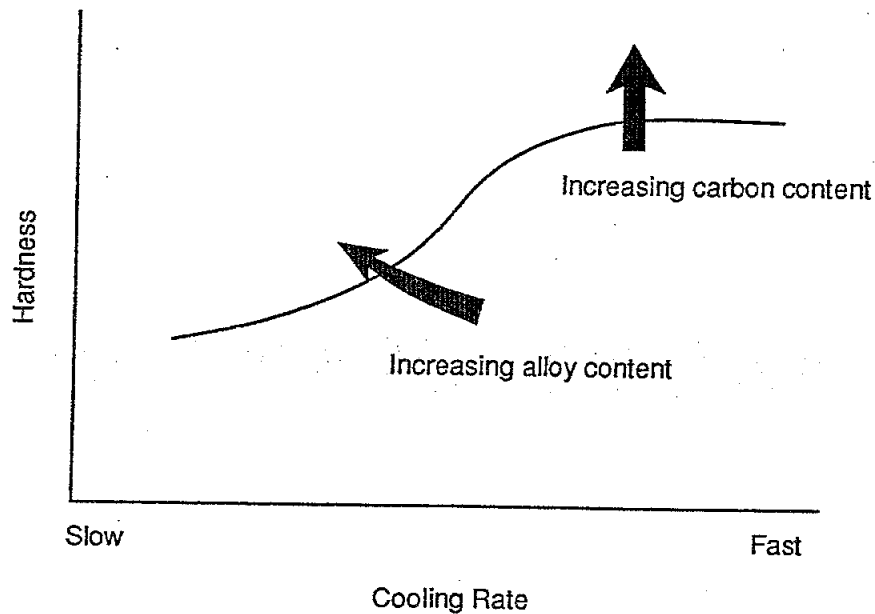


Figure 20. HAZ hardness curve for steels containing alloy elements.

The carbon equivalent is given by:

$$\text{C.E.} = \text{C} + \frac{\text{Mn} + \text{Si}}{6} + \frac{\text{Cr} + \text{Mo} + \text{V}}{5} + \frac{\text{Ni} + \text{Cu}}{15} \quad \%$$

where the symbols represent the weight percentage of the elements.

Because the carbon equivalent measures the hardenability, it gives a rough indication of the risk of cracking and has been widely used as a "weldability" index. More precisely, it may be employed to estimate the maximum cooling rate allowed in a weld without forming an excessively hard HAZ. Fig. 21 shows this relationship.

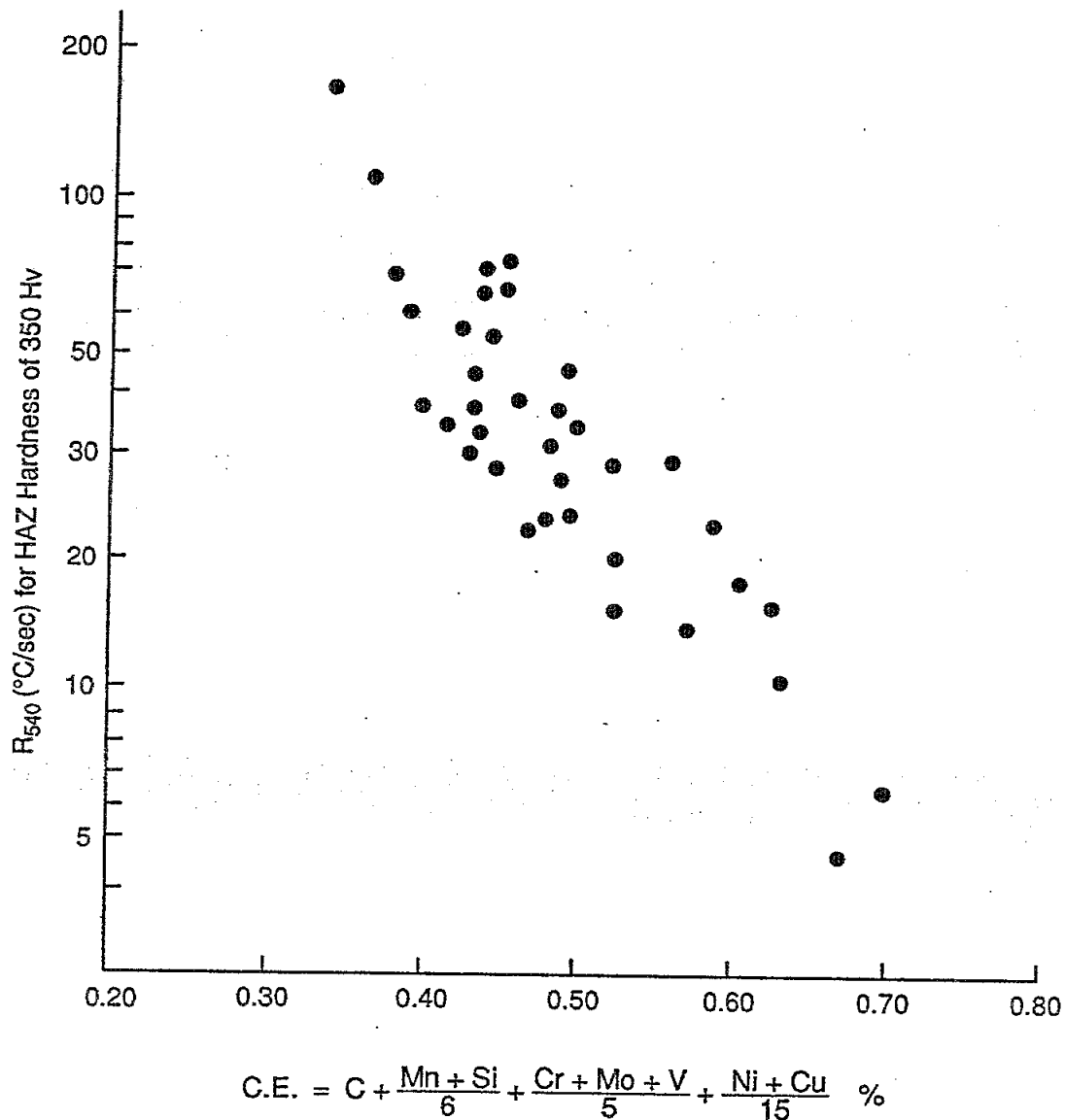


Figure 21. Critical cooling rate to keep the HAZ below a hardness of 350 Hv as a function of carbon equivalent.

If the alloy content is sufficiently high, the formation of martensite cannot be prevented even at slow cooling rates but the structure may be softened by high preheat levels. With alloyed steels, the risk of cracking in the HAZ will depend mainly on the carbon content of the steel. With a carbon content of 0.10% or less the martensite is not very hard and is not likely to crack under most situations. With higher carbon the martensite will be harder and there is a risk of cracking. To avoid cracking, hydrogen control must be used.

A useful diagram that indicates whether the HAZ hardness can be limited by controlling the cooling rate is shown in Fig. 22. The carbon content is plotted against the carbon equivalent and a given steel would fall into one of three zones:

Zone I Carbon and low alloy steels with a carbon content of about 0.10% or less. These include modern low carbon steels such as those developed for pipeline applications and modern high strength steels used increasingly in structural fabrication. A hard HAZ is not produced under most conditions and hydrogen cracking is not likely under most normal circumstances. The weld metal may be more likely to crack than the HAZ.

Zone II Most carbon and carbon manganese steels used for structural and pressure vessel applications, e.g., A516. A hard HAZ may be avoided by controlling the cooling rate, otherwise hydrogen control is necessary.

Zone III Alloyed steels with more than 0.10% carbon. This includes some quenched and tempered steels (e.g., A514). Hardness cannot be controlled by cooling rate and often quite a fast cooling rate is desirable to ensure adequate HAZ toughness. Hydrogen control must be used to prevent cracking.

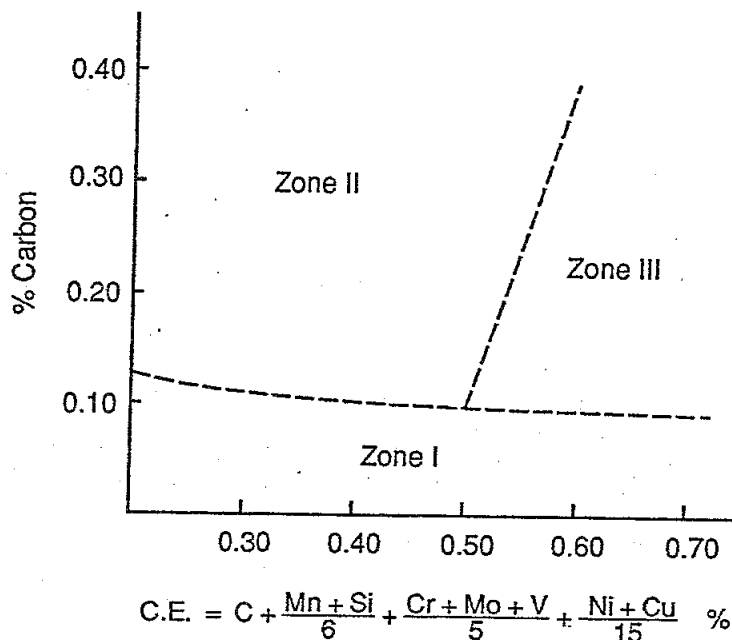


Figure 22. Grouping of steels on the basis of carbon content and carbon equivalent.

Hydrogen control

If a hard microstructure is formed in the HAZ, the only remaining factor that can be controlled to prevent cracking is the amount of hydrogen. Hydrogen can be reduced by a low hydrogen process with careful drying of consumables and by using preheat. A preheated plate will remain hot long enough after welding to allow time for hydrogen to diffuse out of the weld. When the plate finally cools, little hydrogen remains (Fig. 23). Even quite modest preheat levels are very effective in reducing the hydrogen content and, in welding structural steels, this is the main reason for preheating. The level of preheat required will depend primarily on the plate thickness and the carbon content of the steel.

