Basic Materials and Weldability

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The weldability of any material can be classified into two categories namely, weldability for fabrication and weldability for service. While the weldability for service aspects have received considerable attention from research workers in India, the weldability for fabrication has been a neglected field. This paper reviews the above two aspects of weldability as applied to common fabrication materials. The available information has been critically analysed and areas where further research efforts should be directed are outlined.

A. INTRODUCTION

Weldability of a material is aptly defined by the American Welding Society as "the capacity of a metal to be welded under the fabrication conditions imposed, into a specific, suitably designed structure, and to perform satisfactorily in the intended service". Accordingly, the weldability is broadly classified into two categories namely, weldability for fabrication and weldability for service.

Weldability for fabrication encompasses diverse areas like joint design, chemical composition and mechanical properties of both the base metal and weld metal, welding technique, soundness of the welded joint and cracking of weldment. However, it is primarily concerned with cracking problems that might occur especially in the Coarse Grained Heat Affected Zone (CGHAZ) and weld deposit. The most significant cracking problems in steels are the Hydrogen Assisted Cracking (HAC) and the Postweld Heat Treatment (PWHT) cracking. In Cr-Mo ferritic steels, stainless steels, Ni-base alloys, Al-base alloys etc., the problem of soldification cracking inthe weld metal and liquation cracking in the HAZ are of major concern. The PWHT cracking can also manifest itself incertain varieties of precipitation stengthened alloys.

Weldability for service is concerned with potential problems after the weldment is placed in service and principally includes toughness of the CGHAZ and weld metal and the corrosion behaviour of the weldment. The creep and fatigue properties can be of crucial importance for materials intended for high temperature service. Therefore, the weldability for service depends critically on the chemical composition of theweld deposit and base metal, prior thermomechanical history of the base material, welding procedure and heat input employed during welding.

Since the weldability of materials is a vast subject, this paper is restricted in scope with respect to materials covered and weldability problems discussed. The main emphasis is placed on commonly used materials in India and their potential weldability problems. The thrust areas of research and development are identified based on literature survey and keeping in view the indigenous applications and needs.

B. Weldability For Fabrication

Weldability for fabrication has been grossly neglected in India. This could be because of lack of awareness and interest by the Indian fabricators, manufacturers and users. But in the international scene,the material manufacturing industry has given due weightage to weldability problems while developing newer materials. In fact, the main impetus in developing the new thermomechanically controlled processed (TMCP) microalloyed steels has been provided by the need to produce steels with improved resistance to hydrogen asisted cracking and enhanced HAZ toughness. Similarly, nitrogen-added stainless steels have been developed to obviate the problem of sensitisation in the HAZ.

The following are some of the important cracking problems encountered in various materials which need to be addressed while characterising the weldability of any material.

B.1 Hot Cracking

There are three types of hot cracking problems encountered during the welding of a material. These are (i) solidification cracking-cracking in the deposited weld metal, (ii) liquation cracking – cracking in the CGHAZ and in the underlying beads in a multipass weld, and (iii) ductility dip cracking – cracking in both

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HAZ and deposited weld metal; occurs at a temperature well below the solidus temperature.

The phenomenon of solidification cracking in the weld metal can be best explained by the Generalised theory proposed by Borland in 1960(1). He proposed four solidification stages (Fig. 1). In Stage 1 no cracking can take place as the solid dendrites are freely dispersed in a continuous liquid. Both the solid dendrites and liquid are continuous in Stage 2 and healing of cracks is possible. However, in Stage 3 which is called the critical solidification range, no healing of cracks is possible if the accommodation strains are exceeded. The Stage 4 marks the completion of solidification and no cracking can occur.

