Weldability of Metals and Alloys

By S. V. NADKARNI*

Definition :

Defining weldability in specific terms has been a hair-splitting exercise since many years. Finally the International Institute of Welding has come out with the following definition as being most acceptable, which is included in ISO recommendation R 185/1967 :

"A metallic substance is considered to be weldable to a stated degree by a given process and for a given purpose, when metallic continuity can be obtained by welding using a suitable procedure, so that the joints comply with the requirements specified in regard to both their local properties and their influence on the construction of which they form part".

For practical purposes, we have to remember that weldability is not an intrinsic property of a metal like ductility, strength, or toughness. Weldability is a processing property for providing welded joints with the desired qualities. The degree of weldability varies from metal to metal as, for example, when you compare steel and cast iron. The end purpose of welding has to be considered. For example, cast iron is totally unweldable if one has a welded pressure vessel in mind. But if one aims at a repair of a crack in a cast iron machinery part, it is reasonably weldable. The welding process also comes into the consideration. For example, if one had to weld steel to aluminium by manual metal-arc or TIG process, one would say that this combination is unweldable. Yet, it is fully weldable when you use friction welding or explosive bonding.

*Mr S V Nadkarni is Chief Welding Engineer of Advani Oerlikon Limited, Bombay. This was the keynote paper presented at the Calcutta Branch Seminar held on 12-3-76.

Carbon Steels and Low-Alloy Steels :

Problems of weldability arise mainly from the heat of welding which alters the mechanical properties around the joint unfavourably so as to expose the entire welded structure to premature failure in service. Speaking of carbon and low-alloy steels, they, like many other alloys, are subject to the following types of failures in the welded form, and all of them have to be included in the discussion on weldability :

(i) Hot cracking
(ii) Brittle fracture—crack arresting properties
(iii) Lamellar tearing
(iv) Cold cracking

I shall deal briefly with the first three and then in detail with the cold cracking phenomenon which always dominates any discussion on weldability.

(i) Hot Cracking :

Hot cracking consists of micro-cracks in the immediate vicinity of the fusion line. They occur at high temperature as the molten weld metal is solidifying. They occur when low-melting non-metallic inclusions are present in the steel or weld metal. For example, when parent metal or weld metal in mild steel has very low manganese and high sulphur, hot cracks can form because of the low-melting constituent iron sulphide. Hot cracking will rarely occur if one uses standard weldable steels and electrodes conforming to standard specifications.

(ii) Brittle Fracture :

Brittle fracture generally occurs in large welded structures such as bridges, ships and vertical storage tanks. The fracture usually initiates from a small pre-existing defect or notch and propagates very fast, without the indication of any ductility in the steel or its ability to arrest the crack. The failure is therefore sudden and catastrophic.

The main cause of brittle fracture is low ambient temperature often present in cold countries. Many steels which are tough at room temperature suddenly show brittleness at O°C or —20°C. Many 'Liberty' ships broke in two during the First World War because this fact was not known. Today for large structures and for those meant for sub-zero service, one uses what are called "notch-tough" steels i.e. those which give very good Charpy-V impact values at specified temperatures i.e. O°C, —20°C. —30°C, —50°C etc. Aluminium-killed fine-grained steels show good notch-tough properties at low temperatures. For very low temperatures, steels alloyed with nickel are found suitable. Basic low-hydrogen electrodes usually give excellent sub-zero impact properties. The same can be said about basic submerged-arc fluxes. Present-day codes and specifications on bridges, ships, etc. take care of all these factors in specifying steels, electrodes, approval tests, levels of workmanship, etc. If they are strictly followed, one need not fear brittle failure.

(iii) Lameller Tearing :

Lamellar tearing usually occurs in very thick plates where heavy fillet welds are present. This occurs due to tensile stresses acting in the thickness direction of the susceptible plate. I have not yet seen this type of failure in India because we rarely weld plates heavier than 100 mm. But I am sure the delegates will have some cases to report.

(iv) Cold Cracking :

Cold cracking is also called "hydrogen-induced cracking" (HIC) because it is caused by the combination of hydrogen present in the welding arc and hardening of the heat-affected zone due to high heating followed by rapid cooling. Cold cracks occur generally in the HAZ below the weld deposit and therefore they are also referred to as "under-bead cracks". They cannot be seen from the surface, but only when the welded joint is cross-sectioned and etched. Sometimes the cracks propagate and rise to the surface.

It is now understood that HIC depends on the following factors :

(i) Carbon Equivalent of the Steel :

CE is given by the formula CE>

$$C\% + \frac{Mn\%}{6} + \frac{Cr\% + Mo\% + V\%}{5} + \frac{Cu\% + Ni\%}{15}$$

The higher the CE, the harder will be the HAZ with increased risk of cracking.

