

CRANFIELD UNIVERSITY



P. M. R. BARBOSA

**DEVELOPMENT OF A TEST GEOMETRY FOR EVALUATING
THE HYDROGEN CRACKING SUSCEPTIBILITY OF HIGH
STRENGTH GMA WELDING CONSUMABLES**

SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE

MPhil THESIS

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DEPARTMENT OF OFFSHORE AND OCEAN TECHNOLOGY

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STRENGTH GMA WELDING CONSUMABLES**

SUPERVISOR: Dr. J. SPURRIER

SEPTEMBER 2002

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ABSTRACT

This thesis presents the work developed at Cranfield University through a research programme on the hydrogen cracking susceptibility of multipass girth welds of X-100 steel pipeline produced by the gas metal arc welding process (GMAW).

The work aimed to develop a test geometry able to test very low hydrogen content GMAW consumables available in the market. A number of weldability tests were studied and the Welding Institute of Canada Test (WIC) was selected as the initial configuration to be adjusted because of its simplicity and proved correlation of its results and field data in the past.

A simplified one dimensional model of intensity of restraint was derived and the influence of the main geometrical parameters on the intensity of restraint was studied. The restraint length and the sectional area of the restraint plates combined with different groove preparations were employed to achieve four test configurations of successively increased severity.

One particular configuration proved to generate hydrogen cracks and discriminated between the two consumables tested. Another configuration achieved to induce hydrogen and solidification cracks but was considered too much severe as it did not discriminate between those consumables.

Additional adjustment of restraint length and the cross sectional area of the restraint plates in the plane perpendicular to the weld direction were performed. An optimal configuration prevented the occurrence of longitudinal cracking and induced transverse cracks typical of pipeline girth welding.

This work studied a range of heat input from 0.3 to 0.6 kJ/mm. It was found that minimum values of heat input were not always the most critical for hydrogen cracking. It is suggested that there may be significant differences in the residual stress (as a result of the weld heat input) and that these stresses also influence the onset of cracking.

The optimal configuration obtained was sensitive to consumables of very low hydrogen content and discriminated between the consumables tested. In order the test configuration can be validated, further tests are needed covering a wider range of consumables.

Unless the LORD builds the house, its builders labour in vain. Unless the LORD watches over city, the watchmen stand guard in vain.

In vain you rise up early and stay up late, toiling for food to eat – for he grants sleep to those he loves. (Psalms 127:1,2)

“Seaman i am, nothing but a seaman i want to be.”

Marquee of Tamandaré
Patron of the Brazilian Navy

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Appendix B – Procedure specification of small scale restraint cracking test applied to multipass GMAW and consumables with very low hydrogen content.

Appendix C – Procedure for determination of hydrogen content in ferritic steel GMAW.

NOTATION

ADWM – As deposited weld metal
AGA – American Gas Association
API – American Petroleum Institute
 A_s – Sectional area of restraint plates in a SSRC test
AWS – American Welding Society
B – Weld bead length
BM – Base metal
BWRA – British Welding Research Association
CLR – Controlled load rupture test
CPT – Circular patch test
e – eccentricity
h – Plate thickness
HACC – Hydrogen assisted cold cracking
HAZ – Heat affected zone
HICC – Hydrogen induced cold cracking
 h_w – Weld bead thickness
IG – Intergranular fracture mode
IIW – International Institute of Welding
IOM – The Institute of Materials
JOM – Institute for the Joining of Materials
K – Intensity of restraint
 K_e – Intensity of restraint corrected by eccentricity
L – Restraint length
MVC – Microvoid coalescence fracture mode
NCPT – Navy circular patch test
QC – Quasi cleavage fracture mode
 r_f – Root face
 R_G – Root gap
RRC – Rigid restraint cracking test
SAW – Submerged arc welding
SSRC – Small scale restraint cracking test
TMS – The Minerals, Metals and Materials Society
TRC – Tensile restraint cracking test
TWI – The Welding Institute
WIC – Welding Institute of Canada

WM – Weld metal

WTIA – Welding Technology Institute of Australia

γ – eccentricity factor

1 INTRODUCTION

This thesis presents the work developed at Cranfield University through a research programme on the hydrogen cracking susceptibility of multipass girth welds of X-100 steel pipeline produced by the gas metal arc welding process (GMAW).

High strength low alloy (HSLA) steels can provide significant benefits in terms of design efficiency, economics and performance in several fields of industry [1].

The pipeline industry provides a remarkable illustration of that issue. For a typical 500 km long onshore pipeline, welded by a state of the art mechanised GMAW process, the employment of a 46 in diameter X100 pipe can lead to savings in the order of millions of pounds of installation if compared with a 58 in diameter X65 pipe [2]. In addition there is the advantage of achieving increased operating pressures, which in the case of gas transmission, can result in either the transport of a greater volume of gas in a given time period or the ability to transport over longer distances. A pressure transmission of 15 MPa is expected to be achieved with the X100 pipe against approximately 10 MPa contemplated by the standard in vogue [3].

Nonetheless, materials, procedures, standards and tests have to be developed, adapted and qualified if the new grade of steel is to be safely and efficiently used in welded structures. Intensive research and development have been done to lay the experimental foundation needed for X100 steel to be employed in new pipeline projects in the near future [4].

Hydrogen assisted cold cracking (HACC) is a serious problem of weldability, for which the traditional solution in terms of pre-heating and post-heating demands massive costs, not to mention the difficulties of inspection because of the amount of time delay that can occur in crack formation.

Historically, greater risks of HACC have been found in the heat-affected zone (HAZ) than in the weld metal. The reason was the formation of susceptible microstructures in the HAZ as a result of rapid cooling. Weld metal cracking was a concern only in the root pass of a multi-pass weld, due to parent metal dilution into the weld metal allied to applied loads and geometrical defects with consequent elevated stresses at the root. However, this risk has been reduced through the development of HSLA steels, which do not develop hard, susceptible HAZ.

The strength and toughness of higher strength steel pipe (X100 and above) is controlled through a combination of lean alloy design and thermo-mechanical processing. However, for the weld metal to match or overmatch the base material strength and to present an appropriate level of toughness, increased alloying through the welding consumable is needed. This high degree of alloying combined with relatively high cooling rates can result in a greater susceptibility to hydrogen cracking in the weld metal than in the heat affected zone (HAZ). Therefore, the focus of HACC concern has changed from the HAZ to the weld metal.

Besides the improved weldability of HSLA steels, welding procedures to avoid cracking in the HAZ and in the WM have been sought. At the same time, new welding consumables have been developed to combat the problem, notably of very low hydrogen content ($H_D < 5 \text{ ml/100g}$).

In the past, a number of weldability tests to assess the HACC susceptibility were developed and employed to determine safe welding parameters for cracking avoidance, to rank consumables and processes in terms of cracking susceptibility and also to provide a research tool for studying the main HACC causal factors.

Those tests, however, were conceived and correlated to weldments with greater cracking susceptibility in the HAZ than in the weld metal, and for consumables with hydrogen content as high as 40 ml /100 g. Hence, a suitable weldability test compatible with the new field situation is required.

The Welding Institute of Canada test was introduced in the early 1980's. It was originally a general high restraint test for hydrogen cracking susceptibility testing in low carbon steels and was subsequently modified to evaluate the root pass of a girth weld [5]. The test has proved to be useful for assessing the hydrogen cracking susceptibility of root pass welds performed with high hydrogen cellulose electrodes.

Among several others HACC susceptibility tests, the WIC test was chosen to be the principal test to be studied in this research programme, due to its simplicity and economy, besides the good correlation with critical preheat temperatures obtained in full scale tests.

Previous work at Cranfield University [6] adapted the WIC test to simulate the GMAW process for pipelines. The adapted test was applied to a high strength TMCP steel and

two wires. Such work provided initial welding parameters and conditions for this investigation.

The primary aim envisaged in this research programme was to develop a weldability test for evaluating the HACC susceptibility of GMAW high strength weld metals applicable to the multipass girth welding of pipelines.

2 LITERATURE SURVEY

2.1 HYDROGEN CRACKING

The AWS definition for hydrogen embrittlement, '*Hydrogen embrittlement is a condition that causes a loss of ductility and which exists in weld metal due to hydrogen absorption. In some metals the loss of ductility induces cracking*' [7], implies hydrogen embrittlement and the induced-cracking as different phenomena. Nonetheless, the literature has been treated hydrogen cracking and hydrogen embrittlement as the same problem [8-10].

Hydrogen cracking, hydrogen assisted cold cracking, hydrogen induced cold cracking, underbead cracking and delayed cracking are terms used by different authors that refers to the same problem of weldability. In this work the term HACC is preferred to the others and refers to the cracking phenomenon occurring in steel welds, which is caused by the presence of hydrogen among others factors later discussed.

The main characteristics of hydrogen embrittlement in steels are in general as follows [11;12]:

- a) Materials that exhibit a body-centred cubic (bcc) *crystal structure*, i.e. ferritic and martensitic steels are more susceptible to hydrogen embrittlement. Materials with a face-centred crystal structure are usually not sensitive to hydrogen, like austenitic stainless steel and aluminium alloys.
- b) Susceptibility to hydrogen embrittlement is influenced by the *microstructure* of the steel. Martensitic steels are more prone to hydrogen cracking than ferritic steels, although a martensitic structure is not a requirement for crack initiation.
- c) The degree of embrittlement depends on the *carbon content* in the metal.
- d) Hydrogen cracking occurs ordinarily within the *temperature* (T°) range from -150 to $+200$ °C.
- e) For hydrogen embrittlement is a diffusion-controlled process, the cracks propagate in a stepwise manner. *Time* is needed to allow hydrogen from the surrounding matrix reaches the crack tip.
- f) Hydrogen embrittlement is more revelant at low *strain rates* typical of tensile testing. At high strain rates the hydrogen diffusion does not keep pace with the fracture development.

- g) The degree of embrittlement depends on the value, type and distribution of *stresses*.
- h) *Stress concentrators* enhance the hydrogen action.
- i) Embrittlement can be caused by *hydrogen concentrations* below 1 ml/100 g of metal.
- j) The mechanical characteristics of an embrittled metal can be recovered after removal of hydrogen (*reversible* brittleness) but if a certain critical level of hydrogen concentration is exceeded or the time of its interaction with the metal is increased, the brittleness becomes *irreversible*.

2.1.1 PROPOSED MECHANISMS

Over the years several theories have been formulated to explain the mechanism of hydrogen embrittlement. Nonetheless, there are inherent difficulties in each theory and they seem not to be mutually exclusive.

Much experimental work is needed to provide a universally accepted model for the hydrogen embrittlement phenomenon [13;14] and which mechanism or mechanisms are operative under welding conditions is a remaining question [12].