Estimated from data from experiments with G-BOP cracking tests

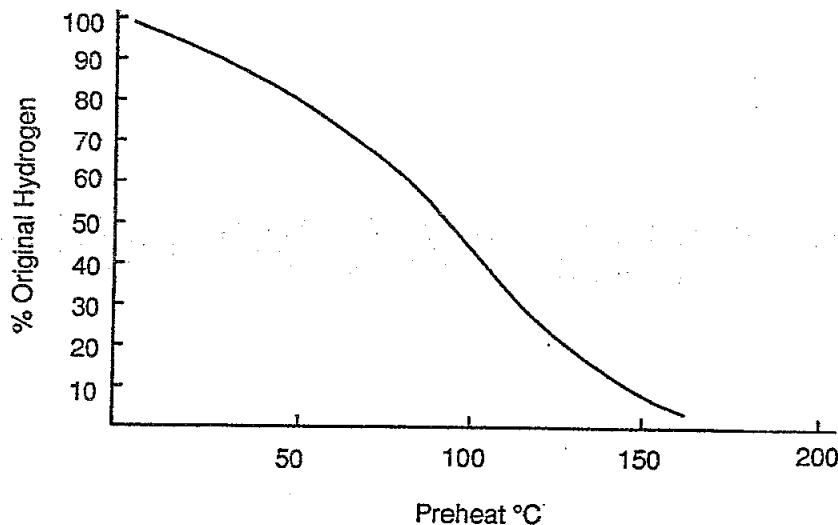


Figure 23. Effect of preheat on the fraction of original hydrogen remaining in a weld when allowed to cool.

With higher carbon alloy steels, preheat alone may be insufficient to diffuse out enough hydrogen and further post weld heating may be required. If the heat affected zone is excessively hard after welding, it may also be necessary to soften it by tempering at some suitable temperature.

It should be realized that the reason for preheating a plate is to allow time for hydrogen diffusion after the weld is made. The effect, therefore, depends as much on the way in which preheat is applied as it does on the actual temperature. Preheating a larger area around the joint will obviously have a greater effect than just applying a local preheat.

When making multiple pass welds, the heat from previous passes will help to maintain the temperature of the plates and this is termed the "interpass" temperature. The interpass temperature should normally be maintained at the same level as the specified preheat to avoid cracking. A common situation that can give rise to a risk of cracking is where a partially completed weld is allowed to cool, rather than maintaining the interpass temperature until the weld is finished.

A summary of factors affecting hydrogen cracking is given in Fig. 24

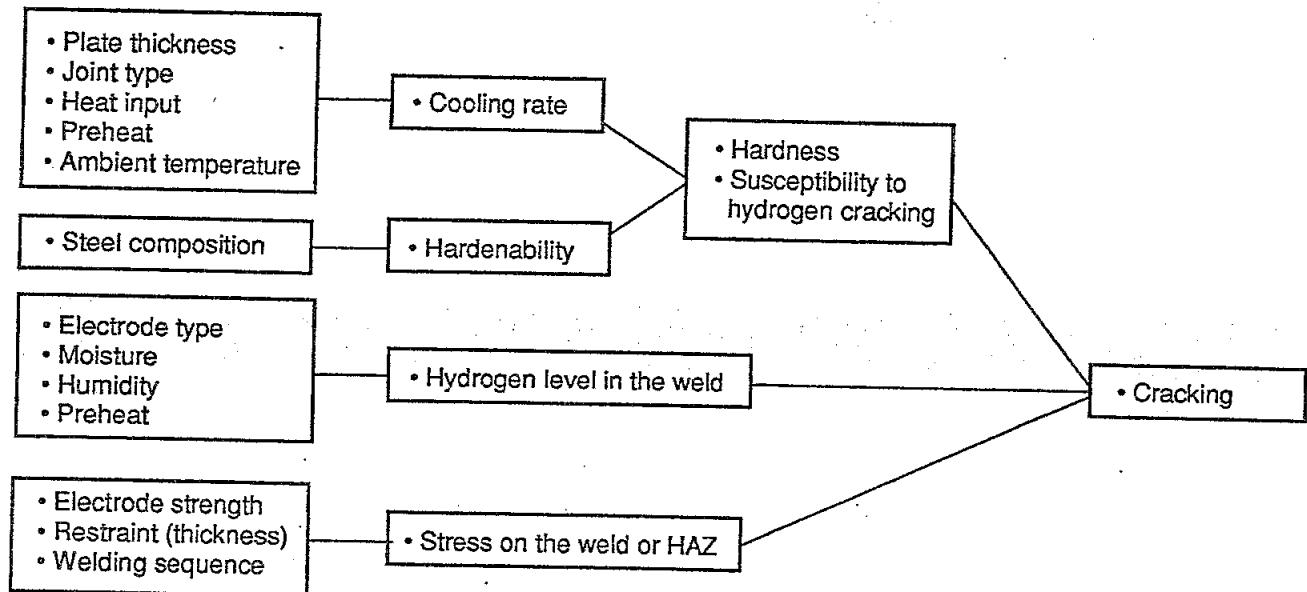


Figure 24. Summary of factors affecting hydrogen cracking.

Practical preheating requirements for structural steels

It is not the purpose of this module to present a detailed method for estimating preheat levels nor to give a list of recommended procedures for all steels. One example, however, will serve to illustrate the practical application of some of the principles discussed in the previous sections. The CSA W59 Standard contains a table listing requirements for preheat and interpass temperatures, and parts of this are summarized in Table 3. It should be noted that the preheat temperatures are higher for thicker plates and for processes that are not hydrogen controlled. These

Basic Welding Metallurgy of Structural Steels

Table 3. Minimum preheat requirements for selected steels extracted from CSA Standard W59-M89.

Thickness of Thickest Part (mm)	EXAMPLES OF SELECTED STEEL TYPES			
	Non-hydrogen Controlled Processes	Hydrogen Controlled Process (SMAW with basic electrodes, FCAW with CH Electrodes, GMAW, SAW)		
Up to 20 over 20 to 40 over 40 to 60 over 60	CSA G40.21-M 260 W & WT 300 W & WT	CSA G40.21-M 260 to 380 W & WT	CSA G40.21-M 400 and 480 W & WT	CSA G40.21-M 700 Q & 700 QT
	ASTM A36 A516	ASTM A36 A572 Gr 42, 50 A633 Gr A, B, C, D A441	ASTM A572 Gr 60, 65 A633, Gr E	ASTM A514
	none 65°C 107°C 150°C	none 10°C 65°C 107°C	10°C 60°C 110°C 150°C	10°C 50°C 80°C 110°C

Note: The Standard should be consulted for complete details.

temperatures cannot be considered exact since many factors such as restraint and actual chemical composition are not included. In an attempt to address these factors CSA W59 and AWS D1.1 provide alternate guidelines but, again, they cannot be considered exact for all cases. In severe situations the temperatures determined may not be adequate to prevent cracking and in other cases they may be overly conservative. Testing may be necessary to validate a selection of preheat.

The energy input is not included in the table, but CSA W59 has a separate requirement allowing submerged arc welding to be used without preheat if adequate energy input is ensured. This is applicable when making fillet welds in one pass and is based on providing enough heat input to limit the cooling rate, thus avoiding excessively hard heat affected zones. This leads to a simple requirement for a minimum size fillet weld depending on the carbon equivalent and thickness of the steel (Table 4).

Table 4. Minimum single pass fillet weld sizes to eliminate preheat (SAW only).

Plate Thickness (t)	Carbon Equivalents					
	0.35	0.40	0.45	0.50	0.55	0.60
t ≤ 12 welded to t ≥ 40*	8	8	8	10	10	12
t > 12 welded to t > 40	8	8	10	10	12	16

*This thickness is 20 mm for some steels. Consult CSA Standard W59-M1989 for details.

$$\text{C.E.} = \text{C} + \left(\frac{\text{Mn} + \text{Si}}{6} \right) + \left(\frac{\text{Cr} + \text{Mo} + \text{V}}{5} \right) + \left(\frac{\text{Ni} + \text{Cu}}{15} \right) \%$$

Cracking tests

Many different types of tests have been devised to reveal hydrogen cracking and three are described here. The first is the *Controlled Thermal Severity (CTS) Test* (Fig. 25) and uses a fillet weld. Two blocks are bolted together with one block machined to provide a small gap at the root. Two test welds can be made on a single specimen and the "thermal severity" or cooling rate can be changed by using plates of