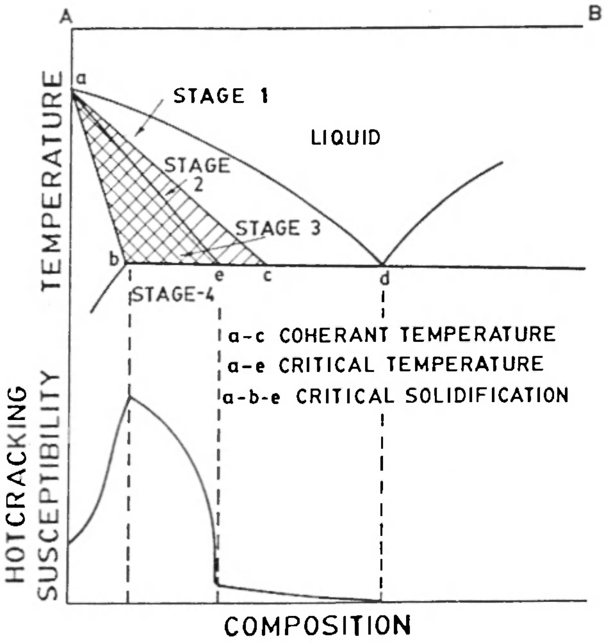

Fig. 1 Effect of constuitutional features on the hot cracking susceptibility in bunary systems [1]

The liquation cracking in the base metal HAZ andweld metal HAZ can be because of (i) liquation of grain boundaries, (ii) low melting segregates, (iii) absorption of solutes from the weld pool, and (iv) constitutional liquation of inclusions and second phase constituents. The susceptibility of any material to liquation cracking or ductility dip cracking can be understood from the hot ductility curve (Fig. 2.) The ductility dip cracking takes place in Region I, while in Region III the liquation cracking occurs.

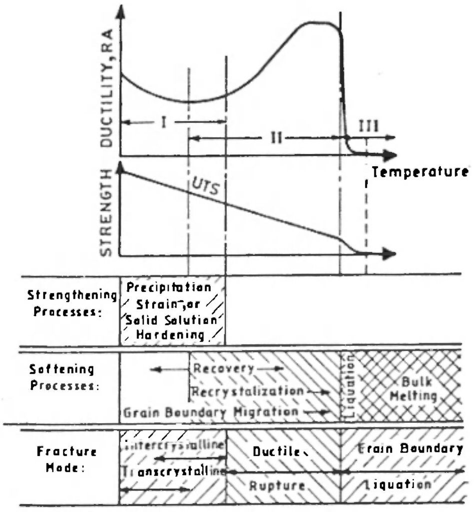

Fig. 2.Typical hot ductility response of the heat affected zone in a material

B.1.1 Cr-Mo Ferritic Steels

The Cr-Mo steels have beenshown to be prone to both solidification cracking and liquation cracking. A strict compositional control is required to overcome the problem of cracking in these steels. The elements S, P, Ni and Cr have been found to increase the susceptibility of Cr-Mo steels to hot cracking, whereas Mn and C help in decreasing the incidence of hot cracking. (Fig. 3) sums up the results of Varestraint testing of various Cr-Mo steel weld metals and shows the benefificial effect of increasing carbon content on the hot cracking suceptibility (2). However, in 9 Cr-1Mo steels the increase in carbon content has been found to increase the hot cracking tendency. Abe et al (3) observed a linear increase in the total crack length with parameter (50C+6Nb-Mo-1) for 9Cr-1Mo steels.

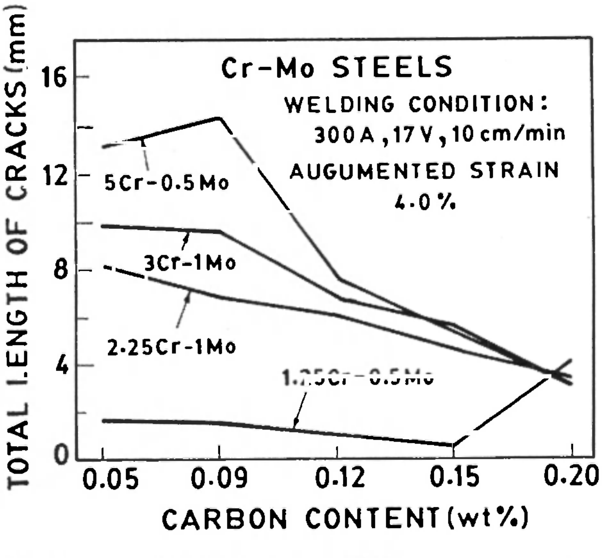

Fig. 3. Hot cracking suspectibility of Cr-Mo ferritic steel weld metals as a function of carbon content [2]

B.1.2 Stainless Steels and Ni-base Alloys.