The following summary on the main theories of hydrogen embrittlement mechanisms is based on reviews provided by the literature [15-17].

2.1.1.1 INTERNAL HYDROGEN GAS PRESSURE ON MICROVOIDS

This theory proposed by Zappfe [18], assumes that dissolved H atoms diffuse through the lattice to pre-existing voids and discontinuities. A very high pressure is reached when the H atoms combine to form molecular hydrogen. The pressure developed by this precipitation is added to the applied stress, lowering the apparent fracture stress.

It has been argued [11] that this effect can not explain several features of reversible hydrogen brittleness, especially the effect of extra low concentrations of dissolved hydrogen unable to provide the critical pressure needed.

2.1.1.2 DECREASED SURFACE ENERGY DUE TO HYDROGEN ABSORPTION

According to Petch and Stables [19;20], cracking is promoted because the surface energy of the surfaces created in crack propagation and the work of fracture are lowered by hydrogen adsorption, in agreement with Griffiths's theory. Since this process is dependent on the diffusion of hydrogen to the crack tip, the theory would explain the variation in the embrittlement with temperature and strain rate.

Pokhodnya [11] pointed out that this theory does not explain why hydrogen embrittles a metal, while oxygen, whose adsorptive effect is stronger according to the same calculations, suppresses the action of hydrogen. Still according to this author [11], the Griffiths's theory assumes the presence of pre-existing cracks in a material without any explanation of their origin.

2.1.1.3 DECOHESION OF ATOMS IN LATTICE REGIONS WITH A HIGH HYDROGEN CONCENTRATION

Oriani [21] and Troiano [22] stated that the cohesive strength of the lattice is reduced by the dissolved hydrogen accumulated in regions of very high elastic stress within a few atomic distances from crack tips. This theory was originally based on the observation that hydrogen-induced failures often show little evidence of plastic deformation, and result in flat inter-crystalline or cleavage fracture faces.

According to the theory, this hydrogen stress-induced diffusion depends on the initial hydrogen concentration, the hydrogen diffusion rate and the time for hydrogen to diffuse. The crack may initiate in the lattice at the point of maximum triaxiality at a critical combination of stress state and hydrogen concentration, because the fracture strength or the bonding energy of the lattice is lowered in that zone.

The decohesive effect of hydrogen is difficult to be proved by direct experimentation and this hypothesis is weakened before the fact that catastrophic failure can occur at hydrogen concentrations below 1 ppm [11].

2.1.1.4 SLIP SOFTENING DUE TO ENHANCED DISLOCATION MOBILITY

This model stands for the enhanced local plasticity rather than a truly embrittlement of the lattice. Beachem [23] suggested that the presence of sufficient hydrogen in the lattice just ahead of the crack tip, interferes with dislocations and favours different types of fracture, including microvoid coalescence, quasi-cleavage fracture and intergranular fracture.

2.1.1.5 DECREASED SURFACE TENSION DUE HYDROGEN ION LAYER FORMATION AT THE CRACK'S SURFACE

More recently, Pokhodnya and Shvachko [24] studied the state of hydrogen in iron by secondary-ion mass spectrometry method, which allowed a precision of an atomic monolayer. It was found an intensive emission of secondary negative hydrogen ions H^-

from hydrogen-saturated samples, which decreased with time, while the emission of positive hydrogen ions H^+ was independent of time. Based upon iron surface work function and electron affinity of hydrogen considerations, the researchers concluded that the atoms in the metal surface had a negative charge.

The resulting theory states that a formation of a layer of the negative hydrogen ions at the recent surface of a crack initiated in the bulk of the metal should lead to a decrease in the surface tension, which eventually should lead to a change in its behaviour in the stress field.

2.1.2 HACC CAUSAL FACTORS

Notwithstanding the uncertainty of the hydrogen embrittlement mechanism operative in welding conditions, the causal factors for its occurrence are well established and this knowledge has been largely employed to predict and prevent hydrogen cracking.

The four requisites to be fulfilled for HACC to occur are:

- a) Presence of hydrogen;
- b) Stress;
- c) Unfavourable microstructure; and
- d) Low temperature.

The conditions are interrelated. Figure 1 [25] highlights the interplay between the causal factors applied to the pipeline girth welding. In this particular application, the heat input provides an interesting example of influence on the four parameters. The main issue is that low heat inputs favour HACC in terms of temperature, microstructure and hydrogen effects. On the other hand, higher heat inputs are expected to provide greater thermal expansion and shrinkage with consequent greater stress levels.

2.1.3 HYDROGEN CRACKING MORPHOLOGY

Normally of intergranular nature, weld metal cracking follows the prior austenite grain boundaries of the columnar grains in the as-deposited weld. Nevertheless, depending on the strength of the steel, microstructure, stress intensity factor and concentration of hydrogen at the crack tip, weld metal cracking may exhibit different types of crack surface morphologies [26].

Beachem [23] found that in presence of hydrogen, increased stress intensity factor leaded to a change in fracture mode, from brittle intergranular fracture to quasi cleavage and finally transgranular microvoid coalescence.

Studying the crack morphology of a high-strength armour steel, Gedeon [27] observed that the stress intensity at which microvoid coalescence occurs decreases with increasing hydrogen in the crack zone.

Trevisan [28] used the implant test and the acoustic emission technique to test flux-cored arc welding of a high-strength low-alloy steel using CO_2 and $\text{CO}_2 + 5\% \text{H}_2$ as shielding gases. Different fracture modes were correlated to the acoustic emission signal. The study also found that for $\text{CO}_2 + 5\% \text{H}_2$ shielding gas, quasi-cleavage area increased with increasing stress.

According to Wang [17;29], the fracture mode of low carbon-low alloy weld metals changes with increasing strength of the material, from microvoid coalescence to quasi cleavage, quasi cleavage plus intergranular fracture and finally intergranular fracture along prior austenite grain boundaries.

The hydrogen-assisted cracking fracture mode in the HAZ is also influenced by the prior austenite grain size. Using slow bend tests, Kikuta [30] found that specimens with a fine prior austenite grain size fractured by quasi cleavage, while specimens with a coarse prior austenite grain presented intergranular fracture.

An increase in oxygen was found to cause an increase in intergranular fracture in 690 MPa weld metal [31]. The increase in Oxygen particles on prior austenite grain boundaries caused the change in fracture mode as they act both as hydrogen traps and as local stress concentrators.

Despite the variety of fracture modes associated with hydrogen-assisted cracking, Davidson [32] differentiates hydrogen-assisted cracking from weld metal solidification or liquation cracking by cracking fracture morphology (Figure 2). Engel and Klingele [33] present typical microfractographic features of hydrogen-assisted fracture (Figure 3 and Figure 4).

2.1.4 HYDROGEN CONTROL

Davidson [34] highlights the main areas of research with respect to hydrogen control which are presented in the following sections.

2.1.4.1 REDUCTION OF HYDROGEN CONCENTRATION AT POTENTIAL CRACKING SITES

2.1.4.1.1 Control of arc chemistry

The amount of hydrogen in the welding arc has been reduced by the development of flux systems with low baseline moisture content and low moisture pick up rates.

The other aspect is to prevent the hydrogen present in the arc from enters the weld pool, which can be achieved by modifying the chemistry of the welding arc plasma. Additions of selected oxides and fluorides in the flux decompose in the welding arc. Liberated oxygen and fluorine combine with hydrogen in the arc atmosphere, decreasing the hydrogen in the weld [35-37].

2.1.4.1.2 Hydrogen sensor

In-process sensors have been developed to measure the hydrogen concentration of the welding arc [38;39]. The spectra of the weld plasma are analysed and the arc hydrogen concentration is determined by comparing the relative intensities of the hydrogen and argon peaks. Figure 5 shows the effect of shielding gas on hydrogen as measured by this method.

2.1.4.1.3 Martensite start temperature

Granjon [40] identified the relative start temperatures of the weld metal and HAZ as an important factor in determining the location of HACC. Two situations should be considered:

a) Under-matching weld metal

When the weld metal is less alloyed than the parent metal, the weld metal has a martensite start temperature (M_s) higher than the parent metal, therefore the weld metal transforms first. The austenitic HAZ thus serves as a barrier to the rapid hydrogen transport from the transformed weld metal, causing a build up of hydrogen at the HAZ (Figure 6), which can lead to the occurrence of underbead cracking.

b) Over-matching weld metal

In cases where the weld metal is more alloyed than the base metal, high strength weld metals, the opposite phenomenon occurs. The martensite start temperature is lower in the weld metal than in the base metal, hence the base metal transforms first. The celerity of the hydrogen transport from the HAZ into the plate greatly exceeds the hydrogen transport from the weld metal, resulting in increased hydrogen content in this region

(Figure 6b). This may be a contributing factor to the increased likelihood of weld metal cracking of HSLA steels in comparison to conventional C-Mn steels [41].

2.1.4.1.4 Hydrogen trapping

When the weld pool solidifies, the concentration gradient makes the hydrogen to diffuse from the just-solidified weld metal. During this process, hydrogen may become entrapped at particular trapping sites like dislocations, grain boundaries, ferrite/carbide interfaces, etc.

Hydrogen traps are classified as irreversible or reversible traps, depending on whether they act purely as hydrogen sinks or accept hydrogen under some circumstances and act as hydrogen sources in others. In fact, both kinds of traps will liberate hydrogen at a sufficiently high temperature, which is a function of the trap energy. Hydrogen traps exert an influence on the likelihood of cracking, as they control the hydrogen availability at potential cracking sites.

The effect of hydrogen trapping on the diffusivity of hydrogen can be seen from Figure 7, which presents the apparent diffusion coefficient as a function of temperature. At 400 °C the apparent diffusion coefficient approximates to the lattice diffusion coefficient. The number of traps increases inversely to the temperature and to the apparent diffusion coefficient.

The transformation products also affect the number of reversible traps. Tempered martensite, for instance, will have more trapping sites than pearlite, owed to the increased surface area of the finer carbides in the martensite.

Welding consumables are being designed to use the effect of hydrogen trapping to reduce the amount of hydrogen available for transport to potential cracking sites, but adverse impacts of trapping additions, as in toughness, should be taken into account [34].

2.1.4.2 THE ROLE OF MICROSTRUCTURE

It is not clear which particular aspect of a microstructure determines its susceptibility to hydrogen induced cracking [42]. In general terms, the hydrogen induced cracking susceptibility of a microstructure varies in the same way as its hardness (strength) [43].

It has been pointed out that the particular microstructure used to achieve the strength has a greater influence on hydrogen embrittlement than its strength level per se [44], and

that hardness [45;46] and strength [47] are not absolute indicators of hydrogen induced cracking susceptibility.

