THE HISTORY AND DEVELOPMENT OF A NEW SOHIC TEST METHOD

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Abstract

Stress Orientated Hydrogen Induced Cracking (SOHIC) has been the mechanistic cause of a number of pipeline and pressure vessel failures, operating under sour service conditions. The crack morphology is now recognized in NACE MR0175/ISO 15156 as being caused by an independent mechanism. Within the Testing Appendix the standard says "other test methods under development can be used," such a method is now available. Previous test method NACE TM0103, published by NACE, has now been withdrawn. This paper will follow the history of SOHIC, the development of a new small-scale, short duration test method, and the possible relationship with hardness and microstructure. Now that a true test method is available, the mechanism of SOHIC can now be better studied and understood. Finally, the control of yield strength and ferrite hardness by use of niobium will be considered.

Introduction

Stress Orientated Hydrogen Induced Cracking (SOHIC) was first reported in the early 1980s during a testing program aimed at qualifying spiral welded linepipe for sour service [1]. It was immediately recognized that residual stress played an important part in promoting the cracking mechanism. From the early work a test method was developed and eventually published as OTI95635 [2] by the UK Health and Safety Executive (HSE). This method was called the Full Ring Test, and by its name the method was designed for linepipes, using a full section of linepipe as the test piece.

Over the course of some years, an API sponsored project was undertaken and a test method was eventually published by NACE International (TM0103) [3]. This method used what was termed "double beam" samples. This method has subsequently been withdrawn at the instigation of the original author. Thus a void in the testing armoury still exists.

A significant number of years ago, three organisations: Bodycote (now EXOVA), Force Institute and TWI, joined forces in an attempt to design and validate a genuine SOHIC test method. After 7 years of work, a method has been defined that can be used on both pressure vessel plate and linepipe (although the Full Ring Test is still favored for circumferentially welded pipe). This work was followed up by a student from Aalen University undertaking his Bachelor Thesis on the test development – Ulrich Pflanz [4].

Now that a test method is available, the study of the cracking mechanism can begin. In the following sections, examples of SOHIC failures will be given, the new test method will be described with early results, and further work will be proposed that will lead to the understanding of this cracking mechanism. One such study has already been started and the first results will be published at the NACE 2013 Conference in Orlando.

Background

SOHIC has been reported as the failure mode on at least 12 major pipelines, in addition, numerous reports of SOHIC occurring in pressure vessels are in the literature. Reference [5] contains some details of documented failures. Figure 1 illustrates a SOHIC pipeline failure. Figure 2 illustrates a micrograph of a SOHIC crack.

Figure 1. SOHIC failure of spiral welded pipe, courtesy Shell Canada.

Figure 2. Microstructural features of SOHIC.

Generally the cracking is known to occur adjacent to a weld, however, one reported failure in Germany was in seamless pipe [6]. Results from the early investigations indicated the importance of residual stress, not only its magnitude, but also and probably more importantly, its direction.

Figure 3 illustrates the residual stress effect in a large diameter linepipe. Besides overlap, longitudinal displacement can be also observed.

Figure 3. Residual Stress, a “Critical Factor” – cut section of linepipe exhibiting displacement due to residual stress.

ISO 15156/NACE MR0175 [7] and EFC 16 [8] attempt to account for the loss of residual stress when a small sample is cut from a plate or pipe by increasing the load conditions. However, this applied load is all in the same direction and does not reflect the true stress distribution. A tri-axial stress is required to simulate the real conditions. Hence, some of the test methods cited in the test standards will not show if a material is SOHIC susceptible or not.

In addition to these observations, both EXOVA and a major oil and gas exploration company have encountered a number of instances where fittings exposed to hydrogen sulphide in laboratory tests, exhibited SOHIC. Figures 4, 5, and 6 illustrate such SOHIC failures. In all cases the materials were well below the Rockwell Hardness threshold for cracking (22 HRC) and had good, clean microstructures.