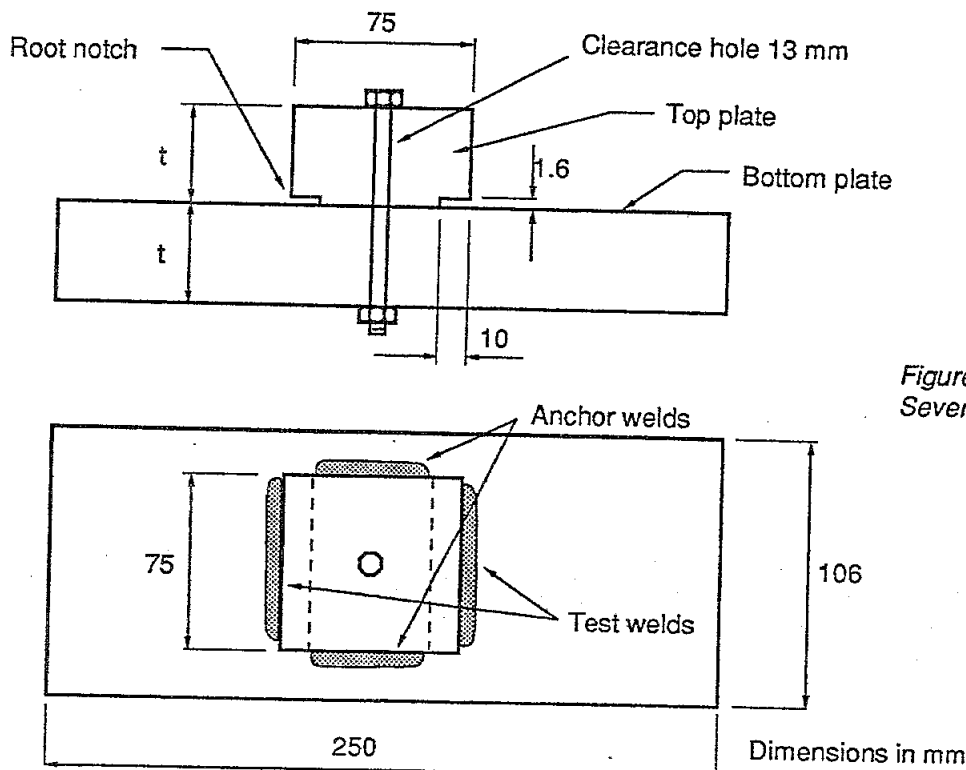
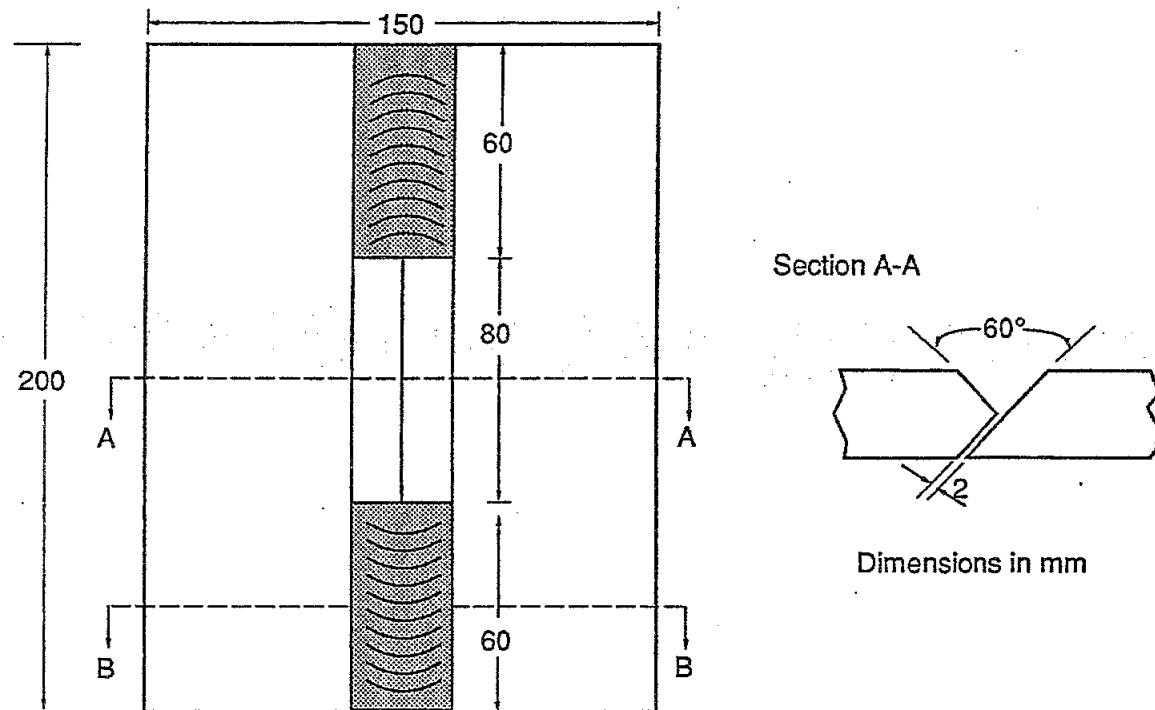


Figure 25. Controlled Thermal Severity (CTS) Test.

different thickness. As with all hydrogen cracking tests, a certain time is allowed to elapse before examination for cracks, in this case usually three days. The welds are sectioned, polished, and examined for cracks under the microscope.

A test useful for studying crack susceptibility in a groove weld is the *Tekken Test* shown in Fig. 26 which was developed in Japan. The use of a sloping Y groove preparation promotes HAZ cracks, while the straight Y encourages the weld metal to crack. It is a high restraint test with the restraint increasing with the thickness.



Groove Preparation in the Slit Test Used as Weld Metal Cracking Test

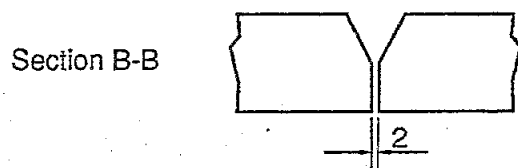


Figure 26. The Tekken Test.

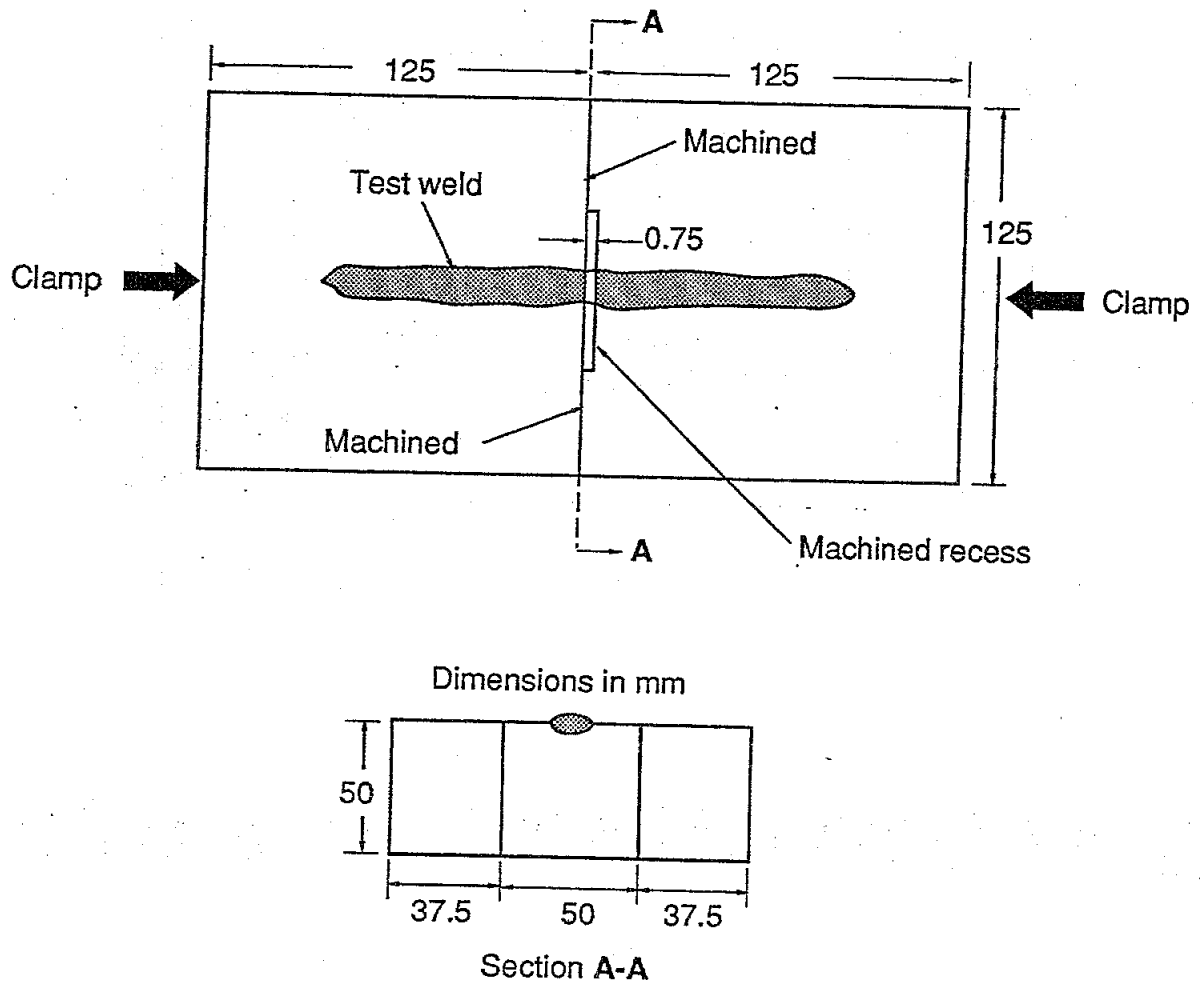


Figure 27. The Gapped Bead-On-Plate (G-BOP) Test.

In Fig. 27 the *Gapped Bead-On-Plate (G-BOP) Test* is illustrated. This is a simple test for weld metal hydrogen cracking and comprises two blocks which are clamped together. The mating faces are machined to bear upon one another and one block has a recess machined in it. A weld bead is deposited across the gap and the blocks are left in the clamps for 48 hours after welding. To examine for cracking, the welds are heated with a torch to a dull red heat in the vicinity of the gap, allowed to cool, then broken open. Discolouration of the fracture surfaces indicates that a crack was present before heating (Fig. 28).