In the case of weld metal hydrogen induced cracking resistance, the relationship between hardness and cracking susceptibility is also complicated by the welding parameters, which affect both the hydrogen concentration and hardness. Previous work that studied the HACC susceptibility of HSLA steels using the RRC test and the Tekken test found that microstructure was the dominant factor in contributing to cracking below a certain level of heat input [48].

The work of Hobson and Sykes [47] illustrated the dependence of hydrogen assisted cracking resistance on both strength and microstructure. They found that the embrittlement of a quenched 3% Cr-Mo steel decreased with the strength level down to 750 MPa, but then increased as the strength was decreased further. The spheroidisation of carbides occurred at increased tempering temperatures used to obtain the lower strength levels was responsible for the change in behaviour.

It has also been suggested that microstructures with low toughness are more susceptible to hydrogen induced cracking [49], although the relationship does not always hold and the correlation between toughness and hydrogen induced cracking resistance is not a proof of a causal relationship [42]. The physical process of fracture during a toughness test is normally different from the fracture occurring during hydrogen-assisted cracking and its fracture mode can vary for the same material depending on the hydrogen concentration at the crack tip and the stress intensity factor [23;49;50].

2.1.4.3 REDUCTION OF RESIDUAL STRESSES IN WELDMENTS

Residual stresses are caused by non-uniform thermal contractions during the weld cooling, supplying the driving force for hydrogen induced cracking [34].

Pre-heating of the weld preparation and surrounding base metal may reduce the residual stresses to an extent. The non-uniformity of cooling is reduced, allowing more time for the stress relaxation as the weld metal cooling rate is decreased. Post-heating of the weld region is also employed and is a stress relief measure.

Pre-heating and post-heating temperatures used will depend upon the composition of the steel and the degree of restraint present.

2.1.4.4 COOLING RATE CONTROL

Decreasing values of cooling rate, also translated as increased values of $t_{8/5}$ (time to temperature change from 800 to 500 °C) or t_{100} (time to temperature reaches 100 °C) allows more time for hydrogen to diffuse away from the weld (see 2.1.6.3 and 2.1.6.4).

The heat sinking is provided by the plate thickness and the thermal paths available for the heat flow. See Figure 8 for the concept of thermal path proposed by Cottrell [51].

The cooling rate control is normally achieved by proper choice of heat input (see Figure 9) and the application of pre-heating.

2.1.5 PREDICTIVE METHODS FOR PREVENTING HACC

Dearden and O'Neil [52] (cited by [34]) developed the concept of carbon equivalence, by establishing an empirical relationship between chemical composition and hardenability for low alloy structural steels. The influence of each element of a given plate composition on hardenability, expressed in terms of the amount of carbon which could produce the same degree of hardening, was summed and a carbon equivalence parameter was produced. Such parameter was then used to rank the hardenability of a given plate composition.

Carbon equivalence is the single most important concept in the prediction of a steel resistance to hydrogen induced cracking. However, the carbon equivalence formulae developed since that work (see Table 1) have limited validity in terms of chemical composition and accordingly are only applicable to the class of steels for which they were devised.

Several predictive methods have been developed to establish critical values of a determined parameter for HACC to occur (see Table 2 to Table 4). Most of the predictive methods are based upon experimental results of a determined HACC susceptibility test. Their basis and limitations vary from method to method. Understanding of the limitations or applicable range when applying a certain method is needed to avoid cracking problems or an over-conservative practice [53].

2.1.6 HYDROGEN DISTRIBUTION IN WELDS

2.1.6.1 SOURCES OF HYDROGEN DURING WELDING

The main sources of hydrogen present in the welding arc atmosphere are [9;54;55]:

- a) *Loosely bound moisture* in the coating of shielded metal arc (SMA) electrodes and in the flux of submerged arc (SA) or flux-cored (FCA) welding. Moisture can also be introduced through the shielding gas in gas metal arc (GMA) and gas tungsten arc (GTA) welding;
- b) *Firmly bound water* in the electrode coating or the welding flux. This can occur in the form of hydrated oxides (e.g. rust on the surface of electrode wires and iron powder), hydrocarbons (in cellulose), or crystal water (bound in clay, asbestos, binder etc.);
- c) *Oil, dirt and grease*, either on the surface of the work piece itself, or trapped in the surface layers of welding wires and electrode cored wires.

2.1.6.2 WELDING ABSORPTION INTO THE WELD POOL

Grong [9] interpreted the pick-up of hydrogen in arc welding according to the simplified model outlined in Figure 10. The model considers two zones:

- a) an inner zone of very high temperatures, where atomic hydrogen is absorbed from the surrounding arc atmosphere; and
- b) An outer zone of lower temperatures, where the hydrogen desorption is controlled by the partial pressure of diatomic hydrogen in the ambient gas phase.

2.1.6.3 SOLUBILITY OF HYDROGEN IN STEEL

Due to its size, the hydrogen atom is readily soluble in iron. As can be seen in Figure 11, both octahedral and tetrahedral lattice sites are potential traps for interstitials. According to Fast [56], dissolved atoms of hydrogen are mainly present in tetrahedral positions in the form of protons.

Following the $\delta_{\text{Fe}} \rightarrow \gamma_{\text{Fe}}$ and $\gamma_{\text{Fe}} \rightarrow \alpha_{\text{Fe}}$ transformations, the hydrogen solubility in iron will change stepwise with the temperature due to the difference in the size of the FCC and bcc crystal structures (Figure 12).

In addition to the interstitial fraction, hydrogen may be present in molecular (gaseous) form trapped in microvoids [57] or plane lattice defects. Oxidized hydrogen has been also found associated with inclusions [58].

2.1.6.4 DIFFUSIVITY OF HYDROGEN IN STEEL

At high temperatures, the diffusivity of hydrogen in ferritic steels is compatible with the reported value for lattice diffusion of hydrogen in bcc iron. When the temperature falls below approximately 200 °C, the phenomenon of hydrogen trapping causes the scatter and the discrepancy shown in Figure 7.

Oriani [59] introduced the apparent diffusion coefficient, which takes into account the trapping effect:

$$D_{app}^{\alpha} = \frac{D_L^{\alpha}}{1 + K \exp(E_B / RT)} \approx \frac{2.0 \times 10^{-7} \exp(-6950 / RT)}{1 + 4.4 \times 10^{-3} \exp(26000 / RT)}$$

Eq. 1

Where:

D_{app}^{α} – apparent diffusion coefficient

D_L^{α} – lattice diffusion coefficient for hydrogen in ferritic steels

K – Density of trap sites (number of trap sites per number of lattice sites)

E_B – binding energy between hydrogen and the trap site

2.1.6.5 HYDROGEN DISTRIBUTION IN MULTIPASS WELDS

Kasuya and co-workers [60] studied the hydrogen distribution in multipass submerged arc welds. The initial hydrogen content in a molten pool was obtained by taking samples directly from the pool (Figure 13) and the transient hydrogen distribution for periods of up to seven days after welding by taking machined samples from the weld beads (Figure 14). The temperature of the test piece during machining was kept below – 20 °C and the samples were kept in liquid nitrogen.

The analytical model of hydrogen diffusion in multipass welded joints using the two-dimensional source solution was adopted and showed consistency with the experimental results obtained. Figure 15 presents the through-thickness hydrogen distribution (calculated and experimental results) for periods of three and seven days after completion of welding.

2.1.7 HYDROGEN DETERMINATION IN STEEL WELDS

The hydrogen determination can be divided into three main groups (Figure 16):

- a) Indirect methods, which are based upon arc observation or upon arc atmosphere examination. In this category the author includes the atmosphere evaluation (arc and post arc) of a weld in a closed chamber [61] and the in-process sensors [38];
- b) In-situ methods[62]; and
- c) Analysis of evolved or extracted hydrogen, in which the diffusible hydrogen is measured after being collected or extracted from a sample.

The amount of hydrogen in weld metal is normally measured and reported as diffusible hydrogen, i.e. the hydrogen which is free to move in the metal lattice and is released at room temperature [63]. From the standpoint of cracking susceptibility and ductility loss the diffusible hydrogen is the fraction of primary interest [55].

The main methods used to determine the diffusible hydrogen in welds belong to the third group and several reviews about these methods have been prepared elsewhere [10;17;63;64].

2.1.7.1 SAMPLING TECHNIQUE

The distribution of hydrogen in welds varies in time and space and a small sample removed at random cannot be representative of the weld system as a whole [63]. More over, normally it is not practical to fabricate several real joints and extract samples from different positions and at different times. Therefore, a model weld is constructed and considered as representative of the studied weld system.

Single bead deposition followed by rapid quenching is prescribed by the main standards [65;66]. Multi-run deposition followed by low temperature machining has also been employed [67;68].

2.1.7.2 ANALYSIS OF EVOLVED OR COLLECTED HYDROGEN

2.1.7.2.1 Collection of hydrogen over a fluid

In the methods in which the collection of hydrogen is made over a fluid, the weld specimen is degassed in an eudiometer tube with the fluid at a temperature near the room temperature. The evolved gases are collected in the upper portion of the tube and the resulting volume is measured. The time needed for hydrogen collection varies from 72 hours to up to 21 days for a standard sample consisting of a weld bead of approximately 4g deposited in a steel test piece of 30x15x10 mm, at a temperature of 25 °C [69].

The mercury method has shown good reproducibility and is prescribed as the primary method in several standards [65;66].

The main disadvantage of this group is the long time needed for hydrogen collection.

2.1.7.2.2 Hot extraction of hydrogen in vacuum apparatus

The sample is kept at the chosen extraction temperature in the transparent silica furnace and the evolved hydrogen is transferred to the analysis volume together with any other gases emitted from the sample. A liquid nitrogen cold trap is used to freeze condensable gases in both the furnace section and analysis volume. When hydrogen evolution ceases, the total pressure indication provided by the pressure gauge is noted. Hydrogen is then extracted from the analysis volume through a palladium/osmosis tube. The amount of diffusible hydrogen is given by the partial pressure of hydrogen. The total time for diffusible hydrogen collection for the standard sample at 45 °C is up to 72 h (Figure 17) [69].

2.1.7.2.3 Hot extraction of hydrogen in a carrier gas apparatus

In this method, the sample is heated in a controlled flow of dried high-purity inert gas (argon or nitrogen). There are systems that use gas chromatography to measure the hydrogen evolved from the sample and others that use a thermal conductivity detector [70](Figure 18).

Jenkins [69] studied the diffusible hydrogen (H_D) determination of standard samples [65;66] for different welding processes and consumables of different levels of hydrogen. The extraction time of 20 min and temperature extraction of 400°C are optimal for extracting the diffusible hydrogen while avoiding the risk of residual hydrogen (H_R) releasing.