The problems of hot cracking in stainless steels and Ni-base alloys has been extensively studied. It is now known that in stainless steels the solidificationcracking is critically dependent on the mode of solidification. The stainless steel welds solidifying in the primary austenitic mode are considerably more prone to cracking than those solidifying in the primary ferritic mode. (Fig. 4), which illustrates the influence of (P + S) and mode of solidification on the hot cracking tendency of stainless steels using sigmajig test (4). Also shown in the Figure are two fully austenitic alloys containing Ti 8(D9 and D9I alloys), which are being considered for fuel cladding and wrapper applications in Fast Breeder Reactors. For a constant (P + S), there is a rapid decrease in the threshold stress for type 316 stainless steels when the solidification mode is changed from primary ferritic to primary austenitic, whereas for a given solidification mode the increase in (P + S) decreases the threshold stress gradually

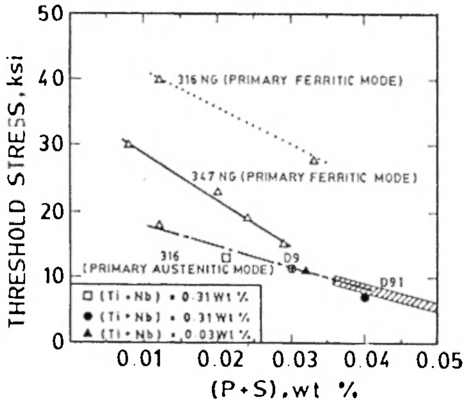

Fig. 4.Threshold stress variation with (P + S) content in different stainless steels as evaluated by Sigm-a-jig test [4]

The susceptibility of liquation cracking in stainless steels has been quantified by Morishige et al (5),(Fig. 5) According to Norishige the materials with H greater than 100 are not prone to hot cracking. Though the parameter H is not universally accepted as it does not contain the contribution from impurity elements like S, P and B but it indicates the relative effect of various elements on the liquation cracking. susceptibility. According to Matsuda(2) the addition of rare earth metals (REM) increases the resistance to hot cracking both in the fusion zone and HAZ.

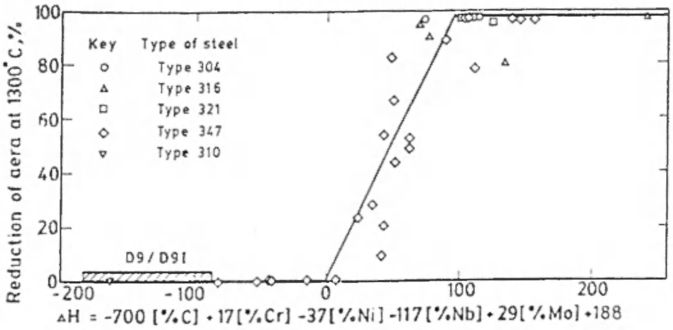

Fig. 5. Liquation cracking tendency of vairous stainless steels (5)

Unlike in stainless steels, in Ni-base alloys and Al-base alloys the hot cracking problem still exists. While it is possible to minimise the problem inweld deposits by carefully controlling the welding heat input and welding procedure, it is relatively difficult to control in the HAZ.

B.1.3 Future Work

- ☐ Role of C, S and P should be clarified in 9Cr-1Mo and 12Cr-1Mo ferritic steels.
- ☐ Influence of Nb, Ti and V should be investigated in stabilised ferritic steels.
- ☐ Since fully austenitic weld metal is desirable from the point of view of service at cryogenic and high temperatures and in certain aggresive environments, efforts should be made to document the influence of S, P, Si and N in fully austenitic stainless steels.
- ☐ Addition of REM and its influence on weld metal and HAZ hot cracking tendency should be studied.
- ☐ A weldability criterion should be developed for the indigenously developed stainless steels.

B .2 Hydrogen Assisted Cracking :

The hydrogen assisted cracking (HAC) commonly occurs in the grain coarsened HAZ and is frequently described as toe cracking, root cracking, or underbead cracking depending on crack location. It is also known as delayed cracking or cold cracking because cracking usually occurs after an incubation period, which may vary from a few hours to days and generally does not initiate until the weldment has cooled to below 200°C. The three most important factors responsible for HAC in a steel weldment are (i) the chemical composition and hence hardenability, which in turn determines the HAZ microstructure, (ii) the diffusible hydrogen content of the weld deposit, and (iii) the restraint associated with the welded geometry and the attendent residual stresses.