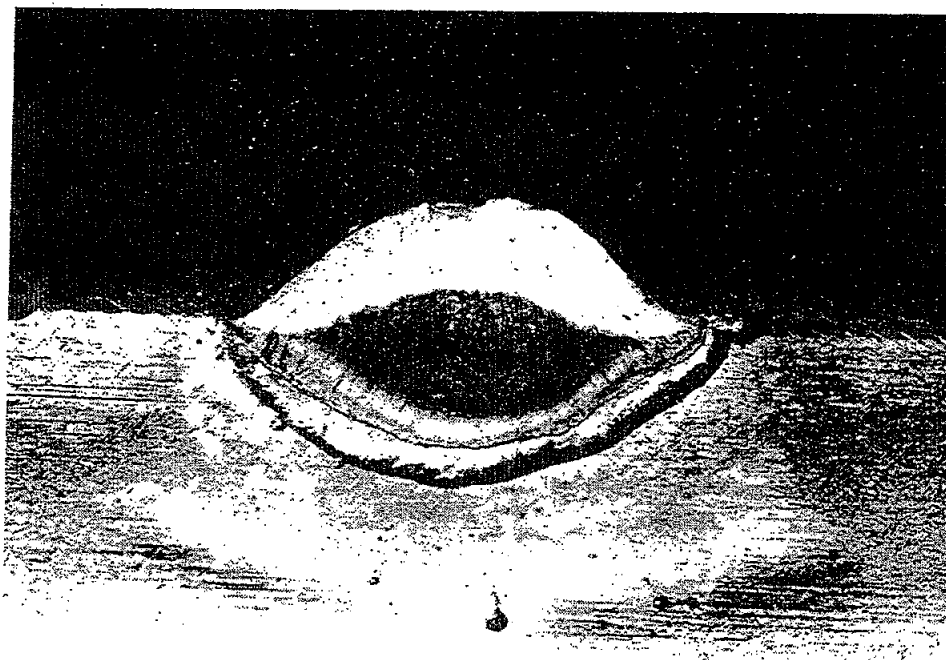


Figure 28. Typical fracture appearance in the G-BOP Test showing the presence of a crack.

Tests of the types described are useful for comparing the relative crack susceptibilities of materials, but generally do *not* establish whether a certain welding procedure would be successful in practice. Since the cooling rates, preheating and restraint are likely to be quite different in practice, results from a cracking test should not be used directly in practice. The G-BOP Test, for example, is far more severe than most practical situations.

LAMELLAR TEARING

The presence of non-metallic inclusions that become flattened out during the rolling of a steel plate results in the ductility through the thickness (Z-Direction) being lower than in the other directions. If welds are made that impose very high strains through the thickness, there is a possibility that cracks can open up in the plate beneath the weld. These cracks are termed "lamellar tears" and the typical location is shown in Fig. 29. *Lamellar tearing* is most likely to occur in large welds where the strains are normal to the plate surface, the most susceptible joints being T-Butt and corner joints. The main factors influencing the problem are:

- The type of joint (i.e., design)
- The through-thickness ductility of the steel
- The restraint of the joint
- Other welding procedural factors such as the hydrogen content

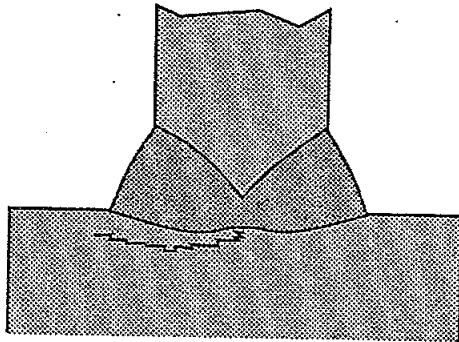


Figure 29. Typical location of a lamellar tear.

The potential for lamellar tearing should be recognized at the design stage and susceptible joints avoided. In critical applications where a high restraint, potentially susceptible joint cannot be avoided, consideration should be given to the use of a premium steel with enhanced through-thickness properties. In some cases a simple change in the plate preparation will reduce the risk of lamellar tearing. For example, Fig. 30 shows how a corner joint may be modified to accomplish this.

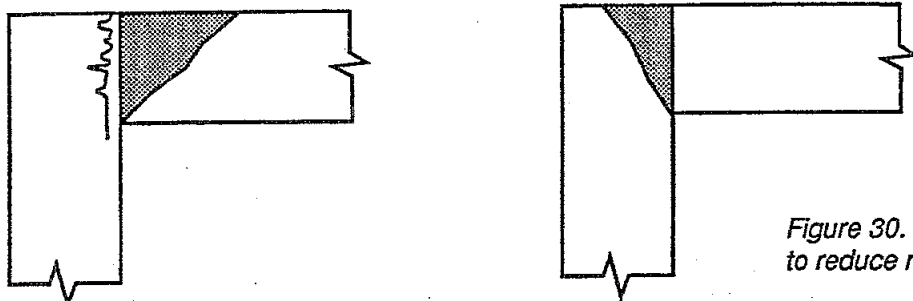


Figure 30. Redesign of corner joints to reduce risk of lamellar tearing.

There are a number of precautions that can be taken during welding that may help to minimize the risk of lamellar tearing. First, all hydrogen control measures, such as well dried electrodes and adequate preheat, should be taken. Partially completed welds should not be allowed to cool down and, in welds made from two sides, a balanced technique should be used to minimize rotation strains (Fig. 31).

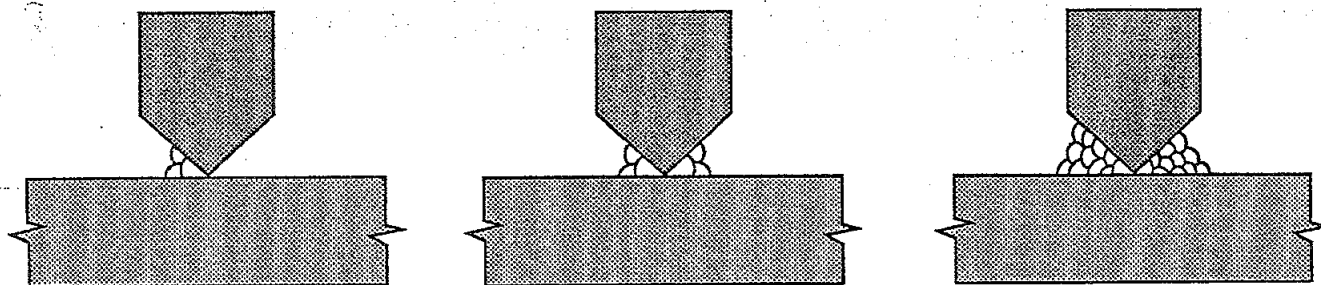


Figure 31. A balanced welding technique minimizes rotation strains.

When welding long joints, a block weld sequence in which short sections are completely welded, appears to be beneficial. Full penetration welds should be used to avoid the stress concentration effect at the root which could initiate cracking.

If the techniques are insufficient, then the plate can be *buttered*, that is, a layer of weld metal deposited on the plate before being welded (Fig. 32). Sometimes buttering can be done "in situ" as part of the welding procedure. The buttering technique removes susceptible steel and may be beneficial for other reasons.

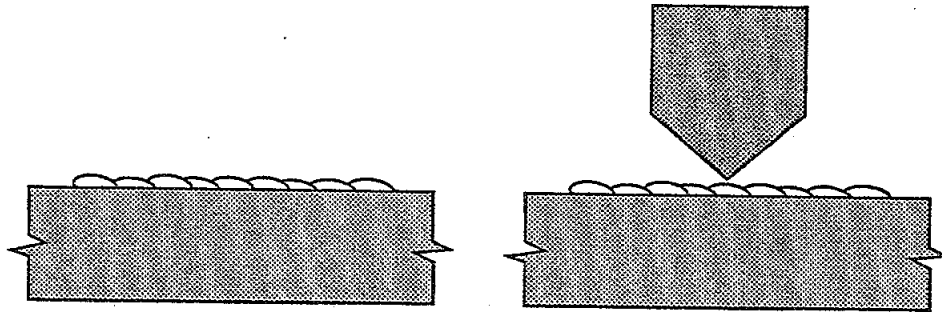


Figure 32. Use of buttering to minimize risk of lamellar tearing.

In cases where a steel with enhanced through-thickness properties is justified to avoid lamellar tearing, steel making techniques are now available which result in excellent properties. Research has shown that in most cases a through-thickness ductility of 20% reduction of area is adequate for most situations and a steel with 30% will not show the problem even under very severe restraint.

WELD METAL

The solidified weld metal will have a microstructure quite different from that of the parent material since it has not gone through the heating and rolling sequence that a plate does. It is, in fact, like a small, rapidly cooled casting and its properties will depend on the microstructure, composition, and cooling rate. The weld metal composition does not usually match that of the parent material even though the strength may be the same. An example is given in Table 5 where a weld metal having equal strength to a carbon steel plate has much lower carbon content.

Table 5. Composition of parent metal and weld metal having similar strengths.

	% Carbon	% Manganese	% Silicon
Typical Hot Rolled Carbon Steel (e.g., A515)	0.24	0.9	0.23
Weld Metal Giving Equal Strength (e.g., E48018)	0.08	1.1	0.35

Weld metal is a mixture of melted parent metal and melted electrode, and its composition will depend on three things:

- The composition of the electrode
- The composition of the parent metal
- Chemical reactions between the weld metal, flux or shielding gas

The proportion of parent metal melted into the weld is known as the "dilution" and is defined as follows:

$$\text{Dilution} = \frac{\text{Weight of Parent Metal Melted}}{\text{Weight of Total Melted Metal}}$$

Dilution

The dilution will vary according to the process and some examples are shown in Fig. 33. If a chemical element *does not* become involved in chemical reactions, then the amount in the weld metal can be determined from the parent metal composition, the electrode composition, and the dilution.