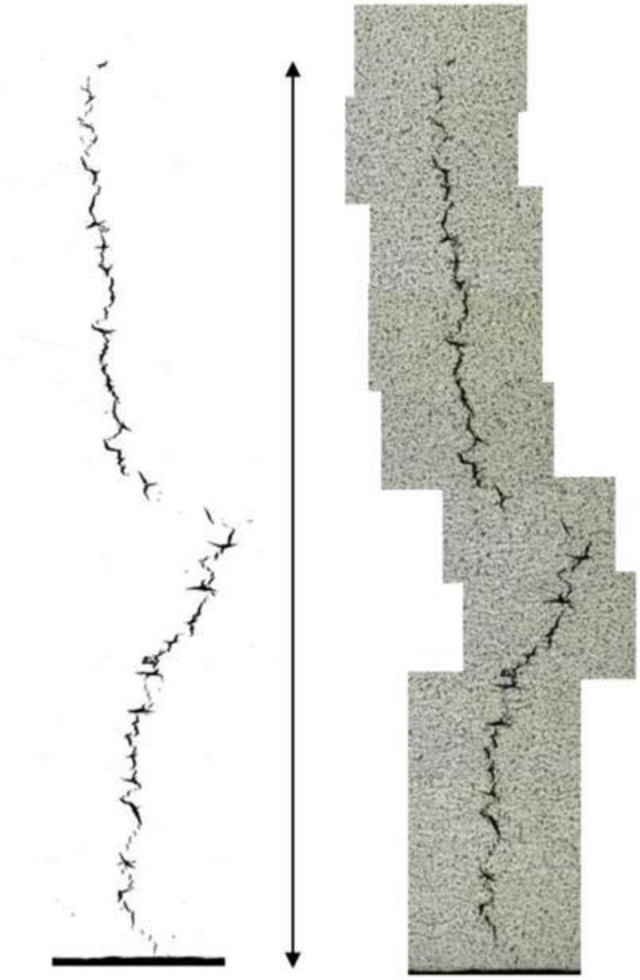

Figure 4. SOHIC in a “T” piece.

Figure 5. SOHIC in a dished end.

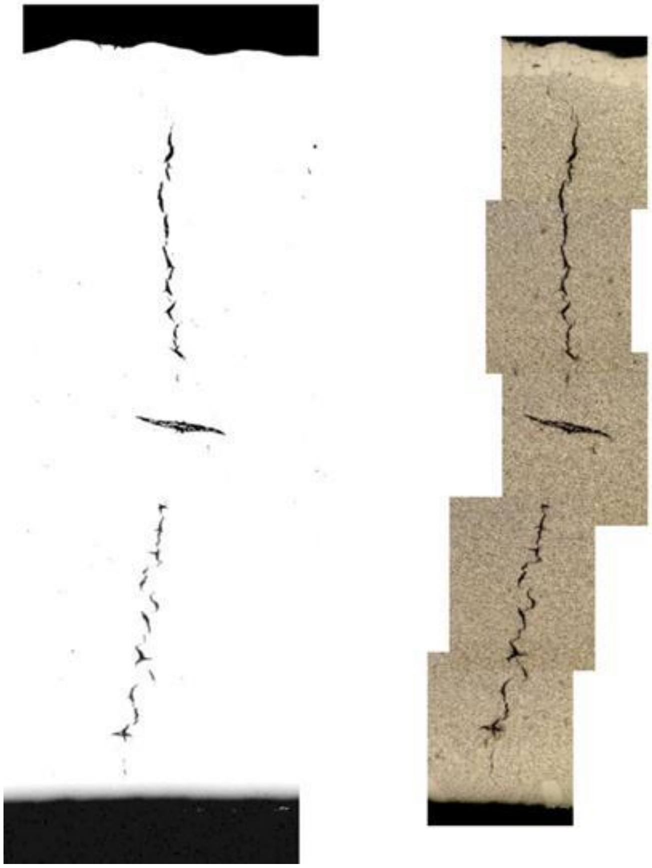

Figure 6. SOHIC in a reducer.

Thus the project aims were:

- Small scale test method;
- Short duration;
- Definitive Go/No Go test criteria;
- Reproducible.

Experimental

From the outset of this work, the complex stress distribution within linepipes and particularly welded linepipes, was recognized**.** Some residual stress measurements have been performed, however, they only provide the residual stress levels up to 1 mm from the surface. So, a more direct approach was embarked upon.

The concept of 'twist and bend' was chosen, because when a spiral pipe is pressurized the weld is effectively twisted, and as most failures have been in spiral pipe it was logical to start with this assumption.

Several carbon steel materials were available, some known to be SOHIC resistant and some with known susceptibility.

In outline, an extended four point bend sample was chosen that could also have a small degree of twist imparted.