2.2 WELDING RESIDUAL STRESSES AND DEFORMATIONS

2.2.1 RESIDUAL STRESSES

Residual or internal stresses are stresses remaining in a body without the application of external forces. They result from different processes that cause inhomogeneous permanent (i.e. plastic) deformation. Machining and grinding, nonuniform cooling of a weld or cast piece, and phase deformations induced upon cooling wherein parent and product phases have different densities are some examples [71].

If the body is supported in a way that it can deform freely, only *constraint stresses* occur. However, if component supports restrain the deformation, *reaction stresses* are superimposed to satisfy the equilibrium [72] (see Figure 19 and Figure 20).

According to the area they act over [72], residual stresses can be divided into *first order or macroscopic* (σ^I), *second order* (σ^{II}) and *third order* (σ^{III}) residual stresses. The first group extends over macroscopic areas and covers several crystallites. Residual stresses around piled-up dislocations or secondary phases are examples from the second group, as they act between crystallites or crystallite sub-regions, with size approximately in the range of 0.01 to 1 mm. The last group refers to residual stresses acting in atomic areas, e.g. the residual stresses around a single dislocation, with size in the range of 10^{-2} - 10^{-6} mm.

Residual stresses are also classified according to the originating process or phenomenon. Hence *thermal stresses* are stresses caused by inhomogeneous thermal expansion or contraction and *transformation stresses* are caused by microstructure transformation.

With respect to the involved strain, residual stresses can be associated with volumetric strain, as a result of thermal expansion, microstructure transformation or change in state, and distortional strain, as a result of plastic and viscoplastic deformation.

In the case of welding, distinction is also made between the *temporary welding residual stresses* during welding and the *permanent welding residual stresses* following complete temperature equalisation. The former determines the weldability; the latter are of interest with respect to the strength of the structure.

According to their direction (Figure 21), welding residual stresses can be divided into:

- a) Longitudinal stresses (σ_x), acting in the plane yz;
- b) Transverse stresses (σ_y), acting in the plane xz; and
- c) Transverse stresses (σ_z), acting in the plane xy.

2.2.2 WELDING

As the arc travels, the weld area is heated up crisply relative to the surrounding area, and fused locally. The surrounding colder area restrains the thermal expansion of the material heated, resulting in (elastic) thermal stresses in this area. The yield limit is lowered at elevated temperatures, as the thermal stresses exceed the yield limit in the

hotter region; the weld area is plastically hot-compressed. After cooling down, it thus displays tensile residual stresses and the surrounding area compressive residual stresses. If the material undergoes microstructure transformation during cooling, e.g. γ - α transformation, which involves an increase in volume, and if this occurs at a temperature at which the yield limit is sufficiently high, this contributes to a compressive residual stresses in the weld area and tensile residual stresses in the surrounding area.

The residual stress after cooling will result from the superposition of the thermal and transformation stresses. Figure 22 presents different distributions of longitudinal residual stress for a plate strip with a centric longitudinal weld made with different materials.

Radaj [72] presents an example of a residual stress field in a restrained multipass butt-welded joint, including the transverse stress in the “z” or through thickness direction (Figure 23). The transverse residual stress σ_z is more significant for plates of increased thickness.

According to Yurioka [26] and Davidson [32], the transverse residual stress σ_y is a function of the level of restraint, although the maximum longitudinal residual stress of a multipass weld is always as high as the yield strength, irrespective to the restraint intensity.

2.2.3 DISTORTIONS

Together with the welding residual stresses there, temporarily or permanently welding deformations also occur. Such displacements and rotations are termed “shrinkage”, “distortion” or “warpage”. Stress and deformation oppose each other in the sense that high stresses occur where the deformation is restrained and low stresses occur where the deformation is unrestrained [72].

Longitudinal, transverse, angular and bending shrinkage are the four basic types of welding deformations, presented in Figure 24 for a rectangular plate with centric jointing weld. A further example of welding deformation in practice is the bending deformation of girders with an eccentric longitudinal or transverse weld (Figure 25) [72].

2.3 HACC SUSCEPTIBILITY TESTS

2.3.1 INTRODUCTION TO WELDABILITY TESTS

Weldability is defined [73] as “the capacity of a material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service”. This concept comprises the material, the fabrication conditions (which include the process), the product desired and the behaviour in service. Such a wide scope prevents the existence of an absolute testing method and weldability tests are employed for evaluating a susceptibility to a specific weldability problem, such as cold cracking of base metal and weld metal.

HACC susceptibility tests can be divided into self-restrained tests, in which the needed strain is provided only by the thermal expansion and contraction of the weld, and externally loaded tests, in which external forces are applied [5].

External restraint tests determine the critical level of stress for HACC occurrence, while self-restraint tests provide values for the critical temperature (critical heat input or critical HAZ hardness can be measured) [26].

Although an external restraint test investigates effects of stress on HACC, external restraint tests do not take into account the beneficial stress caused by phase transformation during post-weld cooling in actual welds.

Another inherent limitation of such a class of tests is that both the stress at the tip of a crack and the crack growth rate increases with crack growth, different from the crack behaviour in actual welds where the stress relaxation allows for the slow down of the crack grow rate as the crack propagates [26].

Generally speaking, the main functions of a weldability test are [74] cracking safety evaluation, relative ranking susceptibility of processes and materials and research support.

In ‘state of the art pipeline’ girth welding, high strength low alloy steels are welded with the application of processes and consumables that result in extra low levels of hydrogen concentration in the welded zone. There is need for developing a new test to couple with this situation. According to Dinovitzer and Blackman [74], the main difficulties of the existing tests are:

a) They are either too severe or not sensitive enough to rank materials;

- b) They are developed to evaluate the potential for cracking in single pass welds only;
- c) They have unknown crack initiation sites and stress states due to restraint uncertainty; and
- d) They do not isolate the individual susceptibilities of the weld metal and heat affected zone.

2.3.2 EXTERNAL RESTRAINT TESTS

The *Constant Rupture Load* (CLR) test [44] assesses the hydrogen embrittlement of steels by measuring the rupture strength of a notched tensile specimen (Figure 26). An embrittlement index provides the hydrogen cracking susceptibility:

$$EI = (NTS - LCS) / NTS$$

Eq. 2

Where EI is the embrittlement index, NTS is the hydrogen free notched tensile strength and LCS is the hydrogen charged lower critical stress.

Susuki and Nakamura [75] developed the *Tensile Restraint Cracking* (TRC) test to study root cracking in butt welds. A single pass weld is made in a grooved butt joint restrained with bolts (Figure 27) and a certain level of load is applied after weld cooling. Stress and time for rupture is assessed.

The *Rigid Restraint Cracking* (RRC) test [76;77] is a constant strain type test in which a load is automatically adjusted so that a restraint length is held constant throughout post-weld cooling (Figure 28).

Granjon [40;78] developed an *Implant* test (Figure 29), in which a cylindrical sample (implant) with a notch or helical notch [50] at one end is inserted in a hole drilled in a support plate. A single pass weld is deposited and when the weld cools to 150°C, a determined load is applied to the cylindrical sample. The critical stress at which no rupture occurs or no arrested crack is found, is measured.

The *Augmented Strain Cracking* (ASC) test was designed to produce a known reproducible strain in the outer fibres of a transverse cross section of a weld (Figure 30). The index of susceptibility of a steel to HACC is the magnitude of strain required to produce cracking in the tested sample, for a given microstructure and hydrogen content. Hydrogen determination and strain tests are performed using different samples prepared at the same occasion for both purposes (Figure 31) [49;50;79].

2.3.3 SELF RESTRAINT TESTS

A plate with a circular hole cut out and replaced by a patch is utilised in the *Circular Patch* (CPT) test (Figure 32). One or more weld passes are deposited in the machined joint.

The *Navy Circular Patch* (NCPT) test is used for evaluating different electrodes on various base metals. This CPT variation includes a backing ring to keep the plate and the patch together when the circular hole is cut. Multipass welding is made according to quadrants (Figure 33). Both hot and cold cracks can be generated with these tests. Visual, radiographic and liquid penetrant inspection can be employed for cracking detection [80].

Three plates tack welded to form a double T-joint [81] are used in the *Cruciform Cracking* (CCT) test. The test fit-up and welding sequence is presented in Figure 34. The test has been employed to assess HACC susceptibility of multipass welding [38]. Cracking determination is performed by metallographic evaluation of the cross sections of the four sections [82].

The *Controlled Thermal Severity* (CTS) test (Figure 35) [83] serves for selection of welding parameters and as a test of quality of the base material [9]. This test is widely used to assess the critical HAZ hardness values for hydrogen cracking avoidance by changing welding heat input [26].

A severe stress is applied to the single weld bead deposited in the *Gapped Bead on Plate* (GBOP) test due to the stress concentration in the gap provided (Figure 36 and Figure 37) [84]. According to Graville [5], the test can be adapted for multipass welding (Figure 38).

The *H Slit Restraint* (HSR) test provides a control of the intensity of restraint by varying the slit length B_s (Figure 39). Instead of varying slit length, the *H Type Restraint* (HTR) test is a variant in which the restraint is controlled by the length of anchor welds that fix the test plates to a base plate (Figure 40).

Developed at Lehigh University, the *Lehigh Restraint* (LRT) test (Figure 41) can be applied to assess both hot and cold cracking susceptibility [80]. The test piece consists of a plate with slots machined into the sides and ends. The weld bead is deposited on a groove weld joint machined along the centreline of the plate. Cracking susceptibility is assessed in terms of restraint needed for cracking to occur. The restraint is provided by

the plate and slots and can be altered by changing the length of the slots. Several samples with different slot lengths are welded and a threshold level of restraint is determined as well as the width sufficient to cause cracking. The work from Stout [85-87] revealed preponderant weld metal cracking when the welds were performed within the slot length. HAZ hydrogen-induced cracking was then obtained by increasing the weld length beyond the slot extremities (Figure 42).

The Naval Research Laboratory [80] or simply the *NRL Keyhole Restraint* test (Figure 43) is a simplified version of the Lehigh test. In this test, the weld groove has a hole in one of its extremities but an open end in the other one. The weld bead is deposited along the groove from the open end toward the hole. The varying degree of restraint obtained along the weld has a minimum value at the edge where welding commences and reaches its maximum at the hole. The cracks are formed at the hole end and propagate outward to a point where the restraint is low enough and the crack growth is arrested.

Developed in Japan, the *Tekken* test can apply several dimensions and joint designs (Figure 44 and Figure 45). It is used to evaluate HAZ cracks and underbead cracks. In this test the stress state is altered by varying preheat and welding parameters [26].