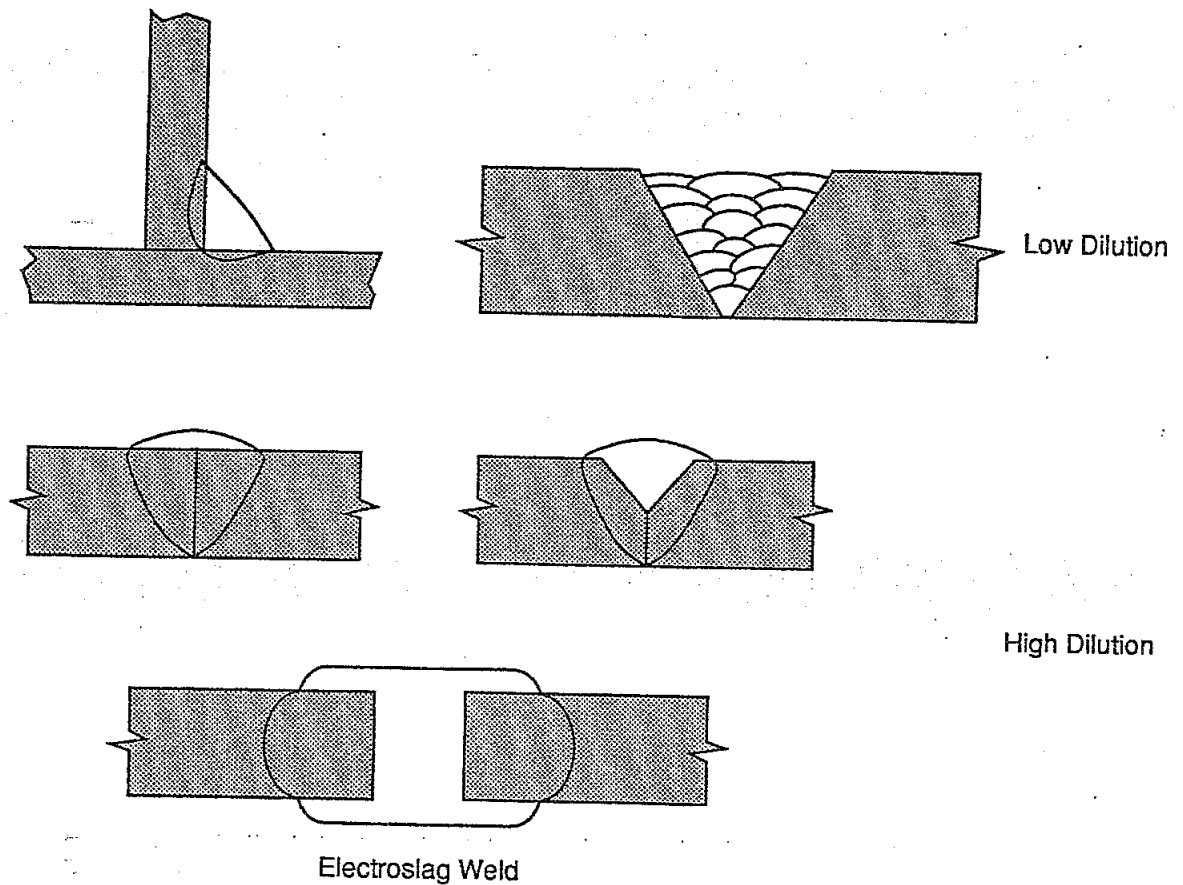


Figure 33. Some examples of dilution factor in welds.

The diagram shown in Fig. 34 is useful for estimating weld metal compositions for such elements. For example, suppose an electrode containing 8% nickel is used to make a one pass weld of 60% dilution on a plate containing 3% nickel. A line is drawn from the 8% to the 3% on the top and bottom scales respectively. The weld metal content can now be read off for a dilution of 60%, giving just over 5%. The diagram is useful for elements such as molybdenum, nickel, copper and chromium, but cannot be used for chemically active elements such as carbon, manganese or silicon.

Basic Welding Metallurgy of Structural Steels

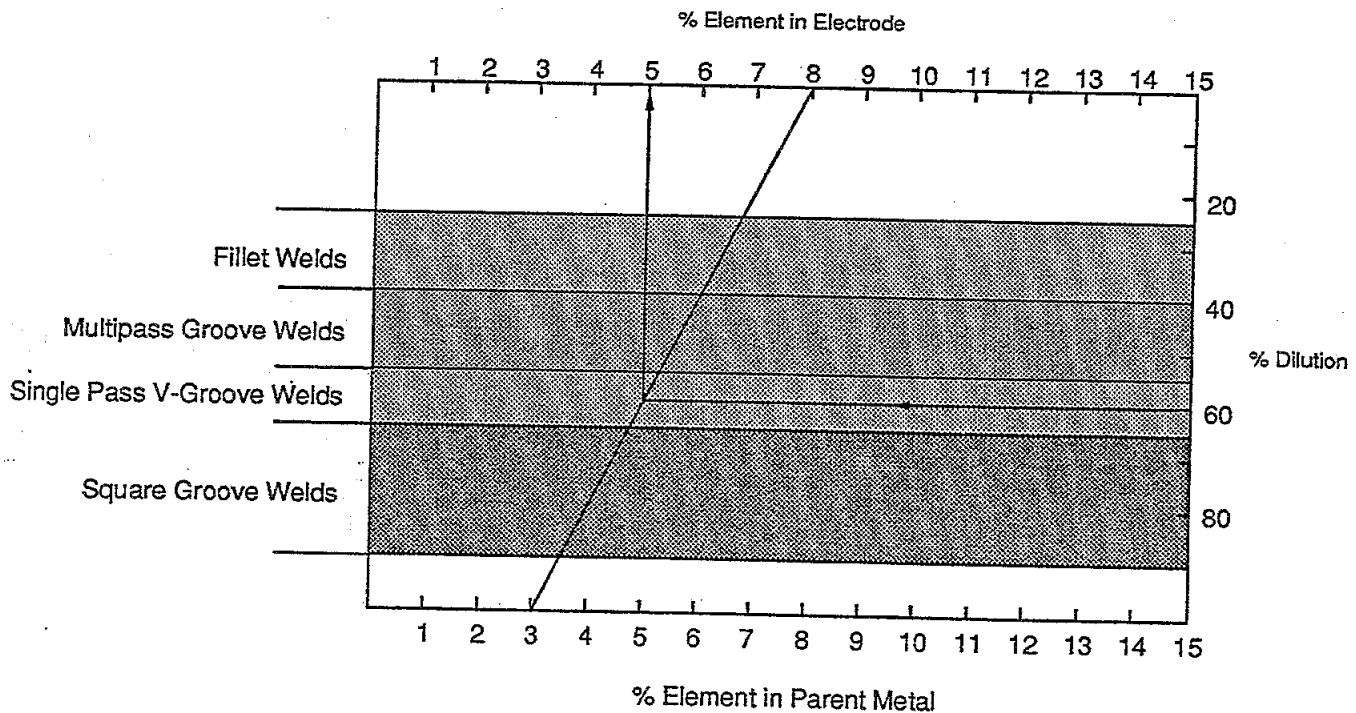


Figure 34. Diagram for estimating weld metal composition for elements that do not undergo chemical reactions.

Chemical reactions

A detailed discussion of the many chemical reactions that can occur is beyond the scope of this module, but those involving the element oxygen will be mentioned. Although the slag or gas is intended to shield the weld metal from the atmosphere, some oxygen may still enter the molten pool. Inert gases, such as argon, provide very effective shielding and the weld metal oxygen content is likely to be low. Carbon dioxide gas, however, can break down in the arc and introduce quite high levels of oxygen.

Submerged arc fluxes contain oxides and these can break down and transfer oxygen to the weld metal. *Silica* (SiO_2) in particular is readily reduced and fluxes containing a large proportion of it will transfer silicon and oxygen to the weld. Fluxes with a low potential for transferring oxygen are often called basic "fluxes" (Fig. 35). Although silica in a flux may transfer oxygen its presence has many desirable features. The selection of a flux in practice will, therefore, depend on many factors.

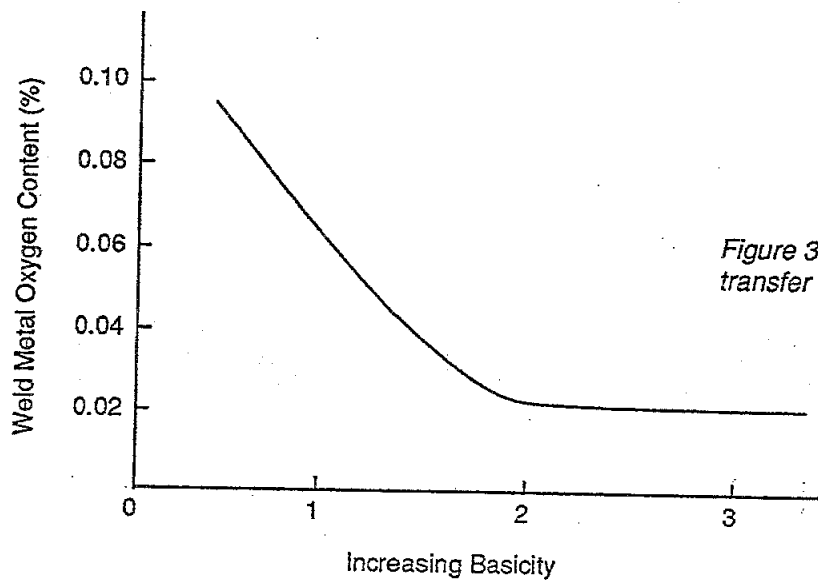


Figure 35. Fluxes that are more basic, transfer less oxygen to the weld.

The presence of a high oxygen content in the weld could lead to porosity when the metal solidifies, in the same way that gas pockets are formed in a rimmed steel ingot. To avoid this, deoxidizing elements (such as silicon, manganese, aluminum) may be added. They react with the oxygen to form non-metallic inclusions. In carbon dioxide welding, the deoxidizing elements are contained in the wire (hence the wire is "hard"). Extra deoxidizing elements may be added to the wire if it is to be used on rusty plate or other situations with high oxygen present (see Table 6). In some fluxes deoxidizing elements are added to the flux.