The design of a suitably useable rig was the most challenging part of this work; several designs were built and discarded prior to the eventual final approved design.

The details of the design work are contained in the Thesis of Ulrich Pflanz [4].

The original plan was to load the different materials to set angles of twist, viz., 5, 10, 15 degrees, etc., and then apply a four point bend load. As the testing program went through an iteration process, it became evident that only a small amount of twist was required to separate good from poor material, and eventually a 2 degree twist and 50% SMYS (specified minimum yield strength) bend was settled upon.

The final rig design is shown in Figure 7. The full details and dimensions will be published later this year.

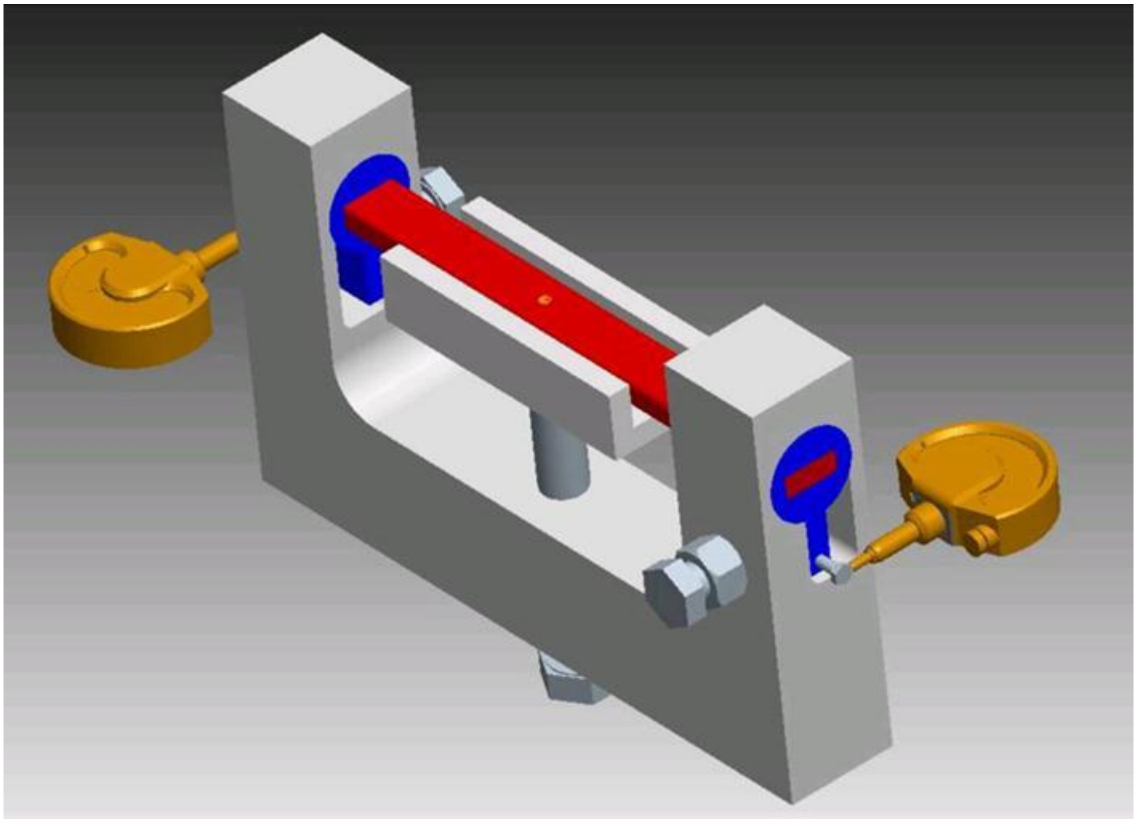

Figure 7. New SOHIC test rig.

Load stability trials were undertaken, and strain gauges were used throughout to monitor loads and strains.

Results

In essence, numerous trials were undertaken at different load/twist levels on several materials.

Figure 8 illustrates a typical set of samples post exposure test.

All exposure testing has been undertaken at 25 ^{o}C, using NACE Solution A for a 10 day duration.

As stated earlier, a 2 degree twist is all that is required if a material has a SOHIC susceptibility. For materials that did not show cracking, a 25 degree twist was used and cracking was not generated. (The samples remained twisted after test.)

As can be seen in Figure 8 the data does not need much interpretation, the SOHIC cracks are clearly visible to the naked eye.