The problem of HAC has been extensively researched for the last 50 years by steel users, manufacturers, fabricators and academic alike. As a result of these sustained efforts, a number of superior grades of steels have been made available to the user with greatly reduced susceptibility to HAC and which can be welded with lower preheat temperatures and over wider heat input ranges than was possible in the years past. The weldability of steels has been improved by (i) the introduction of steels with lowered carbon contents and thus lower carbon equivalents, (ii) the application of various thermomechanical treatments to enhance strength and toughness by grain size and micro- structure control, (iii) lower sulphur content and inclusion shape control, and (iv) the availabililty of high quality low hydrogen consumables. The main advantage derived from the above developments is in terms of improvement in the HAZ properties such as hydrogen assisted cracking, lamellar tearing, reheat cracking, toughness and stress corrosion cracking.

One of the widely used method to avoid the occurrence of HAC in a steel weldment is the application of preheat to the joint to be welded. There are mainly two approaches to estimate the preheat temperature for crack-free welding - Hardness Control and Hydrogen Control.

B.2.1 Hardness Control Approach :

The Hardness Control approach to estimate the preheat temperature was first developed at The Welding Institute (TWI) using steels covered in BS 4360 (carbon and carbon equivalent less than 0.30 and 0.54% respectively) and forms the basis of BS 5135 : 1984. It is based on two assumptions - (i) the incidence of cold cracking is greatly reduced below a certain critical CGHAZ hardness, and (ii) the critical hardness is independent of carbon equivalent, CE (IIW). However, recently the validity of both the assumptions has been questioned, particularly when applied to 'new' steels. Booth by reported [6], based on data from sixteen C-Mn-Nb steels, that 37% of the predictions using the TWI method were unsafe. He suggested that this anomoly may be because of critical hardness being not constant with CE. This was later on substantiated by kirkwood [7] (Fig. 6). The critical HAZ hardness increased linearly with increase in CE(IIW) rather than remaining constant as assumed in the Hardness Control approach. Cottrell [8] expanded the data base to 102 steels (Fig. 7) by including thirty eight low alloy, seven C-Mn, fifty three C-Mn-Nb and four B-mo steels and concluded that 20% of the predicted critical arc energy values were too low. He attributed this anomoly to (i) the inadequacy of CE(IIW) to represent hardenability, (ii) the absence of contribution of inclusion content to the HAC of steels, and (iii) inappropriateness of the cooling rate at 620°C. He proposed several modified nomograms which are claimed to provide a three-fold improvement in the prediction of arc energy to avoid HAC.

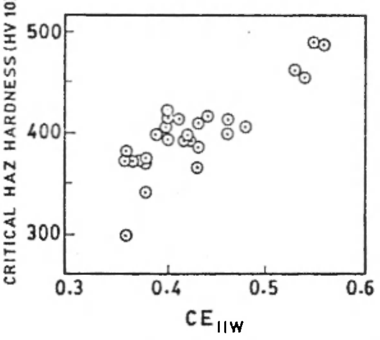

Fig. 6. Variation of critical hardness with CE (IIW) [7]

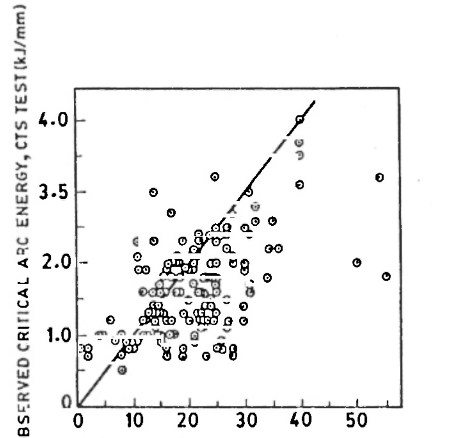

Fig. 7. Comparison between the observed and predicated (TWI method) critical arc energoes [8]

The Centre de Recherches Metallurgiques (CRM), Belgium [9] has proposed another method to estimate the preheat temperature for C-Mn and micro-alloyed structural steels. This method links cooling time from 300 to 100°C to cooling time from 800 to 500°C. The cooling time from 300 to 100°c is importanr as its magnitude decides the time available for the diffusible hydrogen to escape from the weldment, whereas cooling time 800 to 500°C along with the steel chemistry defines the microstructure and thus maximum hardness of the CGHAZ. When the predicted values from the CRM methods are conpared with the conventional hardness approach for micro-alloyed steels, it was overly conservative in predicting the preheat temperature (Fig. 8), thus indicating considerable economic advantage in using the CRM method.