(ii) Thickness of Sections :

The thicker the plate, the faster is the cooling rate of the HAZ with increased risk of cracking. Correctly speaking, when it comes to plate thickness the main criterion is the "combined thickness" (i.e. total thickness of the plates meeting at the joint line) and therefore we have to distinguish among different joint configurations. For example a butt weld between two 25 mm thick plates is equivalent to a fillet weld between two 17 mm thick plates as far as the rate of cooling they will impose on the weldment is concerned. This is because in the fillet weld the heat loss is in three directions whereas, in the case of butt weld, it is in two directions.

(iii) Heat Input Rate :

Another very important parameter previously ignored is 'heat input rate'.

This is given by the formula :

$$\text{Arc Energy} = \frac{V \times A \times 60}{S} \text{Kilojoules per mm.}$$

where V=arc voltage, A=welding current, S=arc travel speed (mm/min)

In discussing heat input rate, we have to add to the arc energy the preheat and interpass temperature maintained during welding.

The higher the heat input rate and/or the higher the preheat and interpass temperature, the slower will be the HAZ cooling and the lesser will be the chances of cracking. And vice versa.

Heat input rates can vary widely (0.6 to 8 kJ/mm) considering, at one extreme, a root pass with a small dia electrode and intermittent arc in a pipe of large wall thickness and, at the other extreme, a multi-wire submerged-arc weld using a combined value of over 1500 amps and a slow speed of travel.

Values of heat input under a few typical welding conditions are given below :

Heat input levels with various electrode sizes

Electrode dia	*Run length per 450 mm electrode*	*Arc Energy kj/mm*	
		Non-iron powder	*with iron powder*
3.2	100	2.0	2.5
	135	1.6	1.8
	180	1.2	1.4
4	150	2.2	2.5
	185	1.8	2.0
	235	1.4	1.6
5	150	3.5	4.0
	205	2.5	3.0
	260	2.0	2.35
6.3	150	5.5	6.5
	200	4.0	5.0
	275	3.0	3.5

(iv) Hydrogen Level in the Welding Consumable :

This is yet another very important parameter for cold cracking. To-day one can distinguish among welding consumables by the levels of hydrogen that are potentially available for absorption by the weld pool during welding as follows :

LH Rating	*Weld hydrogen level ml/100g of deposit*
1 High	Above 15
2 Medium	Above 10 and below 15
3 Low	Above 5 and below 10
4 Very low	Below 5

These ratings are obtained as follows :

Rating	*Examples*
1	Manual electrodes of rutile and cellulosic type LH electrodes which have become wet
	Wet submerged-arc flux and unclean wire and plate surfaces
	Flux-cored wires for CO_2 welding with open seam stored in open for a long time
2	LH electrodes taken fresh from airtight cartons but not dried before use
	Dry submerged-arc flux and clean wire and plate surfaces but flux not heated before use
	Flux-cored wires for CO_2 welding with open seam but kept in airtight container
3	LH electrodes dried above 250°C for 1 to 2 hours before use
	Submerged-arc flux dried at 250°C for 1 hour before use, clean wire and clean plate surfaces Solid unclean CO_2 wires and flux-cored seamless CO_2 wires
4	LH electrodes dried above 450°C for 1 hour before use Agglomerated submerged-arc flux dried at 500°C and fused flux dried at 250°C used with extremely clean wire and plate surfaces
	Solid clean CO_2 wire and clean flux-cored seamless CO_2 wire
	Argonarc welds with solid wires

It is obvious that the smaller the amount of hydrogen in the weld metal, the lesser are the chances of cracking.

(v) Joint Restraint :

Another important factor is joint restraint. The cold cracking tendency increases with joint restraint.

Therefore more stringent welding conditions are necessary in welding heavily restrained joints.

Weldability Data

It is very important that weldability data on standard structural and pressure vessel steels are provided to fabricators mainly to avoid the risk of cold cracking. In advanced countries, such data are provided either in the data sheets of steel producers or in standard specifications, based on systematic laboratory tests and shop experience. The data, to be really useful, should specify clearly ; (i) upto what maximum thickness non-LH electrodes can be used, (ii) beyond what thickness LH electrodes must be used, (iii) upto what maximum thickness preheat is not necessary, (iv) what preheat temperatures are necessary for increasing thicknesses.

It is obvious from the earlier section on 'cold cracking' that presenting weldability data is not simple because we have to take into consideration all the parameters, i.e. carbon equivalent of the steel, combined thickness, heat input rate, hydrogen rating of the welding consumable and joint restraint. One of the first to present data in a compact form was the British Welding Institute who have provided a number of nomograms in their publication called "Welding Steels Without Hydrogen Cracking" (1973). These nomograms help one to arrive at the answers to the four questions listed above and to determine the most efficient welding procedure which will avoid cracking. Based on this publication, BSI published BS : 5135-1974, Specification for Metal-Arc Welding of Carbon and Carbon Manganese Steels".

