A Criterion for Unstable Crack Propagation in Welded Line Pipe Steel

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Abstract

The Modern Fracture Mechnics Concept is used in determining the acceptable defect level in line pipe steel. The toughness properties of the Heat Affected Zone (H. A. Z.) and Weld/Parent metal has been measured in terms of critical crack opening displacement (c.o.d.) values which are found to be more realistic and acceptable compared to other conventional tests. Crack arrest phenomena have been discussed by making use of Charpy V-notch absorbtion energy for the X-52 grade pipe steel. Besides, the development of different test procedures for evaluating the performance of a line pipe has been outlined. The influence of different variables, such as weld flux, heat input and alloying elements on the toughness property of Heat Affected Zone are also incorporated in the present study.

Introduction

One of the more dynamic areas of research in pipeline materials technology during the past two decades has been concerned with fracture toughness. In common with other major engineering structures, a realistic toughness requirement must be built-in in pipe line design and materials specification stages. Such pipe lines are often damaged during service by earth moving machinery, corrosive environment etc. and present special problems. This is especially true for pipeline conveying high pressure oil or gas with a high gas content. If a fracture is initiated in such pipelines, it can propagate for long distances, unless arrested by the inherent toughness of the pipe steel.

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In this paper, the fracture toughness property (CO.D. value) of weld metal, parent metal and heat affected zone (HAZ) at different temperatures will be discussed. The suitability of flux for manufacturing X-52 grades pipe will also be discussed together with the influence of different heat input and alloying elements on the charpy shelf energy value.

Developments on Toughness Property Assessments of Line Pipe Material

In the past, there are many instances where long brittle fracture failures of steels have occurred. Such observations led to an extensive research programme at the Batelle Memorial Institute, resulting in development of the Drop Weight Tear Test to define transition between brittle propagation and ductile arrest, as proposed by McClure, Duffy & Eiber[1]. These studies were further developed by British Gas Research workers Fearnehough, Jude & Weiner[2]. The outcome of such work was a full scale fracture test, which to some extent can successfully predict the behaviour of pipe in service condition. Besides this, British Gas has also established specification data in terms of conventional charpy specimen upper shelf toughness. These values are related to the operating stress levels and individual pipe line dimensions.

The applications of the concept of plain strain fracture toughness are limited to materials which fracture without serious deviation from linear elastic condition. However, for many lower strength structural materials such as the steels used for bridges, off shore structures and pipe lines, it is found that valid plain strain fracture toughness measurements cannot be made for the thicknesses, temperatures and rates of loading

Table - 1A

Chemical Composition and Mechanical Properties of X-52 Grade Pipe Steel

%C	%Mn	%P	%S	%Si	%V	Y.S. Kg/mm²	U.T.S. Kg/mm²	%EL
0.22	1.99	0.033	0.029	0.195	0.04	36	5.05	36

Table - 1B

Chemical Composition of H.S.L.A. Plates

%C	%Mn	%P	%S	%Si	%Al	%Nb	%V
0.17	1.3	0.02	0.02	0.1	0.006	0.042	0.08
0.17	1.3	0.02	0.02	0.1	0.006	0.042	0.15

Table - 2

Weld Consumables & Parameters for Submerged Arc Welding

Type of Flux	Electrode wire & dia	Current (amp)	Voltage (Volt)	Welding speed M/min
Brand A	WHS 2 MO 3.5 mm	540-560 (outside) 570-600 (inside)	30-32	1.2
Brand B	WHS 2 MO 3.5 mm	540-560	30-32	1.2

of practical interest. To enable some assessment to be made, the general yielding fracture mechanics concept of crack opening displacement (C.O.D.) method could successfully be used for predicting the critical crack length, introduced by Wells[3]. Developments in the USA in this area have tended to concentrate on the crack tip contour integral 'J' introduced by Rice[4]. However in the present study, only C.O.D. method has been utilised to assess the toughness property of X-52 grade pipe.

Experimental

In order to assess the critical allowable crack length in the weldments of X-52 grade pipe steel, attempt has been made to assess the C.O.D. value of weldmetal, parentmetal and H.A.Z. at different temperatures. In this regard, the experimental samples were collected from the commercial X-52 grade pipe in the form of plates with weld bead at the centre. The chemistry of the pipe and welding parameters are listed in table 1A and 2. Since the pipe thickness was only 7.2 mm. the fabricated slow bend C.O.D. specimens were 7.0 mm thick with a span of 200 mm. For all test specimens, the orientation of notch was perpendicular to the rolling direction and parallel to the plate surface. These specimens were then tested as per ASTM specification.