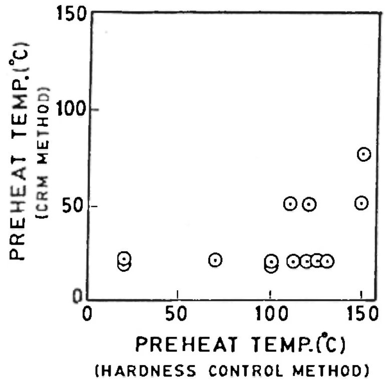

Fig. 8. Comparison between the preheat temperatures predicted by the CRM method and Hardness Control method [9]

B.2.2 Hydrogen Control Approach

The Hydrogen Control approach was developed in response to the recognition that cracking did not always occur when the critical hardness was exceeded. Preheated samples tolerated higher hardness than the unpreheated. Ito and Bessyo [10] carried out a large number of groove weld experiments (greater than 200) using the Tekken test for a wide range of low alloy steels. They proposed a cracking parameter which included a composition characterising factor, diffusible hydrogen content and the intensity of restraint. The critical cracking parameter is related to the time for the weld to cool to 100°C, which is a measure of the amount of time available for hydrogen to diffuse out of the weldment. The Japan Steel Structure Construction (JSSC)procedure [11] is based on Ito and Bessyo approach. However, Ito and Bessyo or JSSC methods did not find universal applicability and consequently several modified cracking parameters have been proposed over the years which are claimed to be valid over a wide composition range [12-15]. Yurioka et al [14] and Suzuki [13,16] have shown poor correlation between the experimental and measured preheat temperatures using several of the proposed crackaing parameters, thus casting doubts about their suitability in predicting temperatures for safe welding.

B. 2.3 Selection of Method to Determine Preheat Temperature

Graville [17] while discussing the suitability of the Hardness Control and Hydrogen Control approaches notes that "Hardness control is most appropriate for carbon steels with limited alloy content. Such steels have a steep hardening curve (i.e., of HAZ hardness vs. cooling rate) allowing a precise determination of critical cooling time. The hydrogen control method is more appropriate for lower carbon steels with significant alloy and microalloy element present. These steel have flatter hardening curves and reducing cooling rate has less of an effect on the hardness".

To assist in deciding which method is appropriate the diagram (Fig. 9) developed by Graville allows one to place a steel in a particular zone on the basis of its carbon content and carbon equivalent value. Zone I steels have low carbon and low risk of cracking in the HAZ but cracking may occur with high hydrogen and high restraint. The hydrogen control method should be used to determine preheat for steels in this zone.

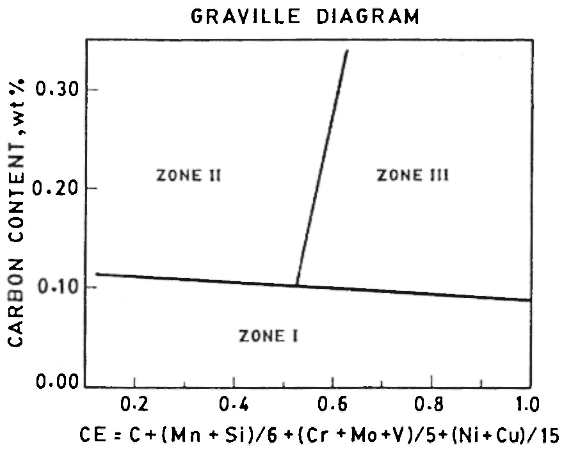

Fig. 9. Comparison between the preheat temperatures predicted by the CRM method and Hardness Control method [9]

Steels in zone II have steep hardening curves and hardness control is possible. Those in Zone III have higer hardenability and flat hardening curves for which hydrogen control is more appropriate.

Although, Graville diagram aids in the selection of a particular approach for determining preheat temperature, it does not specify any particular method among the various methods available in both the Hardness Control and Hydrogen Control approaches. Since no universal acceptable method for estimating the preheat temperature is available, so far, the preheat temperature determination using laboratory or full-scale weldment cracking tests are relied upon to establish safe welding conditions.

B.2. 4 Future Work

☐ The problem of HAC is probably the most extensively researched problem in the realm of weldability of steels. Unfortunately, in India this crucial area has received very little attention. It is very important to carry out a through research and select a suitable method to predict preheat temperature for Indian steels. A software package should be developed for estimating preheat temperature for safe welding.