In India, we still have a confused understanding of the weldability of IS : 226 and IS : 2052 steels because whatever weldability data are available in these standards and in IS : 823-1964, "Code of Practice for use of Metal Arc Welding in Mild Steel" are inadequate and misleading. Also we have not been able to collect systematic data based on shop experience. The situation is expected to improve with the drafting of "Indian Standard Recommendations for Metal-Arc Welding of Carbon-Manganese Steels" by the ISI which has been under wide circulation as Doc. SMDC 14 (1752) P dated 6 Sept. '75 and redated 8 Jan. '76. This is based on BS : 5135-1974 and provides complete guidance on weldability. There are other problems relating to our structural steels. They will be discussed in a later section.

Cold Cracking Tests :

Among a large number of tests mentioned in literature, I would recommend just two : Controlled Thermal Severity Test (CTS test) and Implant Test.

CTS Test :

This is a classical test mentioned in most textbooks on welding and probably known to every student of welding. The test is simple, economical and foolproof. Normally it is used by a welding research organisation or a steelmaker. Large welding organisations have used it in the past for studying steels whose weldability data were not available and on which they had no previous experience. But with the publication of BS : 5135-1974, such testing will be rarely necessary because welding data can be readily obtained by knowing just the CE of the steel.

Implant Test :

Implant test is recognised by several experts in the International Institute of Welding as the most promising cold cracking test because it is a "strain-controlled" test and is aimed at providing a quantitative evaluation of the influence of restraint on cold cracking sesnsitivity of weldments. The test can be made with just enough material to make an implant of 8 or 10 mm dia and approx. 100 mm long. It is not necessary to have plates of different thicknesses. To simulate the rapid cooling conditions present in thick plates, the implant is inserted in a hole in a heavy plate of whatever quality is readily available. The test is outlined in Appendix 1.

In the study of cold cracking phenomena an important point is to study the micro-structure of the HAZ and its toughness, formed under different cooling rates (i.e. to check if martensite is present). In the traditional methods it was necessary to have plates of all thicknesses to duplicate the HAZ cooling rates met with in practice. A new concept has obviated this elaborate procedure. In the HAZ cooling, the critical parameter is the cooling time t between 800-500°C because this value determines the nature of the micro-structure formed. Different tables are now available in the literature giving the relationship between heat input and Δ t 800-500°C for different joint geometries, plate thicknesses and welding procedures. A typical table is reproduced below. During the performance of implant test, one can so control the heat input rate with respect to the plate thickness that one obtains the desired value of Δ t 800-500°C to simulate actual welding conditions. The value of t can be checked by means of a thermocouple introduced into the bead during welding.

Plate thickness "t" mm	Net heat input kj/mm			
	Δt—15 sec.	t=30 sec.	t=60 sec.	t=120 sec.
12	0.93	1.38	2.13	3.28
15	1.07	1.64	2.53	3.90
20	1.32	2.04	3.14	4.83
25	1.56	2.41	3.71	5.71
30	1.79	2.76	4.25	6.54
35	1.89	3.10	4.78	7.37
40	1.89	3.43	5.28	8.31
50	1.89	3.78	6.16	—
60	1.89	3.78	6.98	—

Cold cracking studies have led to a startling revelation that the hydrogen-induced cracks occur only after the weldment has cooled below 150°C. This implies that if one cannot provide right conditions for avoiding cold cracking (i.e. giving enough preheat or ensuring LH level due to moist environment), one can still overcome it by maintaining the preheat temperature 150°C without interruption until the entire welding is completed and then raising the temperature immediately to say 250°—300°C (or stress-relieving the job if this operation is specified) and maintaining it for a few hours. This prolonged "concurrent" heating drives most of the dissolved hydrogen from the weld metal before it has done harm. This technique is used effectively on hardenable steels like 5Cr : ½Mo.

Weldable High Strength Steels :

Mild steel which generally has carbon below 0.25% does not present weldability problems. However, development of high-strength weldable steels posed problems in the early years because high strength required higher levels of carbon and also the presence of alloying elements like Cr, Mo, V (i.e. high carbon equivalent) which would cause high hardening of the HAZ during welding unless very high preheat temperatures were used. It was also a question of getting matching toughness in the weld metal and the HAZ.

This problem is now fully overcome. Firstly, micro-alloyed steels were developed. Micro-alloyed steels are defined as steels treated with small additions of elements which are carbide—, nitride—or carbonitride—forming such as Nb, Ti, V, Al, Ta and Zr, the total content of these elements seldom exceeding 0.15%. These micro-alloyed steels are usually delivered in the normalised or controlled rolled condition as fine-grained steels with good notch toughness properties. C—Mn micro alloyed steels are now commercially available in three recognised minimum levels of yield strength, viz. 36 kgf/mm². 40 kgf/mm² and 45 kgf/mm². A typical example of this steel is Aldur 58 produced in Austria whose specifications are :

C%	—	0.23 max
Si%	—	0.50
Mn%	—	1.60
P & S%	—	0.040 max. each
Maximum thickness		100 mm
Minimum yield	—	41 kgf/mm²
UTS	—	58.68 kgf/mm²
Elongation (L=5d)		22%
YP at max. t	—	38 kgf/mm²

Satisfies minimum impact value of 2.8 kgf. m at—60°C.