Yurioka [88] and Okuda [89] used a *Multipass U – Groove* test (Figure 46).

Especially studying weld metal hydrogen cracking, Jones [90] and more recently, Devletian [91] in shipbuilding, used large plate butt welding to test procedures and conditions, as can be seen in Figure 47 and Figure 48 respectively.

Others relevant multipass tests were used by Ushio and co-workers [92]. A Multipass U – Groove test was applied to X-65 steel, while the *Restraint Multiple-Layer* (RML) cracking test (Figure 51) and the *Window-Type Restraint Multiple Layer* (WTRML) cracking test were applied to X-80 and X-100 steels respectively.

2.3.4 WELDING INSTITUTE OF CANADA (WIC) TEST

2.3.4.1 DESCRIPTION

The *Welding Institute of Canada* (WIC) test or *Small Scale Restraint Cracking* (SSRC) test is a small scale, self restraint test that was introduced in the early 1980's [93;94].

The test assembly (Figure 53) is formed by a weld joint and by a set of restraint plates. The weld joint consists of a root faced, single V preparation (Figure 54) and machined

test pieces welded partially to the restraint set, and perpendicularly to the weld joint. A backing plate and a stiffener compose the restraint set.

The length of the test pieces not welded to the backing plate is the “restraint length” (L). Due to the rigidity of the restraint set, it is within this length that the test pieces suffer restrained expansion and contraction, because the test pieces oppose each other during thermal expansion, as well as they are restrained by the solidified weld metal during contraction. Indeed, it is the later phase that provides the residual stress in the y direction.

Conceived as an evolution of the *H Slit Restraint* test (Figure 55), the *WIC* test was originally a high restraint test for hydrogen cracking susceptibility testing in low carbon steels that was subsequently modified to evaluate the root pass of pipeline girth welding (Figure 56) [5].

Because of the ability to control the residual stress (more specifically the transverse stress σ_y) by the restraint length, the test has proved to be useful for assessing the hydrogen cracking susceptibility of the root pass of pipeline girth welds, which are more likely to present longitudinal cracking. Nonetheless, since multipass pipeline girth welding presents predominant transverse cracks (plane yz), more attention is needed to control the stress in the x direction (hoop stress).

The application of the WIC test is not restrict to the pipeline industry. It was employed by the U.S. Navy research programme for developing high strength weld metals [95].

2.3.4.2 WIC TEST VARIANTS

The test configuration used by Patchett [96] (Figure 57) is a variant of the WIC test where joint geometry was changed and the sectional area of the restraint set was increased; resulting in augmented severity, as will be further discussed.

The **Longitudinal Restraint Cracking** test (LRC test) (Figure 58), conceived by Wang [17] at Cranfield University is also a modification of the WIC test, and provided an improved tool for studying transverse cracks in multipass welds with high strength electrodes [29].

Caizley [6] employed the *Cranfield University Metal Inert Gas* (CUMIG) test for assessing GMAW multipass weld joints.

3 ANALYTICAL MODEL OF INTENSITY OF RESTRAINT

Graville [5] provides an expression for intensity of restraint applicable to the WIC test, nonetheless, the documentation available on Graville's equation [97] for intensity of restraint is [5] not clear about the source and applicability of several correction factors employed (see section 3.1 and Appendix A). Hence, the author decided to derive an intensity of restraint expression applicable to the test configuration studied in this work (section 3.2).

3.1 TRANSVERSE STRESS (σ_y) ACCORDING TO GRAVILLE

An analytical procedure for assessing the severity of the WIC test was provided by Graville [97]. The net contraction of the test pieces (y direction) is calculated using a contraction model adapted from Satoh [76] (Appendix 1). The contraction is then combined with the intensity of restraint concept [98;99] to obtain the transverse stress (y direction) in the joint.

The net contraction is calculated as follows:

$$S = \frac{\alpha H}{g \rho C} \left[1 - \operatorname{erf} \left(\frac{x_0}{\sqrt{4 kt}} \right) \right]$$

Eq. 3: Net contraction of test pieces.

Where:

S – Net contraction

α – Thermal diffusivity

H – Heat input

ρ – density

g – Plate thickness

C – Specific heat

x_0 – Half restrained length

k – Thermal conductivity

t – Time

For the intensity of restraint, Graville [97] adopted the following formula:

$$K = \frac{\frac{AEg}{LB}}{\left(\frac{A}{B} + g\right)} = \frac{Eg}{L\left(1 + \frac{gB}{A}\right)}$$

Eq. 4: Intensity of restraint applied to the WIC test.

Where:

K – Intensity of restraint

A – Cross-sectional area of the restraint plates

E – Modulus of Elasticity

g – Plate thickness

L – Restraint length

B – Weld length

An eccentricity factor was introduced by Graville [97] in order to consider the weld bead not applied at the centre line of the joint eccentricity:

$$\gamma = \frac{e}{g/2}$$

Eq. 5: Eccentricity factor.

$$K_e = \frac{K}{1 + 3\gamma^2}$$

Eq. 6: Intensity of restraint corrected by eccentricity.

Where:

K – Intensity of restraint

K_e – intensity of restraint corrected by the eccentricity

γ – Eccentricity factor

e – Vertical distance between plate mid-thickness and weld metal centre (see Figure 54 for the geometry considered by Graville [97])

g – Plate thickness

The stress acting transversely in the weld metal is finally given by:

$$\sigma = \frac{K_e S}{g_w} (1 + b\gamma)$$

Eq. 7: Weld metal residual stress.

Where:

K_e – intensity of restraint corrected by the eccentricity

S – Net contraction of weld plate between the restraints points

g_w – thickness of the weld fillet

b – Constant obtained empirically

γ – Eccentricity factor

3.2 DERIVATION OF INTENSITY OF RESTRAINT EXPRESSION

Considering the models shown in Figure 59 and initially neglecting the bending of stiffeners and test pieces, an equation of compatibility of displacement [100] of a point in the joint between the test plate and the stiffener is obtained:

$$\delta_N = \delta_{TT} - \delta_{TP} = \delta_{SP} - \delta_{ST}$$

Eq. 8: Equation of compatibility

Where:

δ_N – Net displacement

δ_{TT} – test plate unrestrained thermal displacement

δ_{TP} – test plate displacement due to the reaction force P

δ_{SP} – stiffeners displacement due to the reaction force P

δ_{ST} – stiffeners unrestrained thermal displacement

$$\delta_{TT} - \frac{P \times L}{E_T \times A_T} = \frac{P \times L}{E_S \times A_S} - \delta_{ST}$$

Eq. 9

Where:

P – Reaction force

L – Unrestrained length of test plates

E_T – Young modulus of test plates

E_S – Young modulus of stiffeners plus backing plate

A_T – sectional area of test plates

A_S – sectional area of stiffeners plus backing plate

δ_{TT} – test plate unrestrained thermal displacement

δ_{ST} – stiffeners unrestrained thermal displacement

If:

$F = P/B$; Reaction force per unit of welding length

B – Weld length

h – Test plate thickness

σ_{ST} – is neglected

$$\delta_{\pi} = FBL \cdot \left(\frac{1}{E_{\tau} Bh} + \frac{1}{E_s A_s} \right)$$

Eq. 10

If $E_T \approx E_S$:

$$\frac{F}{\delta_{\pi}} = \frac{Eh}{L \left(1 + \frac{Bh}{A_s} \right)} = K$$

Eq. 11

If the weld bead is applied in a distance e from the neutral axis of test plate, some bending is allowed.

$$\epsilon_B = \frac{\delta_B}{L} = \frac{\sigma_B}{E}$$

Eq. 12

$$\delta_B = \frac{L \cdot \sigma_B}{E}$$

Eq. 13

Where:

ϵ_B – Elongation due to bending

δ_B – Displacement due to bending

σ_B – Normal stress due to bending

$$\sigma_B = \frac{M \cdot y}{I} = \frac{P \cdot e \cdot e}{\frac{B \cdot h^3}{12}} = \frac{12 \cdot P \cdot e^2}{A_T \cdot h^2}$$

Eq. 14

Considering the eccentricity factor (same as Eq. 5 but plate thickness denoted by h):

$$\gamma = \frac{e}{h/2}$$

Eq. 15: Eccentricity factor.

Then the eccentricity “e” is given by:

$$e = \frac{\gamma h}{2}$$

Eq. 16

Substituting Eq. 16 into Eq. 14, the displacement due to bending is obtained:

$$\delta_B = \frac{3.P.L.\gamma^2}{E.A_T}$$

Eq. 17

Adding the displacement due to bending to the equation of compatibility (Eq. 18) and solving for F/δ_{TT} ($F=P/B$), the expression for intensity of restraint corrected by the eccentricity factor is obtained.

$$\delta_{TT} - \frac{P \times L}{E_T \times A_T} - \frac{3.P.L.\gamma^2}{E.A_T} = \frac{P \times L}{E_S \times A_S} - \delta_{ST}$$

Eq. 18

$$K_e = \frac{Eh}{L \left(1 + \frac{Bh}{A_S} + 3.\gamma^2 \right)}$$

Eq. 19: Intensity of restraint corrected by eccentricity.

Considering the possibility of variations in joint geometry, Figure 60 presents combinations of root face and position of deposited weld bead (between the root face or over it).

3.2.1 CALCULATION OF STRESS

The stress in the test plate and in the weld metal can be assessed as follows:

$$\sigma_{\tau} = \frac{P}{A_{\tau}} = \frac{K_e \cdot \delta_{\tau\tau}}{h}$$

Eq. 20: Medium stress applied to the plate.

$$\sigma_w = \frac{P}{A_w} = \frac{K_e \cdot \delta_{\tau\tau}}{h_w}$$

Eq. 21: Medium stress applied to the weld bead.

They are medium values, as the deflections of the whole set due to the eccentricity lead to different values of stress through the weld bead thickness.