Table 6. Typical compositions of wires for carbon dioxide welding.

Wire Type	% Carbon	Manganese	Silicon	Titanium	Zirconium	Titanium
CSA W48.4 E480S-3 Moderate deoxidation. Used primarily for single pass welds.	0.10	1.15	0.60			
CSA W48.4 E480S-2 Triple deoxidized wire. For use on rimmed and semi- killed steels and rusty conditions.	0.05	1.15	0.5	0.07	0.10	0.05

The presence of non-metallic oxide inclusions may influence the toughness of the weld metal and the Charpy V-notch impact energy is likely to be lower if large quantities of oxides are present. Where high toughness is required in submerged arc welds, fluxes that provide low oxygen are often specified. Fig. 36 shows how oxygen content may affect the weld metal toughness.

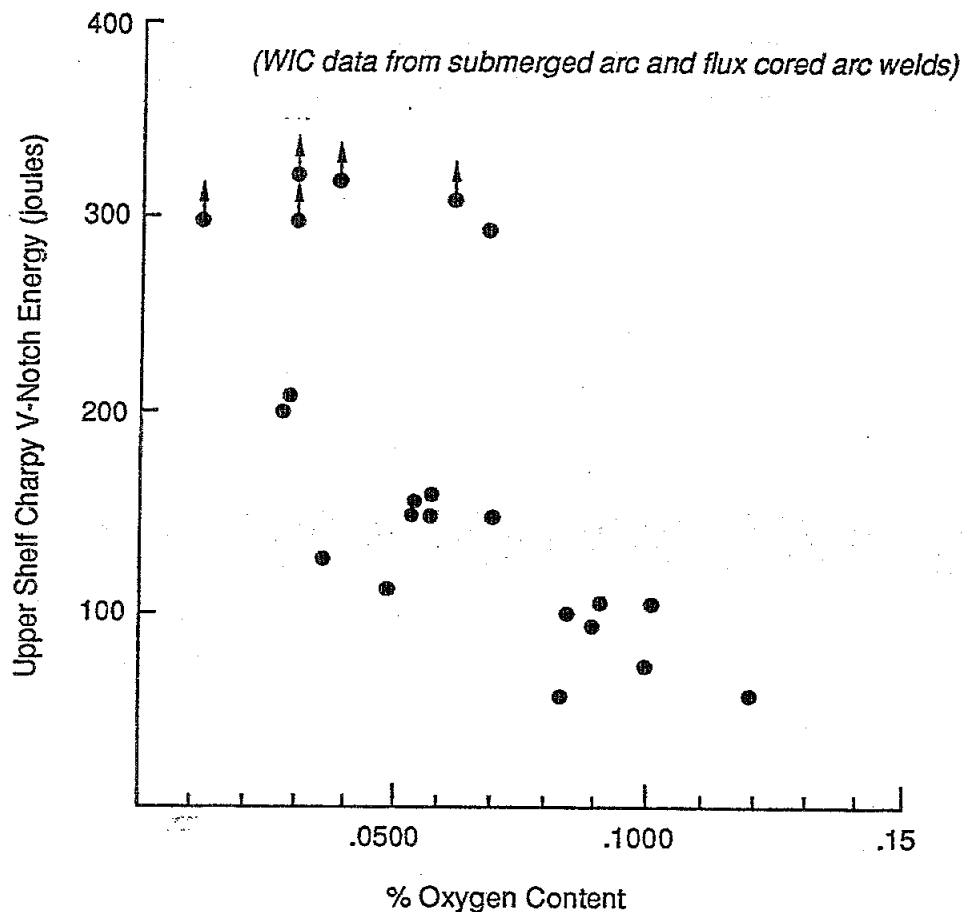
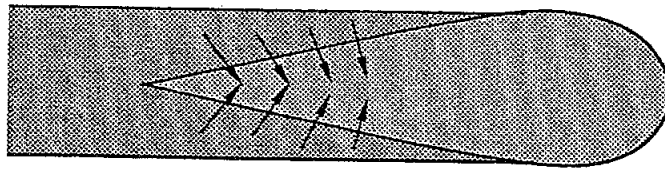


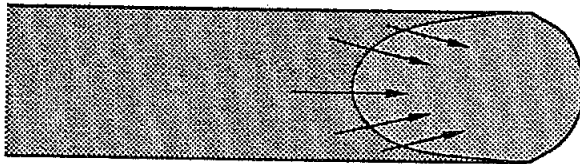
Figure 36. Results of experiments that show how the weld metal toughness may be influenced by the oxygen content.

Solidification

It was mentioned that the weld metal solidifies like a small casting. Crystals begin to form at the solid/liquid interface and grow in towards the centre of the pool. The shape and structure of the growing crystals will depend on the welding conditions. If the welding speed is high, an elongated weld pool will result and the crystals will grow from the sides of the pool towards each other as shown in Fig. 37(a). If the welding speed is slow, then growth of the solidifying crystals will tend to originate from the back of the weld pool—Fig. 37(b).



- a) High welding speed produces a long weld pool.
Solidifying crystals grow from the sides toward each other.



- b) Slow welding speed produces a short weld pool.
Crystals grow forward from the back of the pool.

Figure 37. Effect of welding speed on the solidification structure of the weld metal.

Solidification cracking

Sometimes when the solid crystals grow towards each other, liquid becomes trapped between them. As the cooling weld shrinks, a crack can form where the liquid was trapped. These cracks usually run along the centre of the weld, sometimes the entire length of the weld and are called solidification cracks. Fig. 38 shows the cross-section of a weld containing a solidification crack. The prime causes are the shape of the weld pool and the presence of elements that may cause liquids to remain at temperatures below the solidification temperature. In the example of a high speed weld shown in Fig. 37(a), the advancing crystals may sweep impurities ahead of them which cause liquid to be trapped between the crystals. This is not likely to happen in the slow weld — Fig. 37(b). Excessive welding speed may, therefore, be a cause of solidification cracking along the centreline.

The cross-section shape of the weld is also important. A high welding current or narrow groove angle may produce a deep narrow weld susceptible to cracking (Fig. 38). A rule-of-thumb used for many years is that, for the root run of a submerged arc weld, the current should not exceed ten times the groove angle, e.g., for a 60° groove the current should not exceed 600 amps.

Basic Welding Metallurgy of Structural Steels

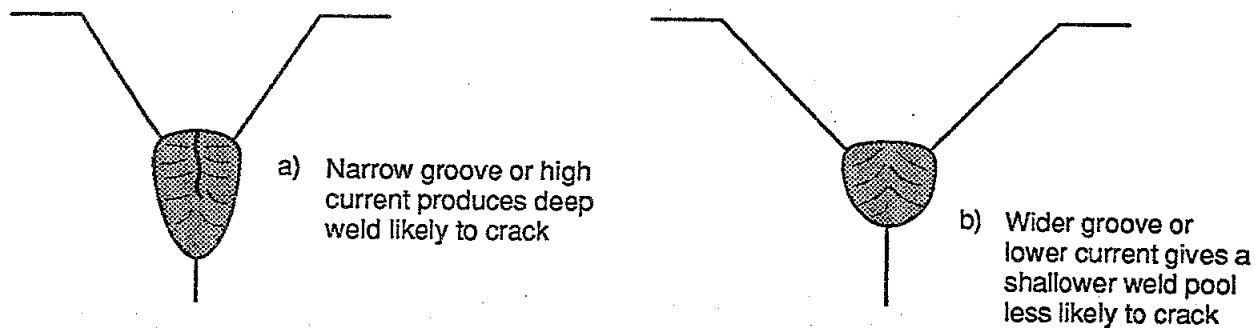


Figure 38. Effect of weld shape on solidification cracking.

Effects of impurities

Certain impurities may lower the freezing temperature of the liquid and this can lead to cracking in the weld metal. The addition of *sulphur*, for example, to iron lowers its melting temperature to as low as 988°C , as seen in Fig. 39. The effect can be offset by the addition of manganese, but sulphur contamination in weld metal is likely to lead to cracking. The risk of cracking from sulphur is even greater if the weld metal contains more than about 3% of nickel.

Another element that can cause cracking is *copper*. Although not usually present in significant quantities in the electrode, it may be introduced accidentally. The copper contact tip of the welding head might accidentally arc to the workpiece and melt some copper into the weld. Proper care and attention to correct procedures and practice is necessary to avoid this kind of contamination.

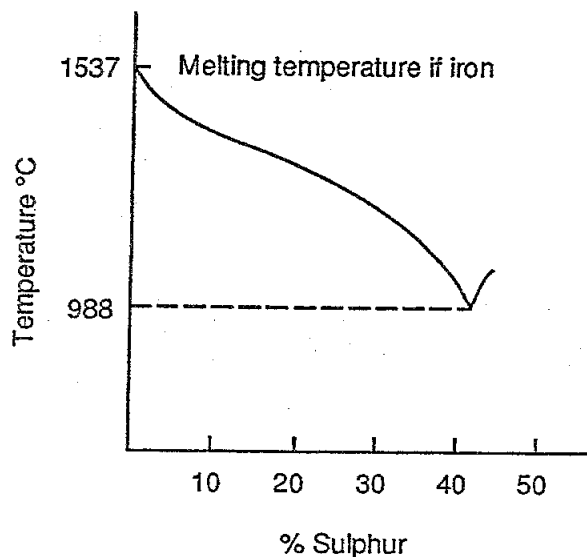


Figure 39. Increasing sulphur content lowers the melting temperature of iron.