Then came quenched and tempered constructional steels in which very high levels of strength and sufficient notch toughness are obtained by the quenching and tempering heat-treatment which results in a micro structure with a high percentage of low-temperature transformation products. Q & T steels, as they are frequently referred to, have minimum yield strength levels ranging from 42 kgf/mm² (for example, ASTM A 537 Gr. B and commercially available CHAR-PAC of U.S Steel Co.) to 70.4 kgf/mm² (example, ASTM A 517 Gr. F and commercially available T-1 steel of U.S. Steel Co.). Lately, the U.S. Navy is using HY 130 Q & T steel (minimum yield strength of 90 kgf/mm²) for hydrospace and aerospace structures. T-1 steel which is used for penstocks, earth moving equipment parts, etc. in India has the following specification :

C%	—	0.10-0.20
Mn%	—	0.60-1.00
Si%	—	0.15-0.35
Cr%	—	0.40-0.65
Ni%	—	0.70-1.00
Mo%	—	0.40-0.60

Controlled traces of V, Cu and B

Minimum yield	—	70 kgf/mm²
UTS	—	81—95 kgf/mm²
Elongation (L>5d)		18%
YP at max. t	—	63 kgf/mm²

In welding these heat-treated steels, one should not exceed certain upper levels of preheat temperatures and heat input rates (in conventional ferritic steels we find that higher the heat input the safer it is) because otherwise the toughness of the welded joint including the HAZ is lowered. To avoid cold cracking with these restricted heat input levels, one must ensure that the consumable is 'very low' in hydrogen level. In welding T-1 steel, the fabricator is advised to bake the electrodes at 425°C for at least 1 hour prior to use.

When United States Steel Co. introduced T-1 steel, they came out with a dramatic announcement that this steel does not require stress-relieving whatever the thickness and nature of welded structure. This contention was also accepted by relevent codes. This was a great boon in certain areas, for example manufacture of steel penstocks in hydroelectric projects. For normal steels, the codes specify that when the wall thickness exceeds 25 mm the welded joints must be stress-relieved. For penstock fabricators this condition meant considerable hardship especially while having to stress-relieve circumferential site-welded joints.

Indian Steels :

Referring to Indian structural steels, I shall first take up IS : 226 and IS : 2062. Though both these standards were revised in 1975, they still have many unwelcome features to cause confusion among users. Firstly, in the titles 2062 steel is referred to as "Fusion Welding Quality" and the 226 as "Standard Quality", thereby creating the first doubt of 226 being a weldable steel. In para 0.3 of IS : 226, the weldability of this steel is explained in vague terms as follows :

> "Steel specified in this standard is suitable for welding provided that the thickness of material does not exceed 20 mm. When the material conforming to this standard is over 20 mm thick, special precautions may be required in case the material is to be welded (see IS : 823-1964, i.e. Code of Procedure for Manual Metal Arc Welding of Mild Steel)"

This has led the fabricators to believe that IS : 226 above 20 mm is unweldable. As explained in the section on "Cold Cracking", weldability is determined firstly by the CE of the steel and not merely by the C content. This means that for C-Mn steels, the upper limit of Mn should also be specified or still better the upper limit of the CE (this has been done in BS : 4360-1972, "Specification for Weldable Steels". Both IS : 226 and IS : 2062 are silent on the Mn content. The upper limit for C in 2062 steel in the product form is 0.23% and for 226 steel it is 0.25% upto 20 mm thickness and 0.28% for thicker sections. Taking the hypothetical case of 30 mm thick plating, if we had a 226 plate with 0.28% C and 0.84% Mn (CE=0.42) and a 2062 plate with 1.20% Mn (CE=0.43), the 226 steel will have lesser chances of cold cracking than the 2062 steel. Even this conclusion will not be final because we have to link it up with the heat input rate and the hydrogen level of the welding consumables.

Assuming that CE limit of 0.40 max is specified for IS : 226 steel, I have prepared a weldability chart which is given in Appendix II. All I have done is to reduce the nomograms given in the BWI publication "Welding Steels Without Hydrogen Cracking" to a single table.

It is pertinent to stress here that BS :4360-1972, "Specification for Weldable Structural Steels" covers steels upto 0.51 max CE. Why then doubt the weldability of 226 steel which can never have more then 0.45 CE ?