Considering beam theory, the deflection angle is:

$$\theta = \frac{M \cdot L}{E \cdot I} = \frac{P \cdot e \cdot L}{E \cdot \frac{B h^3}{12}}$$

Eq. 22

But:

$$K_e = \frac{F}{\delta_{\tau\tau}} = \frac{P}{B \delta_{\tau\tau}}$$

Eq. 23

Substituting Eq. 23 into Eq. 22 and multiplying both numerator and denominator by h_w :

$$\theta = \frac{6 \cdot \sigma_w \cdot \gamma \cdot L \cdot h_w}{E \cdot h^2}$$

Eq. 24

Considering the expression of tangent as a function of the maximum and minimum stress in the weld bead (Eq. 25) and the medium value in the weld bead (Eq. 26), the maximum and minimum stress in the weld bead are obtained (Eq. 25).

$$\tan \theta = \frac{\sigma_{\max} - \sigma_{\min}}{h_w}$$

Eq. 25

$$\sigma_w = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

Eq. 26

$$\sigma_{\max/\min} = \sigma_w \pm \frac{h_w \cdot \tan \theta}{2} = \sigma_w \pm \frac{h_w}{2} \cdot \tan \left(\frac{6 \cdot \sigma_w \cdot \gamma \cdot L \cdot h_w}{E \cdot h^2} \right)$$

Eq. 27

If θ is small enough $\tan \theta \approx \theta$, then:

$$\sigma_{\max/\min} = \sigma_w \pm \frac{3 \cdot \sigma_w \cdot \gamma \cdot L \cdot h_w^2}{E \cdot h^2} = \sigma_w \left(1 \pm \frac{3 \cdot \gamma \cdot L \cdot h_w^2}{E \cdot h^2} \right)$$

Eq. 28

By inspection it is concluded that the correction is negligible.

3.2.2 SUMMARY OF INFLUENCING PARAMETERS ON INTENSITY OF RESTRAINT

Following the intensity of restraint formula derived in section 3.2 above, the effect of **plate thickness (h)**, **weld length (B)**, **weld bead thickness (h_w)**, **root face (r_f)**, **sectional area of restraint plates (A_s)** and **restraint length (L)** on intensity of restraint was studied. The resulting intensity of restraint values due to changing the above parameters are presented by Table 5 to Table 10 and Figure 61 to Figure 66. A summary of the effect of the parameters studied according to the model is presented in Table 11.

Yurioka [88] presented **stress intensity factors** associated with the groove type of the joints (Figure 67). According to Alam [48], in RRC tests, with heat input values from 1.9 up to 2.4 kJ/mm, a single bevel geometry was more crack susceptible than a double bevel geometry [101].

The effect of joint geometry on contraction and reaction stress during cooling is presented in Figure 68, after Graville [5]. For the two joint geometries considered, the same level of contraction was reached, however with notorious differences in reaction stresses. Matsuda [102] presented the effect of the reaction stress through time and the occurrence of either of weld metal cracking or HAZ cracking (Figure 69).

Still according to Graville [5], the **root gap (R_G)** is a mandatory issue of the WIC test for the root pass when using cellulose electrodes. It seems especially consistent with the stress analytical assessment, which relies strongly on the contraction of weld metal. One could see the net contraction force acting on the weld metal in the restrained joint as the sum of the thermal forces resulting from the weld metal and the test piece cooling in

unrestrained condition. In this sense, the root gap is quite relevant to the achievement of high stresses, at least in the root pass.

Another important aspect of the root gap is the notch effect that can provide a preferential site for cracking occurrence facilitating the evaluation of the samples prepared from the tested weld joint. The work of Matharu and Hart [103] is an example of HACC initiating in the gap which were obtained in gapped Y-groove tests.

The **plate thickness (h)** contributes to the transverse stress in the z direction. Thicker plates induce more stresses in this direction. Higher cooling rates can also be achieved as there is more heat sinking effect. Nonetheless, due to materials availability, this work is restricted to the study of plates 19 mm thick.

3.3 POSSIBILITIES FOR TEST DEVELOPMENT

Several theories to explain the HACC mechanism have been formulated. Nevertheless they present intrinsic difficulties that prevent their universal application. Moreover, it can be thought that they represent different mechanisms that are not necessarily mutually exclusive.

The understanding of the interrelated HACC causal factors allied to small scale and full scale testing have been widely employed to qualify procedures, materials and avoid cracking occurrence.

The WIC test is a small scale, self-restraint test that has showed good correlation with field applications. Two of its variants presented adjusted geometric parameters to obtain increased severity and particular cracking direction.

The concept of a model able to predict the hydrogen distribution, microstructure, stress and temperature fields along time is a formidable task that demands extensive experimentation for validation.

Following a one-dimensional model for contraction and the intensity of restraint concept, a model for transverse stress in a butt-welded joint was developed from a previous work.

It was thought that the adjustment of the WIC test geometrical parameters, in the light of the simplified model could lead to new test configurations suitable to test processes and materials that generate weld joints with very low hydrogen content in the fused metal.

Table 12 presents the calculated values of intensity of restraint for some configurations of WIC test and its variants found in the literature, together with other possibilities for test configurations. Values of sectional area of configurations and momentum of inertia in the planes xz and yz were also assessed as an indicative of stiffness of the test configurations and their ability to oppose deformation.

4 EXPERIMENTAL WORK

4.1 METHODOLOGY

The logic of the experimentation process (Figure 70) consisted of verifying the validity of the WIC test or its increased severity modifications until a suitable configuration was obtained. When a satisfactory configuration was not achieved, deeper changes in test philosophy were implemented. Root-pass and multi-pass GMAW were performed with wires of very-low H content. FCAW and MMA welding with wires of higher level of H were employed as “control consumable” to verify the effect of H content.

Once a suitable configuration was obtained, the research focused on the determining of critical heat inputs and preheat/interpass temperature for cracking occurrence.

As part of the experimental procedure, several other aspects than cracking occurrence were studied, including macrostructure and microstructure characterisation, mechanical properties and crack morphology.

Parallel to the development of the weldability test, the levels of diffusible H in the consumables used were assessed for the welding conditions tested.

The experimental procedure can be divided in two main areas:

- a) Development of a HACC weldability test geometry sensitive to the low diffusible hydrogen content of the GMAW consumables available in the market; and
- b) Determination of the levels of H content of the consumables under evaluation for the welding conditions tested.

4.2 WELDABILITY TESTS

4.2.1 STEEL

The metal test pieces were cut from the X-100 1-9887-01-040 Nippon steel plate. Table 13 highlights the plate chemistry and properties.

4.2.2 SOLID WIRES; TYPES AND CHEMISTRIES

A total of 9 wires were employed through the research (Table 14). The description and chemistry of solid wires can be found at Table 15.

4.2.3 TEST CONFIGURATIONS

The test configurations S1 to S4 (Figure 71 to Figure 74) were conceived to provide increased severity according to the intensity of restraint concept, which assessment is presented in section Table 12. The test configurations S5 (following Wang [17]) and S6 have also been tested (Figure 75 and Figure 76) [29] in order to obtain cracks preferentially in the plane yz.

The jig with the test piece, as used for S1 and S2 configurations, is shown in Figure 77. It allowed the positioning of the test piece according to a reference point as used by the robot.

4.2.4 WELDING EQUIPMENT

A MIGATRONIC power source (Figure 78) and a robot PANAROBO (Figure 79) were used in performing the welding tests.

4.2.5 WELDING PARAMETERS AND CONDITIONS

Welding onto a flat plate was used to adjust the welding parameters recommended by Caizley [6] to get a weld free from visual defects, both with 0.9 mm and 1.0 mm wires. Such parameters are presented in Table 16 to Table 18 for a heat input of 0.3 kJ/mm. Increased values of heat input were obtained by properly adjusting the travel speed.

4.2.6 TEST PROCEDURE

The detailed procedure applied for the welding test constitutes the Appendix B.

A number of single-pass and multipass welds were investigate through the different test configurations in order to obtain a test configuration that could promote cracking and discriminate the cracking susceptibility of the consumables in the range of CE and PCM values. Preheat and interpass temperature of 25 (+/- 0.5) °C were employed. Figure 80 shows the layer technique applied to the multipass welds.

The welds were numbered according to a code that presents a combination of wire number, test configuration, an indication of single or multipass weld, the heat input in kJ/mm and preheat/interpass temperature. Following this code, a weld number *IXS3M0.325* indicates that the wire number IX (OKTUBROD 14.06) was tested by using the S3 test configuration for a multipass weld with a heat input of 0.3 kJ/mm and preheat/interpass temperature of 25 °C. Table 19 lists the welds performed.

After each run, the weld was visually inspected. Excessive spattering was removed by steel brush or grinding and the run was replaced in every case of porosity, by removing the defective pass with a grinder and applying a new weld pass. However, a porosity defect occurred rarely and whenever it happened there is an observation in the results presented.

4.2.7 VISUAL INSPECTION

The joints were visually inspected with the aid of liquid penetrant after 140 hours from completion time. After that each joint was cut and prepared for microstructure evaluation.

4.2.8 SAMPLING TECHNIQUE

The WIC test proposed by Graville prescribed 50mm weld length cut transversally into 4 pieces. However, according to DeLoach [95] the crack occurrence in similar experiments carried out by the US Navy was predominantly detected in longitudinally cut samples. Longitudinal sections through butt welds showing weld metal hydrogen cracking are also presented by Bailey [104].

Figure 81 presents the sampling method employed for numbering the samples taken from the joint.

For the configuration S1, the joints were cut in six equals transversal samples, numbered in sequence according to the welding direction. A sample numbered 3F means the forward face of the third piece while the pair 5A is related to the aft face.

The samples 2F, 3A, 3F, 4A, 4F and 5A were evaluated; the remaining samples were discarded in order to avoid defects related to the arc beginning and extinction.

After transverse evaluation, the samples were cut in the longitudinal direction. The letters L or R were added according to the left or right side from the longitudinal centre line.

4.2.9 METALLOGRAPHY AND CRACKING ASSESSMENT

4.2.9.1 SURFACE PREPARATION

The samples destined for inclusion assessment (2F) were polished (1 μ) and examined for inclusions. A 2% Nital solution was used for etching the samples destined for macro

and microstructure characterisation and cracking assessment. An optical microscope was employed.

4.2.9.2 MICROSTRUCTURE CHARACTERISATION

The as-deposited region of the cap pass had its microstructure constituents quantified according to IIW [105]. This was done by applying a grid of 400 points (following Gladman [106]) superimposed to the photograph of the region under evaluation.

4.2.10 MECHANICAL TESTS

4.2.10.1 HARDNESS SURVEY

Hardness surveys were performed using a Matsuzawa Seiki NHT-1 tester. The 1 Kg loading with 15 s loading time was applied to points chosen along the weld cross section centreline and at three heights in the HAZ and parent material (Figure 82).

4.3 HYDROGEN DETERMINATION

4.3.1 HYDROGEN DETERMINATION PROCEDURE

Hydrogen tests were conducted according to the standard ISO 6396 [107]. A detailed procedure for the tests is presented in Appendix C.

For each condition/consumable studied, a weld bead was deposited over a test sample (30 x 15 x 10 mm) placed in a copper jig (Figure 83). The weld was rapidly quenched in water (5 s maximum) and kept in liquid Nitrogen. After the run-on/run-off tabs were broken apart and the weld bead in the sample was cleaned with a steel brush, the sample was introduced in the hydrogen analyser.