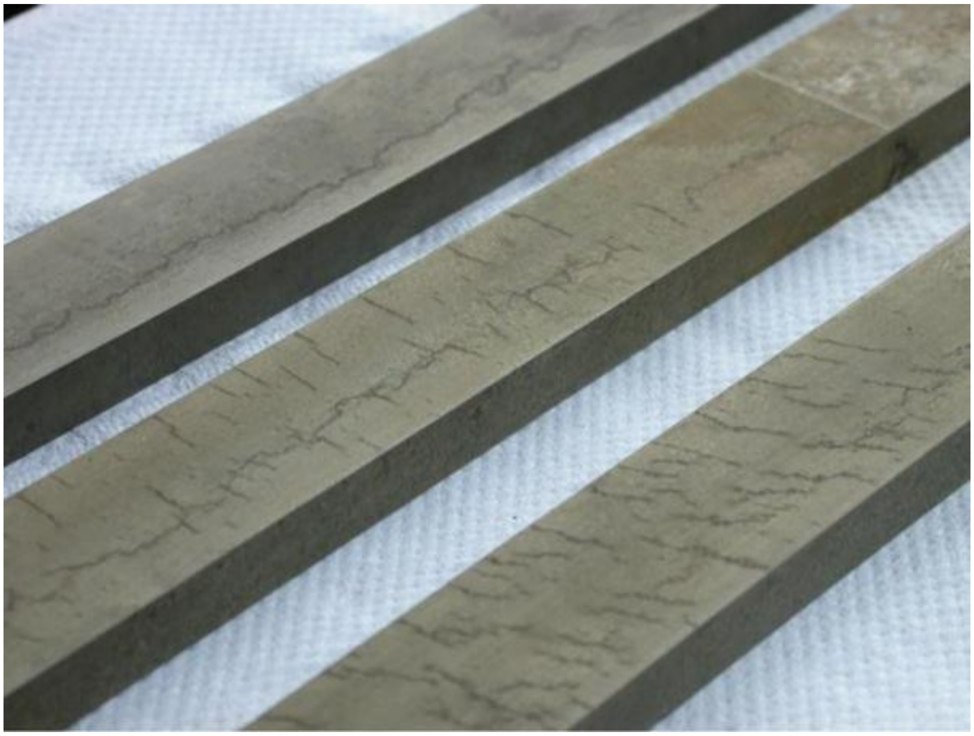

Figure 8. Test Results - Control, 2 degree, and 5 degree twist (from left to right).

Metallurgical Perspective

The metallurgy of steels for use in sour environments has advanced steadily since the early 1970s following the unfortunate accident involving a BP pipeline in the Arabian Gulf.

Great emphasis has been placed on reducing HAZ hardnesses to less than 248 HV 10 which simultaneously improves SCC resistance and eliminates any risk of hydrogen related delayed cracking.

Current steels are typically Nb-V, Nb-Mo or Nb-Cr designs and derive their excellent combinations of strength and toughness from low temperature controlled rolling practices, followed by rapid cooling with water, ie. the so-called Thermomechanical Controlled Processing (TMCP) technology.

The excellent SSC and delayed cracking resistance are attributable to the low carbon content and particularly low Pcm values. Thus, hardnesses are very low even when low heat input welding processes are used, such as when girth welding using mechanized processes (Figure 9). The headlong rush to move to lower and lower carbon and alloying contents to facilitate low heat input welding may have overlooked or neglected potential concerns for HAZ softening at higher heat inputs that are associated with the pipe seam weld and double joint girth welds produced by submerged arc welding. The longitudinal weld may involve a heat input, when using a multiple arc set up, of 6.0 kJ/mm or higher, and the double joint process up to 4.0 kJ/mm. One may also encounter intermediate heat inputs for weld repairs.

The likelihood of troublesome HAZ softening is illustrated by the data in Figure 9. When such steels with Pcm values between 0.10 and 0.14 are welded with a heat input of 3.5 kJ/mm (35 kJ/cm) the hardness approaches the levels associated with the incidence of SOHIC in the present paper. Higher heat inputs could definitely lead to problems. Furthermore, the steel in Figure 9 contained 0.095% niobium (plus 1.57%Mn and 0.27%Cr), whereas lower levels of niobium and absence of chromium would have accentuated the softening tendency.