Another misgiving about 226 steel is in its use for dynamically loaded structures even though IS : 226 states clearly in para 0.3 that it is "intended to be used for all types of structures including those subjected to dynamic loading and where fatigue, wide fluctuation of stresses, reversal of stresses and great restraint are involved as for example in crane gantry girders and road and rail bridges". Fabricators avoid using this steel and go in for 2062 steel. Actually when it comes to fatigue strength, it has been established by experts (especially by the British Welding Institute) that steel strength and composition have no effect on fatigue performance, and steels to IS :226 have been used for dynamically loaded structures all over the world. The fatigue performance is determined more by the type of joint and its workmanship. To quote from an article on "Facts of Fatigue" from the Research Bulletin of the BWI :

> "An important point to remember is that the allowable stresses (as given in BS : 153 or IS : 1024-1968) refer to all types of steel. In other worlds, when welded all steels have the same fatigue strength. This is a very sad fact of life, and so far the scientists have not found the reason. The only time the use of high tensile steel is justified in a fabrication subjected to fatigue loading is when F max is above the permissible stress for mild steel"

An important point to be remembered in choosing a steel for dynamic loading is whether there is a possibility of brittle fracture (due to low ambient temperature), in which case the notch toughness of the steel comes into consideration. Then one has to go in for a better quality steel (fully-killed, controlled grain size, normalised, etc.). In this regard, 226 and 2062 steels become a doubtful entity because no impact values are specified for them (optional in case of 2062).

Coming to IS : 961-1975 steel, it is easy to conclude that St 58-HTW grade should be preferred for welding because it has 0.23 max C in the product form compared to 0.30 max for St 58 HT. Other advantages are that it is fully-killed and above 12 mm it is supplied in normalised condition. At the same time, use of St 58 HT for welding cannot be ruled out if one is prepared to use sufficiently high heat input during welding, adequate preheat and extra-LH-electrodes as demanded by the CE and the combined thickness. In both these steels, CE max. must be specified for a clearer understanding of weldability (more so as hardening elements like Cr may be added).

Indian Weldability Test :

In IS : 2062, weldability test is prescribed for thicknesses between 28 mm and 50 mm. The test consists of laying a bead on a plate and then subjecting it to a bend test. Cracks are inspected during and after the bend. I feel that the test is a little vague in the absence of clear indication of heat input rate and hydrogen level of the LH electrode. Also the test would be superfluous if the CE limit is specified for various thicknesses.

In IS : 961-1975, bead on plate test is specified for St 55-HTW steel for all thicknesses. The criterion is the max. hardness level of 350 HV across the HAZ. The standard states that "if this limit is exceeded, it will be necessary to take special precautions when welding, the thickness of the plate being taken into account". In this case, the hardnesses will depend very much on heat input rate i.e. welding current and arc travel speed, which are not defined here. Also it must be remembered that the critical HAZ hardness level (i.e. the hardness below which the risk of cracking does not occur) varies with the hydrogen rating of the welding consumable. It is 350 HV for 'high', 375 HV for 'medium', 400 HV for 'low' and 450 HV for 'very low'.

Future Developments :

For the healthy growth of our welding industry, our steelmakers should develop a wider range of weldable steels with well defined weldability and clear guidance to designers and fabricators in the matter of choosing the right grade. For example, we could have 5 grades of mild steel as follows, based on BS : 4360-1972, which in turn is based on ISO/R 630 :

Grade A,	semi-killed	as rolled,	no Charpy requirements
Grade B,	,,	,,	Charpy at room temperature if asked for
Grade C,	,,	,,	Charpy at 0°C
Grade D,	,,	+Nb and/or V normalised,	Charpy at -10 to -20°C as required
Grade E,	Si-killed	Al treated, normalised,	Charpy at -20, -30 or -50°C as required

Grade A is similar to our IS : 226. Our 2062 could be made to match grade E in normalised form and to satisfy Charpy requirements down to at least —30°C. I feel that the potential of 2062 steel is not adequately exploited in India.

We should also develop micro-alloyed medium tensile steels and Q & T steels, which are presently imported, and whose demand in the country is rising. A beginning has already been made. The R & D organisation of HSL is working on a series of Nb and Nb-V steels, both in killed and semi-killed varieties, having yield strength levels in the range 32-59 kgf/mm^2 and UTS 45.6-74 kgf/mm^2. Over 300 tonnes of a grade of Nb-treated steel has already been produced in the Rourkela Plant. Some weldability studies have been carried out and they are detailed in document SMDC 5/T-159 dated 29 Dec. 75 issued by the ISI.

Creep–Resisting Steels :

Here I shall deal with Cr : Mo and Cr : Mo : V steels which are used where better yield and creep strengths and greater resistance to hydrogen attack in service are required. The weldability properties of these steels are little understood in India though their use is expanding not only in pipelines but also in pressure vessels. Among these 1 Cr : ½ Mo and 2¼ Cr : 1 Mo steels as pipe material are often welded with rutile electrodes because welders prefer them to basic LH electrodes. But the use of these electrodes imply higher preheat temperatures, less toughness of the joint and greater risk of cold cracking.

With increasing use of larger thicknesses in pressure vessels, the use of high preheat temperatures as specified in the codes becomes expensive and cumbersome. Earlier discussion on cold cracking clearly indicates that preheat temperatures could be considerably lowered by using consumables of 'extralow' hydrogen rating and higher heat input as given by the submerged arc process. Preheat could be further reduced or even eliminated in cases where it is possible to maintain the weld joint hot and commence post heating immediately after welding before the joint has a chance to cool down. The submerged-arc process could easily bring down the preheat temperature because of high heat input rate but the resultant large pool size and slow cooling rate can give rise to coarse macro-and micro-structures in the weld metal with consequent reduction in toughness. This drawback has now been overcome with the development of agglomerated SA fluxes of high basicity used in combination with special alloy wires to suit many standard steels in this class.