☐ None of the methods proposed so far are adequate in assessing the preheat temperatures for TMCP steels. Therefore, an effort should be made to study the effect of prior austenite grain size, S and B on the hardenability of new steels. The validity of conventional carbon equivalent formulae to the weldability of TMCP steels should also be examined.

☐ The HAZs of modern steels have become more resistance to HAC, therefore, the cracking problem has shifted to weld deposit. This is due to the fact that in order to match the strength level with the base metal, the weld deposit has to be further alloyed thereby increasing its carbon equivalent. Very few studies have been carried out so far to quantity the cracking susceptibility of weld metals. An effort should be initiated in this direction.

B.2.3 Other Cracking Problems

The lamellar tearing problem in steel weldments had been a serious problem till sixties when it was found that in the inclusion shape-controlled steels its incidence was greatly reduced. However, in some of the Indian steels, the existance of lamellar tearing problem has been reported which needs further investigation.

The problem of PWHT cracking is generally encountered in precipitation strengthened alloys containing higher content of impurity elements like S, P, As, Sn, Sb etc. The cracking occurs in the CGHAZ. Several predictive equations are available to rank meterials for their susceptibility to PWHT cracking. Since Indian steels contain higher amounts of impurity elements, the problem assumes a special significance. Further research work should be carried out to characterise Indian steels for their suscptibility to reheat cracking and existing prediction equation should be validated.

C. Weldability For Service

The weldabiiity for service has been a strong area of research in India, However, the emphasis was placed on weld metal properties and the HAZ properties did not receive much attention probably because of lack of adequate facility for simulating various regions of HAZ In order to expand the desired region for further evaluation.

C.1 Mechanical Properties of Weld Metal and HAZ

The study of mechanical properties of the various region in a weldment is essential to understand the yield and fracture behaviour of welds and their response to external loading. Several equations have been proposed to calculate the tensile properties and toughness of the weld metal and HAZ of steel weldments. The prediction methods, in general are more successful for HAZs.

The estimation of tensile properties in the HAZs of cold worked alloys, precipitation strengthened alloys and TMCP alloys assumes greater sugnificance as the effect of strengthening processes is erased in the HAZ during welding and a 'soft' zone appears having poor tensile and fatigue properties. The extent of HAZ softening depends on heat input and type of alloy.

As a first step towards developing an empirical formula for calculating HAZ properties, it is essential to accurately calculate the hardness of the HAZ. Thus far the most accurate formula proposed for estimation of hardness is that by Yurioka et al [18]. This formula is applicable to steels covering wide range of compositions. In a recent syrvey, [19] Yurioka formula was found to predict maximum HAZ hardness with greatest accuracy for modern steels when compared to any other formula published so far.

Akselsen et al [20, 21] have proposed equations to calculate the HAZ tensile properties for different steels as a function of welding variables. The distribution of tensile properties as a function of heat input in the HAZ for 2. 25 Cr-1Mo weldment based on their work is shown (Fig. 10). The equation proposed by them are claimed to calculate the tensile properties with acceptable accuracy.

Unlike tensile properties, the estimation of toughness has been a difficult problem as the toughness of HAZ not only depends on the chemical composition, cleanliness of the steel and welding parameters but also on the prior thermal mechanical history of the base metal.

C. 1. 1 Future Work

In India, no systematic attempt has been made to develop a model to establish microstructures property correlation.

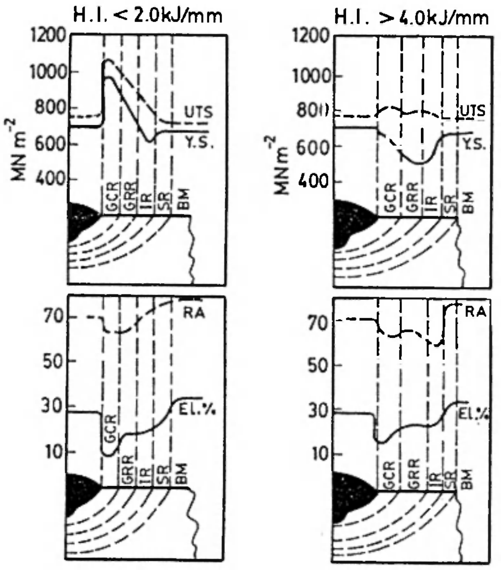

Fig. 10. Variation of tensile properties with heat input in the heat affected zone of 2.25Cr-1mo steel weldment [21]

A serious effort in this direction should be made in developing a heat flow model which should take into account the variation in microstructure with welding heat input. The tensile properties can then be correlated with the microstructure.