Weld metal microstructure

The weld metal microstructure in a structural steel will be quite different from that of the parent plate for several reasons:

- The weld metal is not hot worked like a plate and will have a solidification structure.
- The austenite grains of the hot weld metal are usually large and elongated.
- The weld metal composition is different and it may contain many small oxide inclusions.
- The weld metal cooling rate is usually much more rapid than that of a plate after rolling.

Many types of microstructures may be observed but a typical one is shown in Fig. 40. When the *austenite* transformed, *ferrite* was initially formed at the grain boundaries and the existence of these ferrite "veins" is typical. A large number of small, interlocking grains of ferrite have also formed within the austenite grain and it is likely that the small oxide inclusions played a part in their formation.

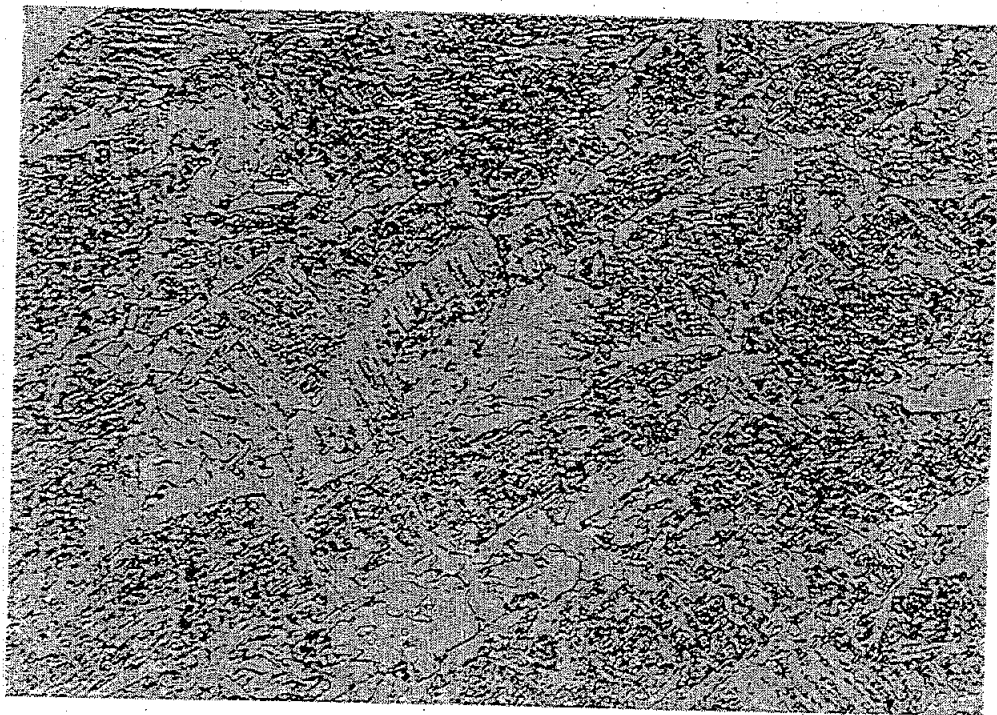


Figure 40. Typical as-welded microstructure of mild steel weld metal.

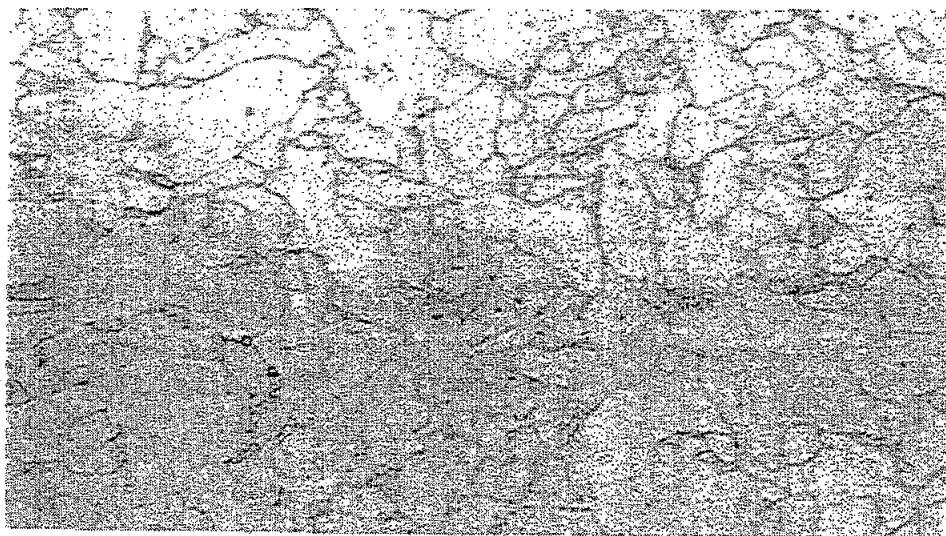


Figure 41. Refined microstructure of reheated weld metal.

If the microstructure in Fig. 40 is reheated to above 910°C , it will be fully transformed back to small austenite grains, which, on cooling, produce a fine ferrite structure. Reheated weld metal is shown in Fig. 41. This effect occurs in a multipass weld where the heat from one pass refines the grains of the previous passes. Since the refined microstructure usually has better toughness than the as-welded structure, a multipass weld will normally be tougher than a single pass weld. Fig. 42 illustrates the effect of multipass welding on the refinement of the microstructure.

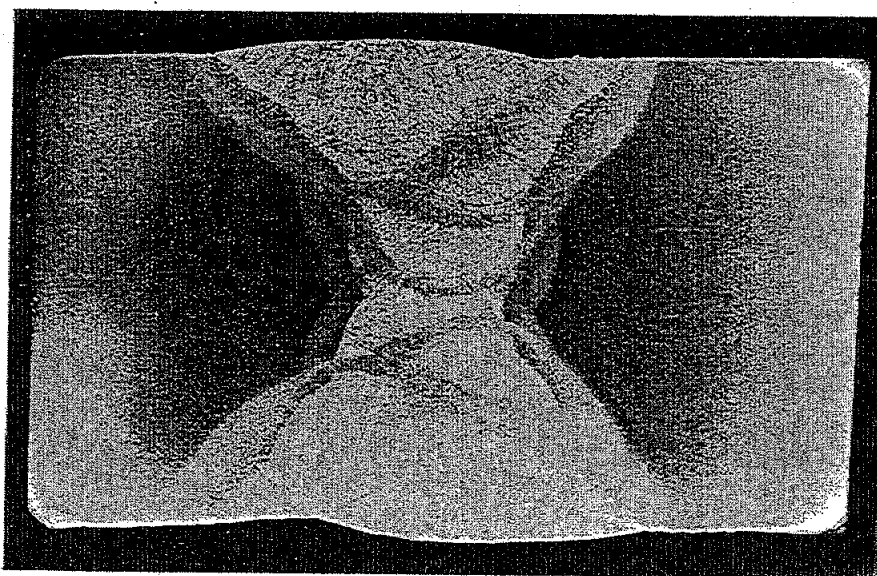


Figure 42. Refinement of microstructure due to multipass welding.

Stress relief

Heating a welded fabrication to about 625°C to reduce residual stresses, is commonly required in specifications, particularly when thick sections are welded. The stress relief temperature is *below* the transformation temperature so there will be no major changes in the microstructure, but hard areas will be softened by tempering. There will, however, be changes in the properties of the weld metal. The tensile strength is likely to be reduced by a substantial amount depending on the length of time of the stress relief treatment. A typical result is shown in Fig. 43, but the exact drop in strength will vary with the type of weld metal.

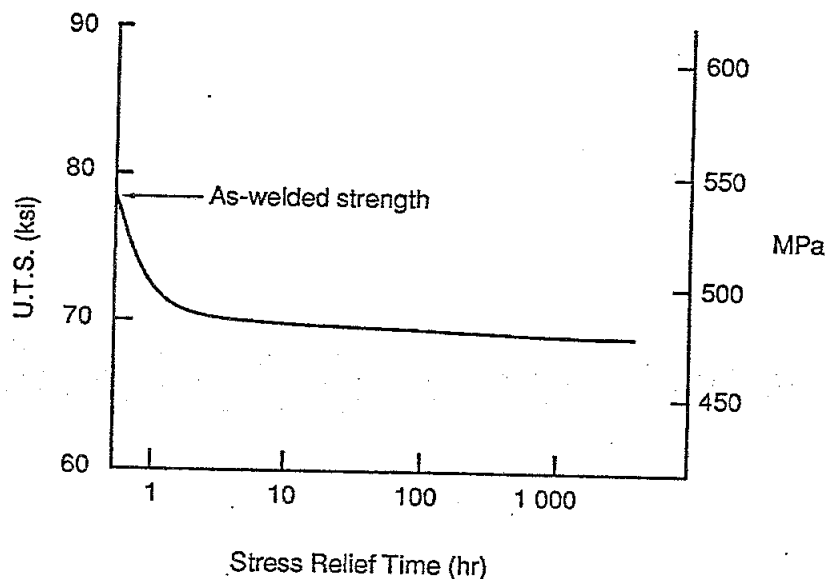


Figure 43. Typical drop in tensile strength of weld metal due to stress relief.

Weld metal and heat affected zone toughness

Careful selection of electrodes is, therefore, important if the fabrication is to be stress relieved. Often, it is necessary to take into account the possibility of several stress relief treatments during fabrication. In these cases alloyed weld metals are usually required and molybdenum bearing electrodes are often specified for stress relieved applications.

A coarse grain structure in the HAZ or weld metal can lead to a decrease in the fracture toughness. For applications where it is necessary to maintain good fracture toughness, procedures that ensure a fine grain structure must be used. This may involve placing a limit on the energy input of the process so that the austenite grain growth in the HAZ is restricted and the weld cools sufficiently quickly. A heat input restriction may preclude the use of certain welding processes, such as electrogas, that inherently have a high heat input.