Use of electroslag welding for these steels also deserves serious study. While advances are being made in improving the toughness of electroslag weld metal, both by the use of basic fluxes and by using multiple, fine welding wires instead of single wires, grain growth in the HAZ still causes such a deterioration in joint properties that most electroslag welds have to be normalised. This does not reduce the impurity level of the weld metal, since the segregates which are partly responsible for the poor toughness of electroslag weld metal are unaffected by normalising.

Solidification cracking in the HAZ are likely to occur unless sulphur and phosphorus are carefully controlled in the parent metal and the weld metal. Close control of them is imposed by most material specification and must be strictly adhered to. Naturally, basic coated electrodes are more resistant to sulphur induced weld metal cracking than rutile electrodes Narrow beads with deep penetration are particularly susceptible to hot cracking

There are instances where use of a lesser alloyed electrode is advisable. An example is tube to tube-plate welding in 2½ Cr : 1 Mo steel. Cold cracking can occur here due to high restraint, small bead size and difficulty of uniform preheating. Here extra strength of the alloy weld metal may not be necessary to the design and a mild steel of less highly alloyed electrode could be used with advantage.

Post-heating data in various codes on creep resisting steels are often in conflict and may not always result in optimum properties. The objectives of postheat treatment are fourfold : (1) removal of hydrogen, (2) relaxing of residual stresses, (3) developing optimum creep-resistant properties, (4) developing optimum notch ductility in the joint. Choice of a suitable temperature for postweld heat treatment can therefore be a more complex matter than the codes of practice might suggest. The discrepancies in recommendation in various codes result in part from the failure of most codes to distinguish the separate effects of postheat treatment on strength at working temperature and toughness at lower temperatures. In fact, it has been observed in the case of many alloys steels used in pressure vessels that the UTS at elevated temperatures is seriously impaired due to stress relief. This has been the subject of study and discussions in TC IX of the IIW. For details please see ref.23. More data on the high-temperature properties of welds, especially the long term creep strength is needed, and the toughness of both wrought materials and welded joints in the creep resisting steels has yet to be studied systematically using modern techniques based on fracture mechanics principles. These results are needed if the codes are to be relevant to the practical problems of designers and fabricators.

In some cases, such as the welding of large fabrications on site, it is difficult to apply a postweld heat treatment. The use of austenitic weld metal such as 25 Cr : 20 Ni or 20 Cr : 9 Ni : 3 Mo is often favoured as a means of producing a ductile joint, free from cold cracking, without postheating ; but this can lead to thermal fatigue of the joint in service because of the different co-efficients of expansion of the austenitic and ferritic materials. For this reason, nickel-based alloys have largely superseded austenitic steel fillers in such applications. This means of avoiding a postweld treatment is mainly applied to the 5 Cr : ½ Mo plate materials which are used as much for their corrosion resistance as for their creep strength ; in other cases, tempering is still necessary to develop the high temperature strength of the HAZ.

Heat Treatment Cracking :

The problem of stress-relief cracking in creep-resisting steels has come into prominence since vanadium-bearing steels were welded with matching weld metals. Vanadium carbide has been shown to be chiefly responsible for the hardening observed in the range 400-700°C in these steels and helps to provide two of the conditions necessary for cracking : a HAZ in which hardening continues to high temperatures, and slow relaxation of residual stresses in the weld metal. As a result of these early cracking troubles, it became normal practice to specify Cr : Mo weld metals for welding Cr : Mo : V steels, for example, $2\frac{1}{4}$ Cr : 1 Mo filler for $\frac{1}{2}$ Cr : $\frac{1}{2}$ Mo : $\frac{1}{4}$ V plate. While this move has eliminated cracks in most cases, cracking is still sometimes reported in heavy sections of Cr : Mo : V steel welded with Cr : Mo filler.

Work now in progress in the research labs. all over the world should result in a new generation of low-alloy, creep resisting steels. Where long-term creep properties are of more concern than high temperature yield strength, there are some indications that alloy contents may be lowered and, in particular, that vanadium contents may be reduced without detriment to the creep strength. This would be one more instance of a general trend in modern steel development towards the achievement of the same mechanical properties as previously with successively lower alloy contents, with resultant benefits in weldability. At the same time, any improvements in parent materials will accentuate the need for corresponding improvements in the properties of welded joints, especially those made with the automatic processes giving high deposition rates. Even at present, it is the embrittlement of welded joints rather than any marked deterioration in parent plate properties, which sets the lower limit for the preheat temperature and hence the upper limit of the strength that can be developed. However, metallurgical developments in both the weld metal and HAZ as seen from current literature are very promising.