C. 2 Corrosion

The weldments are microscopically inhomogeneous and are thus prone to localised corrosion attack in certain aggressive media. For instance, the weld metals of stainless steel contain a certain minimum amount of deltaferrite to avoid the risk of hot cracking. The austenite/ferrite interface is known to be prone to pitting attack in chloride medium. The HAZ become sensitive to corrosion attack during welding as grain boundary carbides formed during high temperature thermal excursions deplete the adjoining areas in chromium. The problem of intergranular stress corrosion cracking in light water nuclear reactors is too well known to merit mention here. The introduction of nitrogen-added stainless steels have mitigated some of these problems. However, the exact role played by nitrogen in enhancing the pitting corrosion resistance is still a matter of debate.

Recently, microbiologically induced/influenced corrosion (MIC) has been the topic of extensive investgations. Investigations in stainless steel weldments, the weld deposits are subject to selective attack by microbials. Both the aerobic and anerobic becteria are known to attack the weld metal selectively. In India a few laboratories are engaged in studying the MIC phenomenon. Needless to say, major efforts are required to understand the underlying mechanisms in this type of corrosion.

Since Indian economy is critically depentent on petroleum the indigenous production of crude oil has to be increased substantially to meet the growing needs of the nation. Fortunately most of the oil wells in India are 'sweet' but several 'sour' wells are also in operation and more may be discovered in the future. The high strength steel weldments are prone to sulphide stress corrosion cracking in sour gas service. In India limited test facilities are available to test weldments according to NACE MR-01-77 standard. Since the actual testing in simulated sour gas service is expensive, it is desirable to develop models to predict the threshold stress in the desired environment. Onsoien et al [22] have recently demonstrated the success of a similar model in predicting the threshold stress in hydrogen sulphide service (Fig. 11).

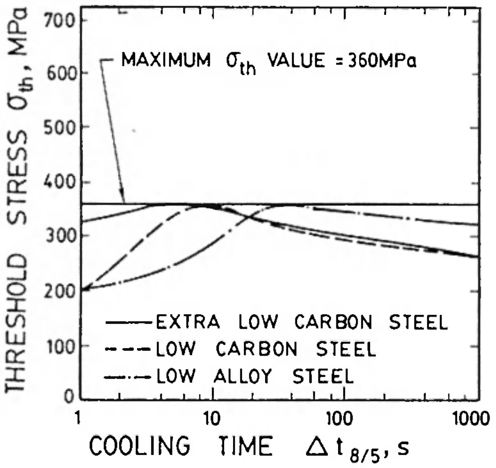

Fig. 11. Variation of the predicted thereshold stress with cooling time in simulated sour gas/oil environment [22]

D. Facilities Required In India

In India, research work in the area of welding is constrained by lack of appropriate facilities to investgate especially weldability for fabrication aspects. As a first step towards this, the following test facilities are suggested to be eatablished –

☐ Weld thermal-mechanical cycle simulator.

☐ Hot cracking testing devices like Tigm-a-jig, Sigm-a-jig etc.

☐ Implant cracking test units.

☐ Testing in sour gas facility.

E. CONCLUSIONS

- 'Real' weld thermal cycle simulator with straining device is a basic requirement for any laboratory that the intends to do welding for fabrication evaluation.
- Established weldability tests like Varestraint and implant cracking testing will continue to be important as they are more likely to be standardised in near future. Nevertheless, many more approaches towards weldability evaluation are emergimg. e. g., sigm-a-jig test.
- With respect to cold cracking tendencies, particularly for new steels, work on Indian steels to choose between Hardness Control approach and Hydrogen Control approach should be given priority.
- Modelling has emerged as a powerful tool for predicting microstructures and properties in different regions of a weldment. This is a virgin area where large experimental data base also needs to be generated for validating models.
- Facilities for SCC testing for sour gas/oil service need to be widely established in the country.
- Microbiologically induced corrosion of weldments is another emerging area that needs attention.

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