4.3.2 HYDROGEN MEASUREMENT EQUIPMENT

A Strohlen H-mat 2500 hydrogen analyser (Figure 84) was employed to determine the hydrogen content of fused weld metals. The H content of the welded samples is determined by hot extraction in a carrier gas method.

The sample is placed into an open quartz tube inside the infrared furnace able to reach temperatures of up to 1050 °C, where the hydrogen evolves. The open end of the quartz tube is arranged to form a gas curtain. The hydrogen released by diffusion passes together with the carrier gas into the analyser.

The analysis gas consisting of CO, H₂ and N₂ passes through a dust trap to remove solid residues. The CO is oxidised in an oxidation column and absorbed. A reference stream of pure N₂ or Ar flows through a thermal conductivity cell in parallel with the analysis gas. The measurement is based on the difference in thermal conductivity between H₂ and N₂ or Ar. Calibration is done either with H₂ gas or with certified reference materials.

5 EXPERIMENTAL RESULTS

5.1 TEST DEVELOPMENT

5.1.1 CONFIGURATION S1

5.1.1.1 MULTIPASS WELDINGS

Nine consumables were initially tested with configuration S1 (Figure 71), multipass welding, 0.3 kJ/mm heat input and 25 °C of pre-heat and interpass temperature (see Table 19).

Although the macroscopic evaluation of the weld surface and the transverse sections did not reveal cracking except for the consumable III and IX, some defects found with the aid of optical microscopy in the solid wires samples are worthy to mention.

Figure 85 presents a weld metal defect found in the region between the second and third layers, in a sample cut longitudinally. A detailed picture is presented by Figure 86.

Another type of defect found is show by Figure 87 to Figure 88. A void connected to an inclusion follows the solidification line.

Small cracks were also found propagating from lack of fusion defects, normally side-wall, as can be seen in Figure 89.

Figure 90 and Figure 91 present a cracking propagating from an inclusion the weld metal approximately at weld joint mid-thickness.

The welding IIIS1M0325 (see section 4.2.6 for welds designation code explanation) revealed transverse surface cracks detected by dye penetrant analysis (Figure 92).

The macro evaluation of the transverse sample 1F revealed a longitudinal crack spread from the fusion line of a side pass, in the weld joint mid-thickness, up to a pass in the last layer. Figure 93 shows the macro picture of the sample 1F. The total crack path is presented by Figure 94 while Figure 95 presents high magnification pictures of the extremities and intermediates portions of the crack.

Two others welds were made with the consumable III and the same conditions but the confirmation welds did not reveal neither surface nor longitudinal cracks as in the sample 1F in the first weld. However, some other defects were detected both by transverse and longitudinal cutting. Figure 96 and Figure 97 reveal two defects found in

the HAZ near to the fusion line. Figure 98 and Figure 99 present a defect similar to those shown by Figure 87 to Figure 88.

The metal cored consumable (IX), with a higher hydrogen content than the solid wires (see 5.4 for hydrogen determination tests) revealed extensive cracking, both in the xz and yz directions. Figure 102 presents the macro picture of the IXS1M0325 weldment surface revealing the longitudinal cracking running through the centreline of the welded joint (Figure 103) and several transverse cracks.

Figure 104 to Figure 106 present the crack path in unetched transverse samples. Figure 107 and Figure 108 show micrographs of transverse samples etched with Nital 2 %. Figure 109 and Figure 110 present cracking in the weld metal and HAZ of a transverse sample.

5.1.1.2 SINGLE PASS WELDING

A single pass weld was also performed to study the difference in severity in comparison with the multipass welding. The test IIS1R0325 did not reveal cracking.

5.1.2 CONFIGURATION S2

The addition of a root gap together with a reduction of the restraint length from 25 to 10 mm produced the configuration S2 (Figure 72), which was tested for multipass welding using the consumables III and VI, chosen for their PCM index. The single pass condition was also tested for the consumable III. Parallel transverse cracking (plane yx) were detected in the transverse sample 2F in the weld joint mid-thickness region (Figure 111 to Figure 113). Cracks were not detected for the consumable III for both multipass and single pass tests.

5.1.3 CONFIGURATION S3

The configuration S3 (Figure 73) was tested for the consumables III and IV and single pass and multipass welding. For single pass welding, consumables III presented cracking propagating from the notch in the root leading to the sample fracture (Figure 114). However in the multipass test cracks, macro-cracks were not found even in the root notch (Figure 115) or propagating from side-wall defects (Figure 116).

5.1.4 CONFIGURATION S4

The configuration S4 (Figure 73) was tested for the consumables I, III, IV and IX (see Table 19).

For the single pass situation (welds IS4R0325, IIS4R0325 and IVS4R0325) extensive longitudinal cracking were found that in the case of consumables I and III lead to the test piece rupture during sampling operation.

Figure 117 (IIS4R0325) presents cracking propagating in a single pass weld from the notch in the root to an apparently centre-line solidification cracking. The same characteristic cracking can be seen in Figure 118 for the multipass weld (IIS4M0325).

Others crack details for the multipass case are presented by Figure 119 and Figure 120.

For the consumable IV and single pass weld, Figure 121 presents a typical solidification centre-line cracking initiating on the top of the weld bead. Multipass welds with the same consumable revealed similar features of centre-line solidification cracks in the root pass (see Figure 122). Figure 123 to Figure 126 present cracking found in the weld joint mid-thickness, with not defined orientation, similar to those found for weld IXS1M0325. An example of cracking propagating from a side-wall defect is presented by Figure 127.

The increasing in heat input from 0.3 kJ/mm to 0.6 kJ/mm was not significant to avoid cracking or improve the welding quality for the consumable III, although no cracks were found for IV, both for single pass and multipass welds.

The consumable IX was tested for multipass weld (IXS4M0325) but excessive use of grinding tools cause this particular weld to be dismissed.

5.1.5 CONFIGURATION S5

The configuration S5 (Figure 75) was tested multipass welding using the consumables III and IV (IIS5M0325 and IVS5M0325). No cracking vestiges were found for this configuration.

5.1.6 CONFIGURATION S6

Configuration S6 (Figure 77) was tested for multipass welding using consumables III, IV and IX and two values of heat input (0.3 and 0.6 kJ/mm).

No cracks were found in welds IIS6M0.325 and IVS6M0.325.

For welds IIIS6M0.630 and IVS6M0.630, a “cracking” sound was perceptible after the deposition of each weld bead since the second layer up to the last pass. Despite the sound indicator, only transverse surface cracks were found (Figure 129 to Figure 134). For the weld IXS6M0.325 several transverse cracks (plane yz) were found evenly distributed along the weld length (Figure 135). No cracks were found in the test IXS6M0.630 (Figure 136).

5.1.7 CRACKING OCCURRENCE AND TEST SEVERITY

A summary of the cracking occurrence according to the configurations tested is presented in Table 20.

5.2 MICROSTRUCTURE EVALUATION

The results of the survey on microstructure constituents for all consumables employed through the research and test configuration S1 are presented in Table 21.

The regions studied for weld metal microstructure quantification were the columnar zone of the root pass and cap pass (Figure 139 to Figure 147).

5.3 HARDNESS SURVEY

The hardness survey results for the consumables studied and test configuration S1 are presented by Table 22 and Figure 148 to Figure 150.

5.4 HYDROGEN DETERMINATION

Table 23 presents the results of the hydrogen tests performed through the research.

Consumables III, IV, V and VI were tested for the heat input values of 0.3 and 0.6 kJ/mm and the results varied from 0 to 1.1 ml/100 g with no consistent trend due to increased heat input value.

Consumable IX was tested for heat input values of 0.3 and 1.42 kJ/mm. The latter value was chosen in order to compare the result with previous analysis performed in another laboratory using the same equipment model and similar conditions, although a different jig. This consumable presented a reduction in H content from 3.1 to 2.3 ml/100g due to increased heat input value.

6 DISCUSSION

6.1 AIMS AND OBJECTIVES

This project investigates the occurrence of cold cracking of X100 steel when welded with a range of 9 commercially available high strength consumables.

The application of this work is concerned with the high speed welding of oil and gas transmission pipeline. A potential problem in welding high strength steel arises from hydrogen cracking, which can be difficult to detect because of the fine crack widths, the occurrence of cracks that do not break the surfaces and especially the time delay after welding which may be required to initiate cracking.

The aim of the work therefore was to develop a simple test which (by means of geometric control) can accurately rank the tendency to cold cracking for a set of consumables, thus allowing an informed choice to be made so that the chance of cracking in service is reduced.

6.2 TEST CONFIGURATIONS

Several theories to explain the HACC mechanism have been formulated. Nevertheless they present intrinsic difficulties that prevent their universal application. Moreover, it can be thought that they represent different mechanisms that are not necessarily mutually exclusive.

The understanding of the interrelated HACC causal factors allied to small scale and full scale testing have been widely employed to qualify procedures, materials and avoid cracking occurrence.

A number of small scale tests were studied (section 2.3) and the self-restraint category was preferred because the behaviour of cracks in this type of test is more representative of the behaviour of cracks in field welded joints (section 2.3.1).

Among the self-restrained tests, the SSRC test or WIC test (section 2.3.4) was chosen due to the following reasons:

- a) The test presented a very good correlation with the field situation for pipeline HACC assessment in the past;
- b) Its low cost and assembling simplicity;

- c) The availability of a simplified one dimensional model (section 3.1). This improvement provided an extra basis for understanding the influence of the geometrical parameters involved (section 3.2.2);
- d) The improved simplified model was found to be consistent with previous work based on the WIC test (section 3.3); and
- e) The test can be used to test pipeline material in the form of small arcs cut from the pipe circumference [5].

It is worth mentioning that the conception of a model able to predict the hydrogen distribution, microstructure, stress and temperature re-distribution with time is a formidable task that demands extensive experimentation for validation. Such a task was considered beyond the scope of this work.

6.2.1 RELEVANT PARAMETERS

According to the intensity of restraint model adopted (section 3.2), the main geometrical parameters influencing the test severity are **plate thickness (h)**, **weld length (B)**, **weld bead thickness (h_w)**, **root face (r_f)**, **sectional area of restraint plates (A_s)** and **restraint length (L)**.

The stress intensity factor associated with the groove geometry is an important geometric characteristic [88] not directly related to the model adopted.

According to Graville [5], the **root gap (R_G)** was a mandatory issue of the WIC test for the root pass test of cellulose electrodes. It seems consistent with the stress analytical assessment particularly in the in the root pass (section 3.2). Another important aspect of the root gap is the notch effect that can provide a preferential site for cracking occurrence facilitating the evaluation of the samples prepared from the tested weld joint. Previous work [103] used gapped grooves resulting in HACC initiating in the gap.