Stainless Steels :

Stainless steels can be divided into four categories for a discussion on weldability : Ferritic, martensitic, austenitic and heat-resisting. Weldability of ferritic and martensitic types, I think is little understood here, even though it is a little complicating Generally speaking, we have to first decide whether matching weld metal is necessary or a ductile austenitic weld metal will do, which again will depend on service requirement. The choice between these makes the entire difference to the requirements of preheating and postheating.

Coming to the welding of austenitic steels with which our industry is well-acquainted, one has to take care of one or more of the following : (i) weld decay or intercrystalline corrosion, (ii) ferrite control in the austenitic weld deposit and (iii) avoidance of the brittle sigma phase in welds having high level of ferrite and subjected to elevated temperatures in service. Sometimes questions are raised about whether ELC steels or Nb-stabilised steels are to be preferred to avoid intercrystalline corrosion. Also what is the justification of some fabrications wanting electrodes of ELC type with Nb-stabilisation ? Many discussions have taken place on these aspects in various seminars in our country.

A very important point is "stress corrosion". This takes place when a fabrication has a high content of locked-up stresses due to bad workmanship. I have seen this occurring whenever a fabricator handles a s.s. fabrication as ordinarily as mild steel. In the latter, one can always resort to stress-relief but s.s. vessels cannot be stress-relieved. Another point is the importance of polished finish of the welded joints which has a direct bearing on the life of the fabricated product.

Normal stainless steel welds with controlled ferrite have excellent freedom from cracking. Fully austenitic welds which are demanded in extreme corrosion environment (generally 25 Cr/20 Ni type) frequently crack during deposition and in underlying weld runs reheated by subsequent passes.

Investigation of micro-cracking in underlying weld runs in fully austenitic stainless steel weld metal carried out by the British Welding Institute has shown that it arose principally as a result of grain boundary liquation ; a ductility-dip cracking mechanism could also be operative, but this was of less practical importance. Variations in consumable composition and welding procedure influenced the incidence of cracking in practice, but at present it is not possible to guarantee freedom from microcracks under production conditions. Based on Charpy impact and COD tests, and long service experience with fabrications, the BWI researchers have concluded that such microcracks were unlikely to have any significant effect in service on the tensile, toughness, or fatigue properties of fully austenitic stainless steel weld metals.

Compositional recommendations for the fully austenitic weld metal to minimise cracking as given by the investigators are : C-0.10 max. Si-0.30 max, Mn-3.0 to 6.0, Mo and N to be increased to 2.5-3% and 0.2% max. respectively, Nb-0.30% max. trace impurity elements to be avoided, basic electrodes coating; Cracking more likely with higher currents.

Lastly, there are unusual weldability problems in cladding mild steel with various grades of stainless steel and in welding clad plates. These form a subject of constant investigation and discussion.

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APPENDIX I

Implant Cracking Test :

An implant is a cylindrical test piece with a diameter of 8 to 10 mm taken from the steel to be tested. At the upper end of the test piece is a notch with an aperture angle of 40°, a depth of 0.5 mm and a width of 0.1 mm at the notch root (see Fig. 1). The purpose of this notch is to produce stress peak at which the hydrogen required for fracture initiation collects. It therefore reproduces the geometrical conditions prevailing at the root of the weld seam. A thread is cut into the lower end of the implant to faciliate load application. The implant is introduced into a bore-hole situated in a steel plate of adequate thickness. A weld bead is then deposited on implant & steel plate by means of the particular welding process in question (Fig. 2). Care must be taken to see that the notch in the implant is situated in the heat affected zone (Fig. 3). The temperature in the heat affected zone is measured by thermocouple elements introduced from the bottom surface of the implant into this region.

The implant may be loaded immediately after the welding operation or after a longer period of time, the