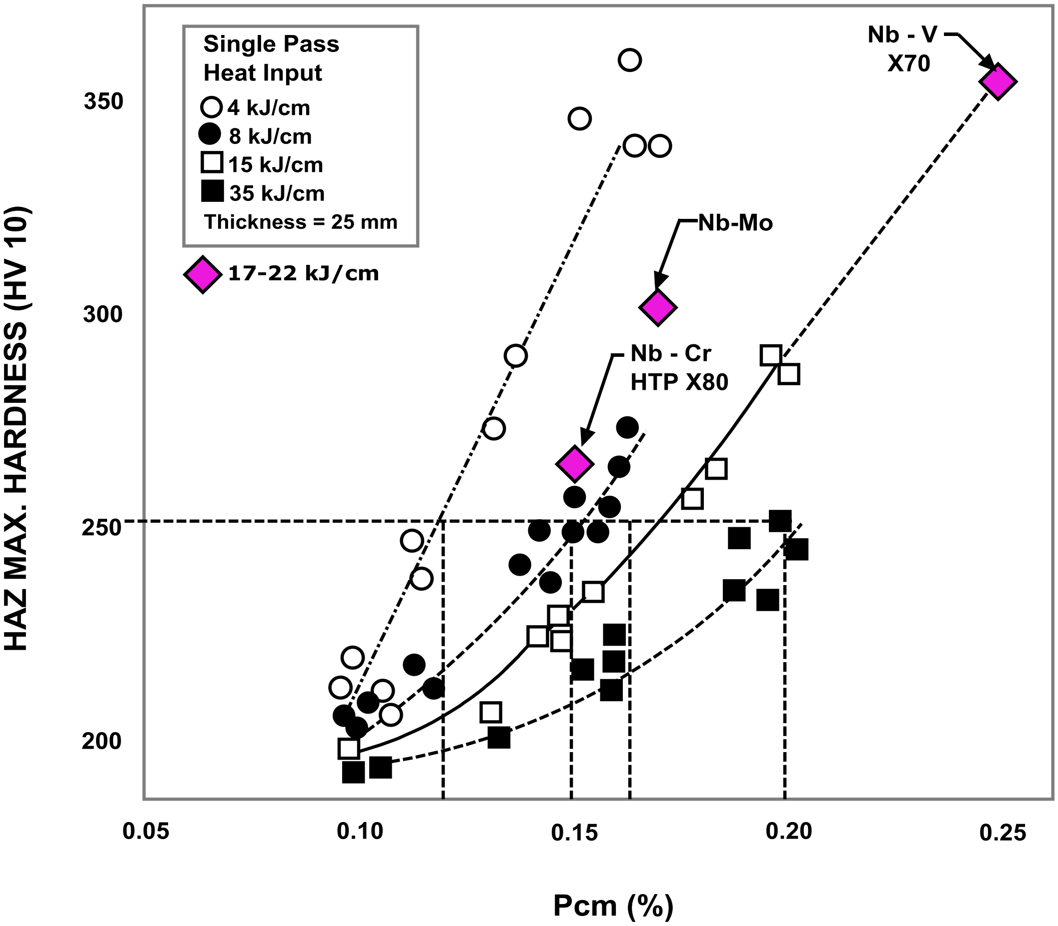

Figure 9. Effect of carbon equivalent (Pcm) and heat input on HAZ hardness of 0.03%C 1.57%Mn 0.27%Cr 0.095%Nb X70 linepipe [9].

Issues related to HAZ softening have generally surfaced when welding ultra high strength steels having yield strengths of 80 ksi and above, or when the linepipe was to be installed and operated using strain-based design principles.

The present paper now suggests that even lower strength steels, such as X60 to X70, may suffer degradation due to SOHIC cracking when they are not properly formulated to be reasonably resistant to softening.

When a TMCP steel is welded, the mechanical properties developed via that thermomechanical process are basically destroyed and replaced in the HAZ region with microstructures which depend on the austenite to ferrite transformation temperature, which is a function of chemical composition and cooling rate, Figure 10.