Heat input restrictions will depend on the type of steel and the level of toughness required, but are usually imposed when welding quenched and tempered steels (e.g., A514). Where low heat inputs are deliberately used to provide good toughness, special attention must be paid to hydrogen control to avoid hydrogen cracking. In many of the new tough steels, the carbon content is very low (Zone I Steels, Fig. 22) and there is little risk of cracking even with fast cooling rates. In some steels with moderate carbon (Zone III Steels) preheat is necessary to prevent cracking but the preheat and interpass must not be allowed to exceed a maximum value, otherwise the fracture toughness will suffer.

Additional Resources

Linnert, G.E., *Welding Metallurgy of Carbon and Alloy Steels*, Volumes 1 and 2 (1965 and 1967), published by the American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126, U.S.A.

Stout, R.D., *Weldability of Steels*, 1987. The American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126, U.S.A.

Lancaster, J.F., *Metallurgy of Welding*, 1980, published by George Allen and Unwin, London.

AWS D1.1. Structural Welding Code. American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126, U.S.A.

Welding Handbook, Seventh Edition, Volume 4. American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126, U.S.A.

GUIDES AND EXERCISES

MODULE 9

BASIC WELDING METALLURGY OF STRUCTURAL STEELS

BASIC WELDING METALLURGY OF STRUCTURAL STEELS

MODULE 9

Guides & Exercises

To obtain maximum benefit from this module we suggest that you follow this guide and complete the exercises as indicated. It is important that you work through the text methodically, studying each section thoroughly before moving on. The exercises are designed to give you an indication of whether you have learned the material and can move on or whether you need to go back and study the section again.

Do the exercises honestly. They will not help you unless you take them seriously. If you get a question wrong go back through the text until you understand where you have gone wrong and know the correct answer.

The length of time required to complete the module will vary from student to student. Find your own pace. Do not rush. Remember you are trying to learn something, not win a race.

Some people like to underline sections when they read a text. We suggest that you use caution if you do this. What you think is important first time you read it may be different after reading it three times. We suggest you read a section three times thoroughly before highlighting anything.

The last exercise is designed to give you an indication of whether you are ready to take the closed-book exams. The exercise questions are of a similar standard to the official exams. Do not take the exam until you feel you are ready and you may wish to study several Modules before taking the exams on each. The details of the examination procedures are on a separate sheet.

If you have any difficulties with this Module do not hesitate to ask for help. You may find you learn more by attending seminars which are given periodically, and you should also contact your local WIC Chapter to see if they can be of assistance. Remember, if you fail the examination you can always try again later.

After working through each guide, check your answers (on page 52) for accuracy. If any of your answers are wrong, restudy the guide subject matter in the text until you understand it before moving on to the next guide.

Guide 1

Read carefully pages 1 to 9 and answer the following questions:

1. During arc welding there is a zone adjacent to the weld metal that reaches high temperatures but does not melt. What is the name of this region?
2. In electric arc welding what is the proportion of total energy that is converted into heat that eventually enters the plate known as?
3. With manual welding the technique will influence the energy input. Of the following techniques, which involves the *higher* energy input?
 - a) Weaving techniques
 - b) Depositing stringer beads
4. Considering that increasing the heat input will reduce the cooling rate, is the following statement true or false?

"For thick plates, the cooling rate is inversely proportional to the heat input."

Guide 2

Read carefully pages 10 to 19 and answer the following questions:

1. In the metal adjacent to the weld pool certain metallurgical changes will occur. What is the condition which will determine what metallurgical changes will occur?
2. Complete the following statement—
"Regions that are close to the fusion boundary can experience temperatures sufficiently high enough that growth of the.....occurs."
3. True or false?
"One feature of hydrogen cracking is that it *only* occurs when the weld and heat affected zone are at very high temperatures."
4. Which of the illustrations shows poor ductility?

a)



b)



5. True or false?

"Hydrogen will not cause cracking in a weld unless there is stress present."

Guide 3

Read carefully pages 20 to 30 and answer the following questions:

1. Complete the following statement—

"In the heat affected zone of a carbon steel weld fast cooling rates will form a hard....."

2. Which of the following types of steel is the *least* susceptible to hydrogen cracking in normal circumstances:
- a) Most carbon and carbon steels used for structural, and carbon manganese steels used for structural and pressure vessel applications
 - b) Carbon and low alloy steels with a carbon content of about 0.10% or less
 - c) Alloyed steels with more than 0.10% carbon

3. True or false?

"The reason for preheating a plate is to allow time for hydrogen diffusion after the weld is made."

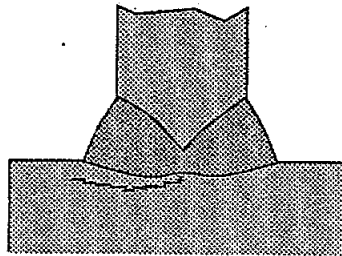
4. Three types of tests are described in this module. What is the full description of CTS.?

Basic Welding Metallurgy of Structural Steels

Guide 4

Read carefully pages 31 to 38 and answer the following questions:

1. What condition does the illustration depict?



2. True or false?

"Solidified weld metal will have a microstructure the same as that of the parent material (plate)."

3. Complete the following statement—

"The proportion of parent metal melted into the weld is known as the....."

4. In submerged arc welding, what are fluxes with a low potential for transferring often called?

Guide 5

Read carefully pages 38 to 44 and answer the following questions:

1. What effect does the presence of large quantities of oxides have on the Charpy V-notch impact energy?
2. What type of weld pool does high welding speed produce?
3. Centreline solidification cracking is most likely caused by:
 - a) Welding speed too high
 - b) Welding speed too slow
4. When a carbon steel weldment is stress relieved at 625°C are there any major changes in the microstructure?

ANSWERS

Guide 1

1. The heat affected zone
2. The efficiency
3. a)
4. True

Guide 2

1. The peak temperature reached
2. Austenitic grains
3. False
4. a)
5. True

Guide 3

1. Martensitic structure
2. b)
3. True
4. Controlled Thermal Severity

Guide 4

1. Lamellar tearing
2. False
3. Dilution
4. Basic fluxes

Guide 5

1. It is likely to be lower
2. A long weld pool
3. a)
4. No

MODULE 9

TEST

This test is designed to determine whether you are ready to attempt the formal examination.

Complete the ANSWER SHEET and compare the results with the TEST KEY. If you score less than 70% we suggest you restudy the material.

1. A large ASTM grain size number indicates:
 - a) medium sized grain
 - b) a coarse grain
 - c) an elongated grain
 - d) a fine grain
 - e) none of the above
2. What type of groove preparation does the Tekken test use?
 - a) the J groove
 - b) a square groove
 - c) the double V groove
 - d) a sloping or straight Y groove
 - e) none of the above
3. What is the main reason for preheating a plate?
 - a) to allow time for hydrogen diffusion after the weld is made
 - b) to limit slag inclusions
 - c) to ensure underbead fusion
 - d) to ensure complete root penetration
 - e) to preclude hot cracking
4. Select the answer which will complete the following statement.

"The risk of cracking from sulphur is even greater if the weld metal contains more than about.....of nickel."

 - a) 0.13%
 - b) 0.3%
 - c) 3%
 - d) 0.03%
 - e) 1.3%

Basic Welding Metallurgy of Structural Steels

5. An electric arc converts electrical energy into heat and light at a specific rate. At what rate is heat and light produced from an arc of 300 amps with an arc voltage of 25 volts?
- a) 5700 joules per second
 - b) 7500 joules per second
 - c) 750 joules per second
 - d) 75,000 joules per second
 - e) 12 joules per second
6. If a hard microstructure is formed in the HAZ, what is the only remaining factor that can be controlled to prevent cracking?
- a) the amount of flux
 - b) the amount of helium
 - c) the amount of carbon
 - d) the amount of oxide
 - e) the amount of hydrogen
7. Select the answer which will complete the following statement.
- "At about.....hydrogen will have NO embrittling effect."
- a) 70°C - 90°C
 - b) 25°C - 40°C
 - c) 45°C - 70°C
 - d) 150°C - 200°C
 - e) 15°C - 20°C
8. For steel, at which temperature is there a *partial* transformation to austenite?
- a) exceeding 723°C
 - b) exceeding 970°C
 - c) below 723°C
 - d) exceeding 1723°C
 - e) exceeding 910°C
9. What type of cracking may be caused by excessive welding speeds?
- a) cold cracking
 - b) HAZ cracking
 - c) solidification cracking along the centreline
 - d) hydrogen cracking
 - e) lamellar tearing
10. Why would a multipass weld normally be tougher than a single pass weld?
- a) because the heat from one pass enlarges the grains of the previous pass
 - b) because the carbon content of previous passes is reduced
 - c) because the heat from one pass refines the grains of the previous pass
 - d) because the grains of the previous passes are elongated
 - e) because the heat from the previous pass refines the grains of the next pass

Basic Welding Metallurgy of Structural Steels

Canadian Welding Bureau Answer Sheet - Module 9

Complete the "Answer Sheet" and compare the results with the "Test Key". If you have a pass mark less than 70%, you are advised to re-study the material.

Please circle only ONE letter corresponding to the answer you think is most correct.

QUESTION	ANSWERS				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

The answer key below is provided for your use in the event that you wish to retest yourself.

QUESTION	ANSWERS				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

Basic Welding Metallurgy of Structural Steels

Canadian Welding Bureau Test Key - Module 9

Compare your answer sheet to this key.

QUESTION	ANSWERS				
1	a	b	c	(d)	e
2	a	b	c	(d)	e
3	(a)	b	c	d	e
4	a	b	(c)	d	e
5	a	(b)	c	d	e
6	a	b	c	d	(e)
7	a	b	c	(d)	e
8	(a)	b	c	d	e
9	a	b	(c)	d	e
10	a	b	(c)	d	e