To assess the suitability of Brand B flux in welding X-52 grade pipe steel, two sets of plates of approximate size 600 mm×1200 mm×7.2 mm thick, were welded with Brand A and Brand B flux with electrode wire (WHS 2MO). Before welding, the test pieces were flattened, edges ground and clamped in the cross seam welding head of the spiral welded machine. The weld geometry was a square butt with a root gap of about 0.2 mm and had a copper backing strip. The Brand B flux was conditioned for about 20 mts. at 200°C. After depositing the first layer, the plates were reversed and a second bead was deposited. The entire length of the weld bead was subjected to radiography examination. Following this, charpy V-notch specimens of size 5 mm×10 mm×55 mm were fabricated with notch position at three different zones and tests were carried out at different temperatures.

In order to assess the influence of different heat input on the HAZ toughness property, High Strength Low Alloy Steels with two Vanadium levels were chosen with constant percentage of Niobium. For experiment purposes, two plates of thicknesses 50 mm and 25 mm were selected. Each plate was sliced and machined to make 'K' type weld assembly. These pieces were then welded together by Manual Arc Method using low hydrogen electrodes equivalent to E7018 specification with a net heat input of 1.9 KJ/mm for the 50 mm plate and 1.5 KJ/mm for the 25 mm plate (assuming 70% thermal efficiency), when cooling rate was about $\triangle t=$ 15 sec. During welding all weld passes were conducted with the same heat input and the direction of the welded joints were perpendicular to the rolling direction of the base plate, when preheating and interpass temperature were controlled at 125°±15°C, as recommended in the IIW document. The charpy specimens were then machined out of these welded plates, when the direction of the notch was perpendicular to the surface of the base plate and the exact location of the notch was ensured by etching technique.

H.A.Z. toughness propety was evaluated on three different types of X-52 grade steels when welding conditions were strictly followed as per table 2.

Results and Discussion

Prediction of Crack Nucleation and Arrest :

Table 3 indicates some of the typical C.O.D. values measured for the weldmental, parentmetal and HAZ at different test temperatures. Estimation of critical through thickness or buried crack could be arrived at by multiplying the critical C.O.D. value with the C.O.D. multiplying factor (f). This factor could be directly noted from a standard plot of C.O.D. multiplying factor versus the total strain ahead of the crack, just before initiation, as given by Cotton[5], assuming that the operating stress does not exceed half the yield stress. The estimated value of critical crack length for the parentmetal was 20.4 mm at room temperature, assuming that fracture strain measured in a normal tensile specimen is approximately equivalent to the total strain ahead of a crack just before initiation. A similar approach could be made in estimating the critical crack length for all three zones at different temperatures. Based on these data, prediction of performance of line pipe having a certain length of defect in it could easily be assessed for a particular service condition. Besides this, behaviour of a propagating crack emanating out of the welded joints could be assessed from the most conventional charpy value. Maxey[6] has proposed an empirical relationship which could successfully predict whether a crack of such kind will be arrested by the parentmetal or not. For X-52 grade line pipe with 42 inch outside diameter and 0.28 inch gauge thickness, the minimum charpy value required for crack arrest in the parentmetal is approximately 15 J which corresponds to an operating stress equivalent to 62% of the specified minimum yield stress. In other words, maximum operating stress of a pipe line for a particular service condition could be predicted by knowing the Charpy V-notch absorption energy at that condition and the pipe geometry.

Influence of Flux on Weld Metal Property

Fig (1) indicates that weld metal charpy property derived from Brand B flux is much lower than that of with the Brand A flux. Such a lower toughness property may be due to improper weldmetal chemistry. In the same plot, some typical properties obtainable from some other combination of consumables are also plotted. Lower toughness property of the weld metal associated with the Brand B flux is further demonstrated by the hardness survey across the weldments Fig (2). It is important to point out that besides the physical factors, the weld metal composition, degree of deoxidation, presence of trace elements and microstructures of the weld bead are the primary factors which contribute to the toughness of the weldmetal (Garland & Bailey[7]).