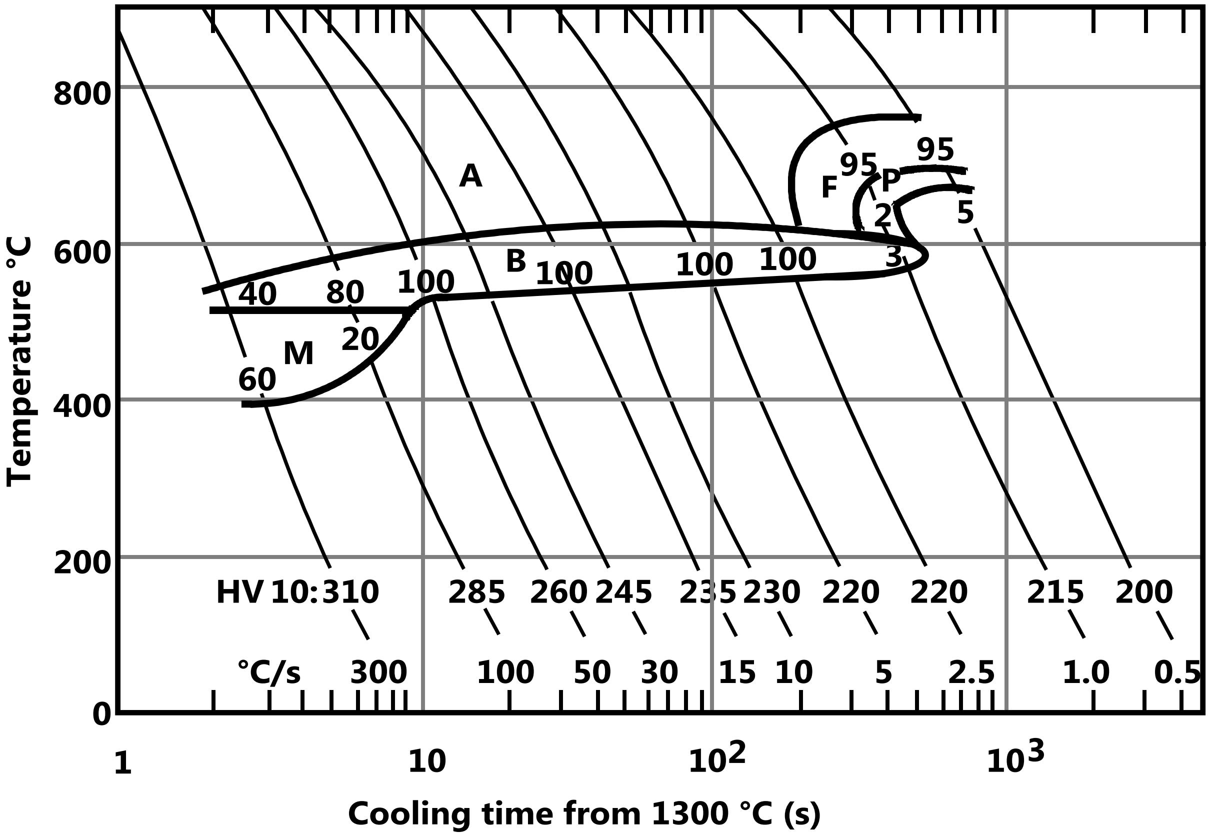

Figure 10. Transformation behaviour for simulated HAZ (peak temperature 1350 °C) of HTP steel with 0.03%C - 0.10%Nb and 1.75%Mn [10].

In the case of this heavily microalloyed steel, the hardness in the simulated HAZ does not fall below the "SOHIC threshold" until the 800 to 700 °C cooling rate drops to 0.40 °C/s. Such cooling rates are associated with welding processes such as flash butt welding which are rarely used or promoted today for these applications. However, the particular steel in question stood up well when joined by that process, Figure 11.

It should be recognized and noted that more conventionally formulated Nb-V linepipe steels performed poorly during SAW, tending to have HAZ hardnesses which can drop below HV 10 190 even at moderate heat inputs, as shown in Table I.
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Table I. Hardness Traverses (HV 10) for DSAW Weld in 30 mm X65 Linepipe.
Heat Input 6 kJ/mm

Location	**Body**			**HAZ**			**Weld**			**HAZ**			**Body**		
OD	217			177	188	191	216	211	208	191	178	165			218
Center	196			171	174	193	212	208	215	190	170	174			197
ID	219			178	185	192	219	210	217	196	188	185			215

CHEMICAL COMPOSITION wt.%						
C	Mn	Cr	Nb	V	Ti	Pcm
0.04	1.54	0.17	0.045	0.02	0.013	0.14