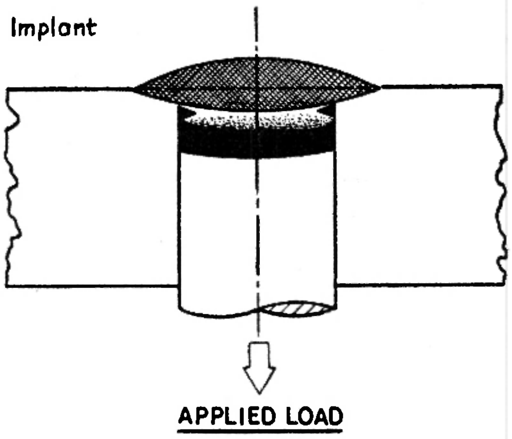


Fig. 3

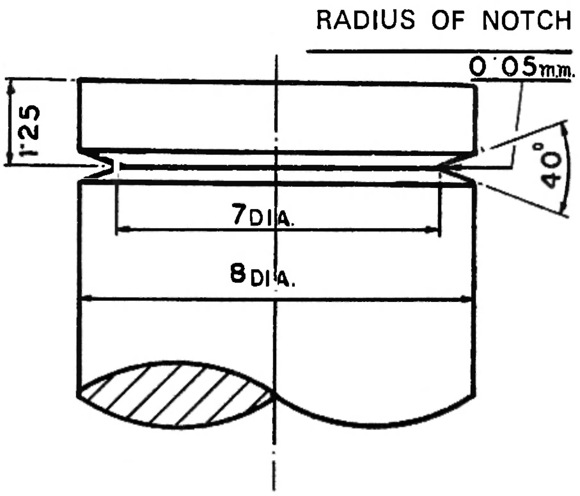


Fig. 1

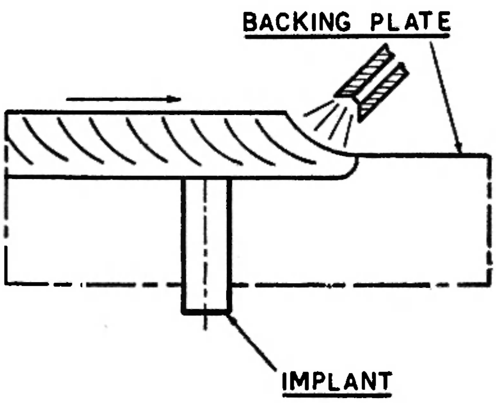


Fig. 2

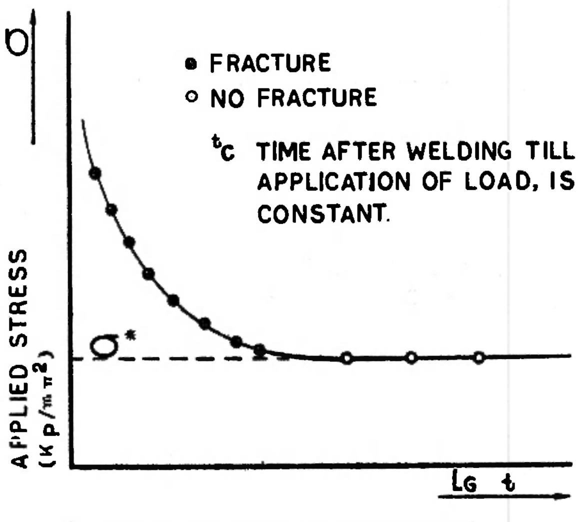


Fig. 4

applied load remaining constant during the test. In the first case, the cracks and the fracture appear very quickly, whereas in the case of delayed loading, they appear very late or not at all. If a test piece remains unfractured at the end of the test it is removed from the steel plate and examined metallographically. In this way the ratio of the cracks to the cross-section of the notched plane can be determined.

As a result of the test one obtains the time after which the crack or the fracture appeared in the test piece. In this connection, there are two possibilities for the carrying out of the test :

1. The time between the conclusion of the welding operation and the application of the load, tc, remains constant during the whole series of tests. The loading stress is varied by means of varying loads. The results of the tests can be represented graphically as in Fig. 4. The bigger the applied load, and hence the stress, the shorter the time to crack appearance. Conversely, the endurable duration of load application continues to increase with decreasing stress until for a certain load the test piece no longer fractures. This stress, o*, is called the "static fatigue limit" and differs from material to material and for every set of test parameters.

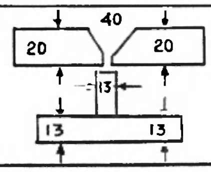
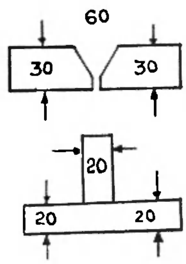
2. The load remains constant for all tests ; tc, the time between welding and loading is varied. Experience has shown that above a certain tc value, tc*, no fracture appears even after a very long load duration.

Besides the movement of loading and the size of the applied load following quantities can be varied :

1. Energy input (e.g. different welding processes).

2. H-content (e.g. different electrode or filler and auxiliary metals).

APPENDIX II

Combined Thickness	Heat input rate kJ/ mm	Hydrogen level	Preheat and interpass temp. °C
	Any	Any	20
	1·2	1	100
		2	75
		3	20
		4	20
	1·8	1	75
		2	20
		3	20
		4	20
	2·2	1	20
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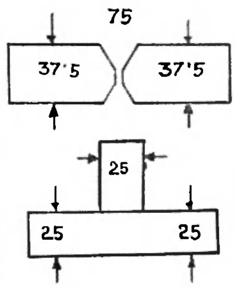
		3	20
		4	20
	1·2	1	125
		2	100
		3	50
		4	20
	1·8	1	75
		2	50
		3	20
		4	20
	2·2	1	20
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	4	1	20
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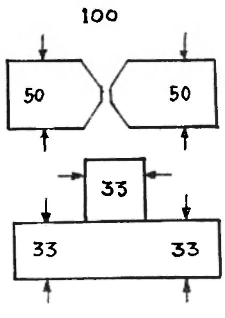
		3	20
		4	20
	1·2	1	150
		2	125
		3	75
		4	20
	1·8	1	125
		2	100
		3	50
		4	20
	2·2	1	80
		2	50
		3	20
		4	20
	4	1	70
		2	20
		3	20
		4	20

All Dimensions Are In Millimetres