Table - 3

Critical C.O.D. Values Corresponding to the Maximum Load

Location of Notch	Test Temperature	Critical COD Values (min)
Parent Metal	+25°C	0.227
	+ 0°C	0.181
Weld Metal	+25°C	0.466
	0°C	0.279
	—20°C	0.185
H.A.Z.	+25°C	0.237
	0°C	0.187

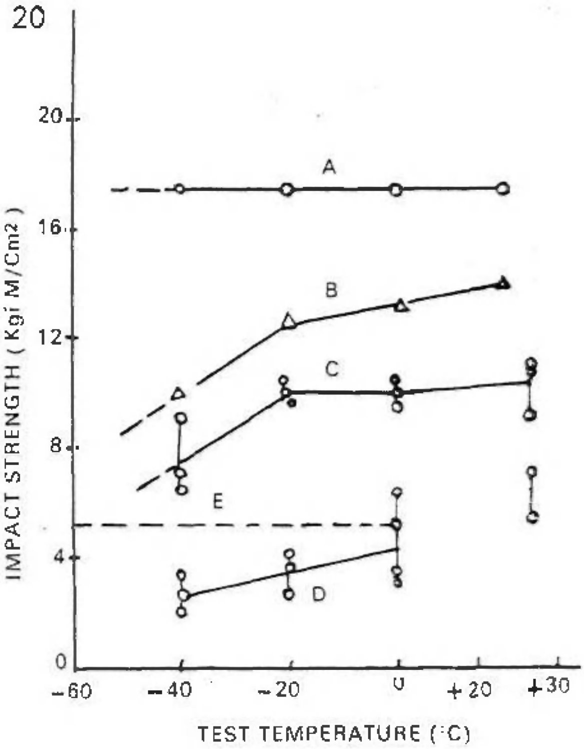

Fig. 1. Effect af different wire and flux combination on the weld metal toughness property of X52 Type Pipe Steel.

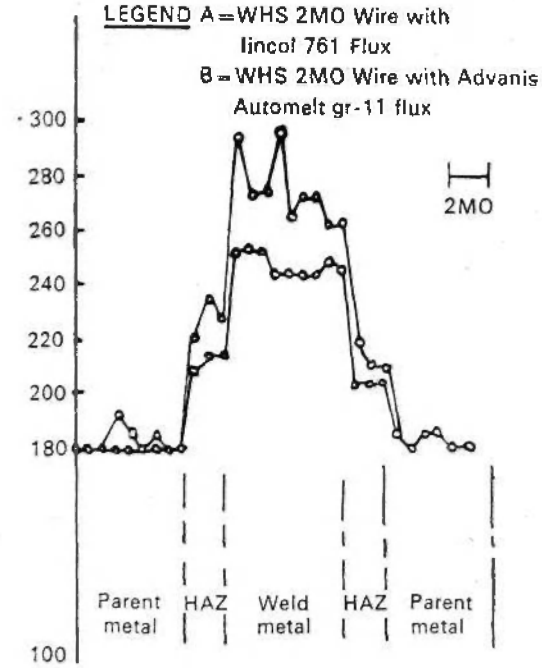

Fig. 2. Variation of hardness across the weldments.

Influence of Heat Input on H.A.Z. Toughness Property

In the H.A.Z., the welding process leads to a rapid heating to the peak temperature and a consequent cooling, when cooling rate depends on the plate thickness and the amount of heat input. In general, with higher heat input, the H.A.Z. toughness property reduces, mainly because of two reasons e.g., it destroys the initial structures and imposes high stress due to thermo-cycling.

Fig (4) shows that with higher heat input (1.9 KJ/mm) with 50 mm thick plate, the H.A.Z. toughness property was found to be low for the higher Vanadium bearing plate. This is also found to be true for the lower heat input (1.5 KJ/mm), with thinner plate thickness. According to the findings of Hannerz & Jonsson—Holmquist[8], Vanadium in excess of 0.01% enhances the embrittlement of H.A.Z. at higher heat input, when transition temperature also increases with Vanadium content in a semi-parabolic manner. Besides this, at lower weld energies a Vanadium content 70.25% is detrimental to the toughness property. The loss in ductility can be attributed to hardening by Vanadium Carbides precipitation presumably in the form of coherent precipitates.

In a separate attempt, toughness property of H.A.Z. of Nb and V bearing X-52 grade pipe steel has been compared with the plain C-Mn steel of the same kind. Fig (3) clearly shows that Vanadium bearing X-52 grade steel has higher H.A.Z. toughness value compared to the rest.

Influence of Nb and V on Weld Metal Toughness Property

Garland & Kirkwood[9], have clearly demonstrated that in Submerged Arc Welding, if the percentage of Nb or V is restricted to a certain limit, the weldmetal toughness property is expected to increase both in as welded and stress relieved condition. This is simply because of formation of acicular ferritic structure. Moreover, V also increases the total amount of retained martensite which generally segregate during the solidification at the phase transformation boundaries. This may sometimes cause little decrease in toughness property. However, it is important to point out that on stress relieving the retained martensitic structure gets transformed to ferrite/carbide aggregate which allows the full potential of the original acicular ferritic structure to be achieved. This means, a greater resistance to cleavage rupture. This situation is true only when no other detrimental changes like precipitation hardening takes place. However, at higher V (.12%) or Nb (.12%),