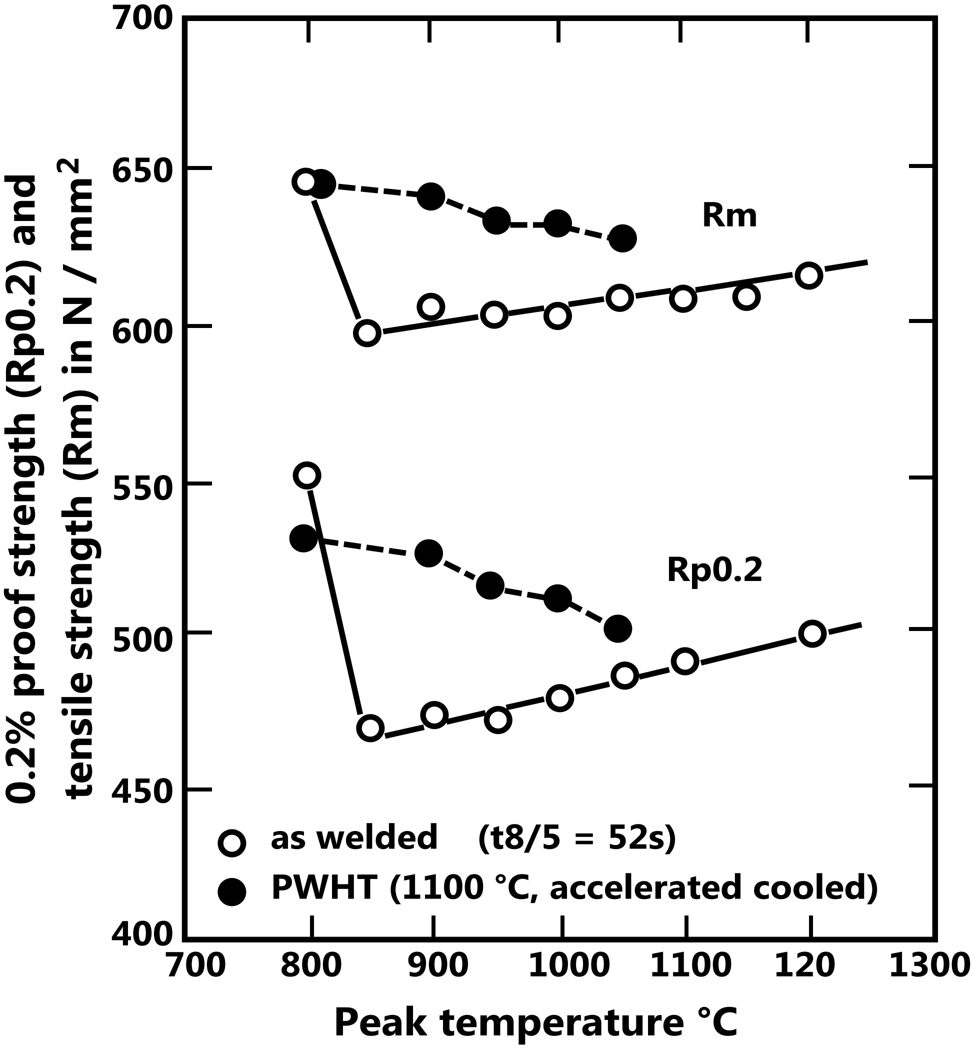

Figure 11. Tensile properties of a flash butt weld [10].

Hardness traverses for two X80 steels, having the chemical compositions shown in Table II, are presented in Figures 12a and 12b.

Table II. Chemical Compositions of X80 Steels Submitted to Hardness Measurements

Steel	Sampling	Chemical Composition (wt.%)											CE
		C	Si	Mn	P	S	Mo	Nb	V	Ti	B	Al sol	
A	Product	0.07	0.28	1.66	0.017	0.001	0.13	0.033	0.075	-	-	0.035	0.39
B	Product	0.05	0.21	1.89	0.011	0.001	0.25	0.044	-	0.025	0.0014	0.035	0.42

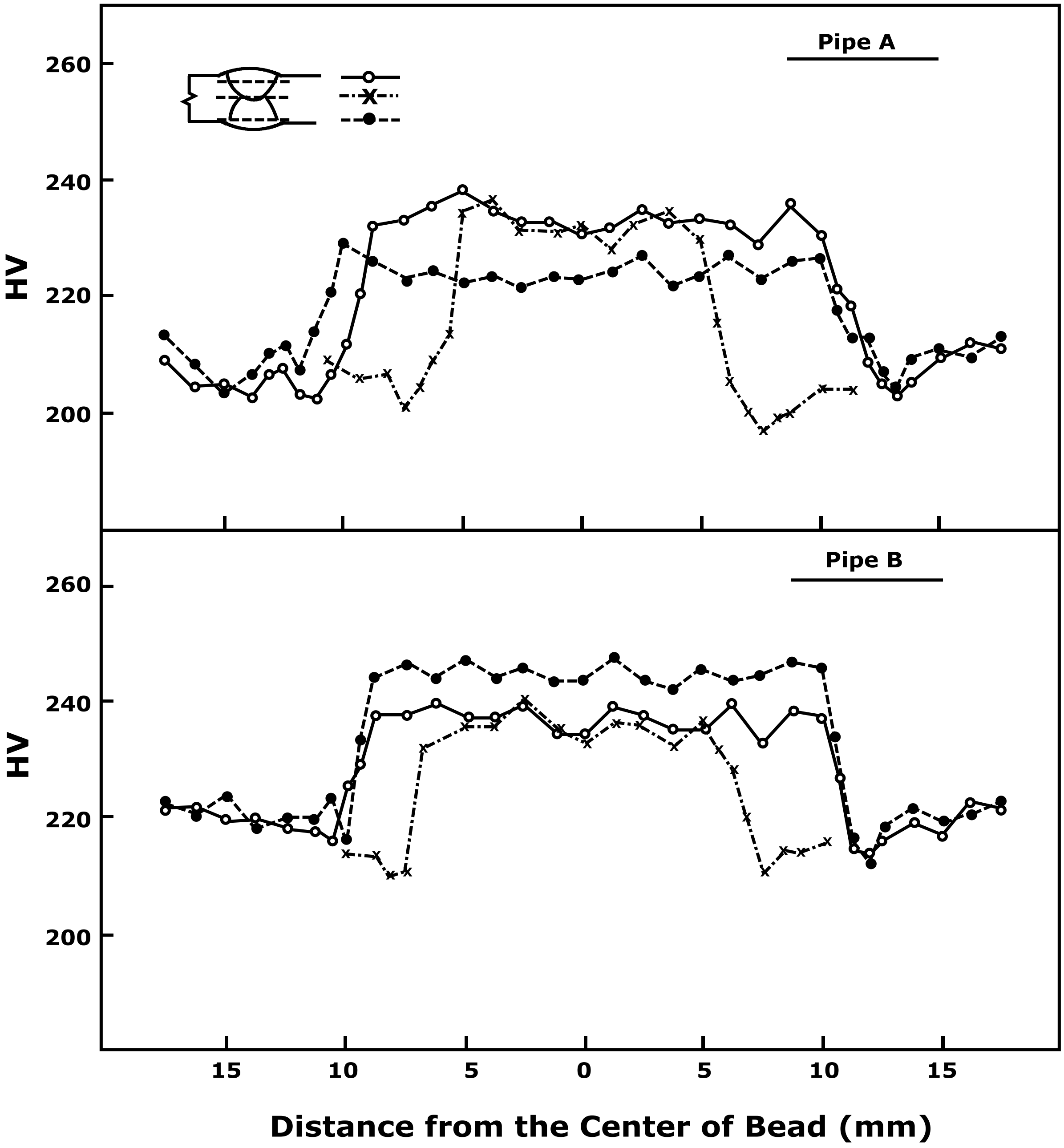

Figure 12. Hardness distribution of seam welds in 48" OD x 0.75" wt pipe, welded with a heat input of 4.7 kJ/mm [11].

Further investigation of the interactions between hardness, microstructure and residual stress on SOHIC resistance is clearly required.

Conclusions

A dedicated SOHIC test method which is reproducible and has a short duration, has been developed which can be used for both pressure vessel steels and linepipe steels.

Although validated in-house, an interlaboratory validation needs to be undertaken and welded samples need to be used to check the loading requirements.

Further Work

The effects of the following variables on SOHIC susceptibility now need to be investigated:

- Manufacturing Route;
- Microstructure;
- Hardness;
- Chemistry;
- Weld and HAZ Properties;
- Level of Hydrogen Charging.

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