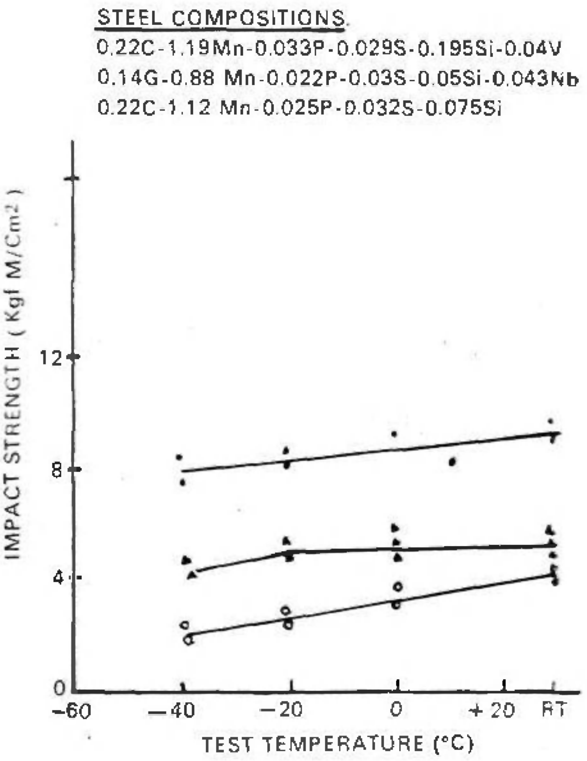

Fig. 3. Variation of Haz toughness property of three different X52 Grade Pipe Steels.

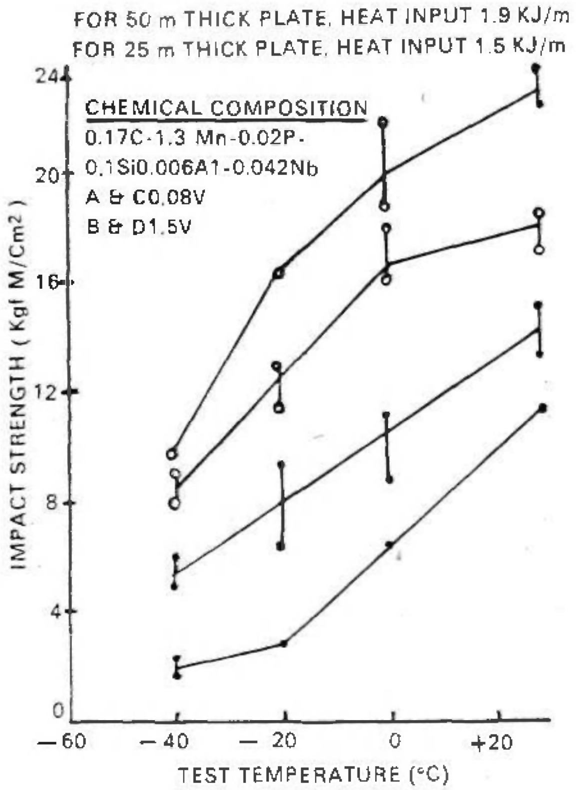

Fig. 4. Effect of Vanadium on the toughness of HSLA Steels.

content, the precipitation hardening appears to be sufficiently strong which brings down the stress relieved properties despite the degeneration of heavy segregation of retained martensite. Besides this, high percentage of microalloying element causes an increase in dislocation density associated with the finely dispersed carbides, resulting in increase in internal stresses.

In conclusion, a higher toughness property of the weld metal in submerged arc welding of microalloyed steels could be achieved by restricting the transfer of micro additions into the welding by establishing acceptable levels of micro-additions content in steels and by the use of suitable welding procedure.

Conclusions

1. Crack nucleation and arrest can be successfully predicted from C.O.D. and Charpy property respectively. The estimated critical crack length for the parent metal at room temperature is 20.4 mm and the minimum required charpy value to produce crack arrest for the parent metal is 15 J at room temperature, when operating stress does not exceed 62% of the specified minimum yield stress.

2. Weldmetal toughness property is found to be inadequate when Automelt grade II flux is used in combination with WHS 2 MO electrode wire.

3. Higher Vanadium bearing High Strength Low Alloy Steel plates found to have detrimental influence, irrespective of plate thicknesses and heat input.

4. Vanadium bearing X-52 grade pipe steel with little higher Mn content has better H.A.Z. toughness property compared to Nb bearing and plain C-Mn steels.

5. In Submerged Arc Welding, higher weldmetal toughness property could be achieved by controlling the amount of microalloying elements in the weld pool and suitable selection of welding process.

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