According to the literature [5;108] the restraint length (L) is the dominant parameter for adjusting the test severity, which is consistent with the model adopted and the study of the effect of the geometrical parameters on the intensity of restraint (section 3.3).

6.2.2 METHODOLOGY

The test configurations used in this work (S1 to S6) were not chosen aprioristically but were conceived gradually by changing geometrical parameters in order that increased

severities were obtained (S1 to S4) and to induce cracking preferentially in the yz plane (S5 and S6) as it is found typically in pipeline girth welding.

Following the model adopted and the trend found in the literature [96;108], the parameters selected for adjustment in this work were the intensity of restraint (L), the weld bead length (B) and the sectional area of the restraint plates in the plane xz (A_s or A_{xz}). A root gap (R_G) was introduced as well as joint configurations of increased stress intensity factors. Configurations S1 to S4 (Figure 71 to Figure 74) were produced on this basis.

The nine consumables employed (eight solid wires and one metal cored wire) provided a range of strength and composition available in the market. The metal cored wire was chosen as a “consumable of control” because of its relatively higher diffusible hydrogen content in comparison to the others (see section 6.10). Due to budget restrictions it was decided to employ only two of the solid wires available (consumables III and IV, see Table 16) chosen because of their higher and lower PCM values respectively among those 0.9 mm diameter consumables.

It was decided not to employ values of restraint length (L) less than 10 mm because, according to the model adopted, in that region of the curve “restraint length (L) x intensity of restraint (K)” relatively small changes in L lead to large changes in K and the reproducibility of the test could be affected.

Test configurations S5 and S6 (Figure 75 and Figure 76) followed previous work [29] and provided increased sectional area in the plane yz and increased value of L (less severity according to the model).

The values of intensity of restraint obtained for the configurations tested are presented by Table 12. Values of sectional area of configurations and moments of inertia in the planes xz and yz were also assessed as an indicator of stiffness of the test configurations and their ability to oppose deformation.

6.3 CONFIGURATION S1

The configuration S1 (Figure 71) proved to be severe enough to generate extensive cracking for the consumables III and IX.

In the case of consumable III one test (IIIS1M0.325) revealed two superficial transverse cracks and at least one longitudinal crack but this result was not repeated in any of the

two confirmation tests performed with the same welding conditions and parameters (Figure 92 to Figure 95).

For the metal cored consumable IX (test IXS1M0.325), extensive longitudinal and transverse cracking were obtained (Figure 102 to Figure 108).

Considerations of the nature and morphology of cracks found with configuration S1 are presented in section 6.7.1.

The cracking occurrence was consistent with the P_{CM} , CE and C values of consumable III compared to the others 0.9 mm diameter solid wires. However, the 1.0 diameter wires Union X85 and Bohler X90-IG have higher PCM and CE values and roughly the same C content and did not reveal cracking. One reason is likely to be the current difference between 0.9 and 1.0 mm, which average values are 144 and 173 A respectively. According to Chew and Wigless [109], in gas-shielded welds the weld metal hydrogen content is dependent on the applied current, changing the hydrogen content inversely to the current alteration.

The cracking occurrence for the consumable IX can be attributed to its greater hydrogen content in comparison to the solid wires, which did not revealed extensive cracking for this configuration.

The lack of repeatability of the cracking occurrence for the consumable III could be explained by differences in composition of a particular portion of the wire (segregation). Consumable III was also tested for single pass weld and did not produce cracking. However it was not possible to establish a comparison in terms of severity between the single pass and multipass situation because of that lack of repeatability.

Although the sampling method adopted included longitudinal cutting to facilitate detection of subsurface transverse cracks, it is still limited and some cracking cannot be detected or assessed. If a small number of cracks or defects are produced, it poses a difficulty for a susceptibility index to be established, which would be desirable bearing in mind that the test would function as a tool for ranking different consumables in a procurement process.

6.4 CONFIGURATION S2

This configuration (Figure 72) was conceived in an attempt to increase the test severity by minor geometric adjustments in the previous configuration tested.

The restraint length L was reduced to 10 mm in order to increase the intensity of restraint in accordance to the model adopted and a root gap was included in accordance with the original test (section 3.2.2).

The consumable III was tested for this configuration, both for single pass and multipass welds but the severity achieved was not sufficient to generate cracking.

The impact of reduction in restraint length L over the intensity of restraint K was not as significant as expected considering the model adopted for intensity of restraint assessment. It is thought that this disparity is due to the fact that the model is based on a one dimensional analysis. If the dimension in the weld length direction x is not neglected, one could see that and only the “fibres” of the test pieces near to the weld bead used to connect the test piece to the backing plate are quasi-ideally restrained while the “fibres” in the half length of the tested weld have more freedom to deform.

6.5 CONFIGURATIONS S3 AND S4

Beyond the inclusion of a root gap and the reduction of restraint length (L) and decreasing the weld bead length (B), configurations S3 and S4 (Figure 73 and Figure 74 respectively) were conceived for increased severity by augmenting the sectional area (plane xz) of the restraint plates, increasing the root face (r_f) and by adopting different groove geometries.

A root face of 9 mm was chosen because it introduced more severity in the root pass according to the intensity of restraint model adopted (Figure 65) and the groove preparations, single bevel and Y preparation respectively for configurations S3 and S4 followed the stress concentration factors provided by Yurioka [88] (Figure 67).

6.5.1 CONFIGURATION S3

For the single pass tests, the root gap proved efficient in providing a particular site for crack initiation, since both consumables III and IV produced cracking propagating from the root notch.

The fact that the multipass tests for the same conditions and consumables did not crack supports the idea that the cracks found in single pass tests were hydrogen cracks. The heating provided by subsequent passes possibly allowed more time for hydrogen to diffuse away from the joint and provided some stress relaxation. However, no cracks were found in the last layer.

6.5.2 CONFIGURATION S4

This configuration seems to have provided too much severity, as apparent solidification cracks were produced together with HACC like cracks, both for single pass and multipass tests (see section 6.7).

The effect of increased heat input was positive for consumable IV although for the consumable III did not make any perceptible difference. It seems to be consistent with the CE/PCM values but it is not clear that continually increased heat input values would be necessarily advantageous in avoiding cracking for any of the consumables.

6.6 CONFIGURATIONS S5 AND S6

Configurations S5 (Figure 75) and S6 (Figure 76) were based upon previous work [29] and were included in this work because of the need for producing transverse cracks, typical of pipeline girth welding, rather than longitudinal cracks. Configuration S6 provides an increase sectional area (plane yz) of the restraint plates in comparison to configuration S5 (see Table 12).

The adoption of S6 configuration was successful in obtaining cracking in the desired prevailing direction for the consumable IX. Weld IXS6M0.325 produced only transverse cracks while the equivalent test for S1 configuration (IXS1M0.325) presented also extensive longitudinal cracking (Figure 102).

The effect of increased heat input (0.6 kJ/mm) was positive for consumable IX as no cracks were found in weld test IXS6M0.630.

None of configurations S5 and S6 provided the necessary severity for producing cracks in multipass tests performed with consumables III and IV with heat input of 0.3 kJ/mm. For those consumables, however, the increased heat input of 0.6 kJ/mm proved to be deleterious, as can be seen from the transverse surface cracks found in the welds IIS6M0.630 and IVS6M0.630.

The fact that no cracks have been found in the sample sections despite the “cracking” sound perceptible since the second layer could be explained as follows:

- a) It is possible that the “cracking” sound referred to in section 5.1.6 was associated with transverse surface cracks occurring in the weld beads just after their deposition.
- b) The deposition of subsequent weld beads or layers remelted the cracking region before the cracks had the opportunity to propagate in the z direction.

c) Due to the heating, hydrogen from the former cracking region is allowed to diffuse away and the surface of the new bead becomes the critical region for cracking occurrence.

d) The process is repeated successively up to the last layer that produces the transverse cracks.

A possible way to confirm the validity of this hypothesis is to perform tests with an intermediate number of layers and examine the surface.

It is thought that the very low hydrogen content found in the solid wires studied demands more severity than that produced in configuration S6. A reduction of restraint length L and an increase in the sectional area of restraint plates both in plane yz and plane xz could provide the severity needed to generate hydrogen cracks for the test plate thickness employed. However further tests should be done using the configuration S6 to test different base plate compositions and thickness.

6.7 CRACK IDENTIFICATION

The identification of hydrogen cracks is not simple, as they can occur in a variety of locations, orientations and appear in different forms (transgranular, intergranular) (section 2.1.3). Fractographic evaluation with aid of electron microscopy (SEM and TEM) is recommended for an accurate characterisation of cracks (Figure 2 to Figure 4)[32;33], however, the optical microscopy of cracked weld sections has been also employed to study the crack characteristics [90;103;110].

In this work it was decided to opt for employing the optical microscopy in this work due to schedule restrictions and a more detailed fractographic electron microscopy evaluation was left to further studies.

The cracks presented in the following sections were considered to be HACC unless a different classification is stated. Most of the cited defects have parallels in the literature [54;110], which provided elements for comparison.

6.7.1 CONFIGURATION S1 AND S2

The small defect presented in Figure 85 was detected in a longitudinal cutting of the weld IS1M0.325. It was approximately 0.5 mm long and presented an angle of approximately 30° to the weld surface. Detail provided by Figure 86 revealed original material between the two surfaces.

Some hydrogen cracks were also found propagating from lack of fusion defects (Figure 89) and propagating from inclusions in the weld metal (Figure 90 and Figure 91), although the presence of relatively large end elongated inclusion were not necessarily the cause of cracking (Figure 100 and Figure 101).

The longitudinal crack found in tests IIS1M0325 (Figure 92 to Figure 95) extended from the fusion line of a side pass in the mid-thickness up to a pass in the last layer. Although the initiation site of the cracking it is not clear, it probably initiated in the region of greater stresses and hydrogen accumulation, which is thought to be in the mid-thickness of the weld joint (see Figure 15 and Figure 23).

Test IXS1M0325 (Figure 103) presented a longitudinal centre-line cracking extending through the weld joint thickness with a wider opening than the crack found in test IIS1M0.325 cited above. It also presented transverse surface cracks and small transverse cracks, some of them connected to the main longitudinal cracking (see Figure 104 to Figure 108).

One could think the main longitudinal cracking was produced by solidification crack. However, according to Bailey [110], even when a second run is deposited over a previous run containing a solidification cracking, the first crack would not initiate a second one, unless the portions of the two runs that are the last to solidify are in line with each other. This is not the case of the test in question, as can be seen from the weld pass sequence adopted (Figure 80), the geometric and the “heating” centre-line of the subsequent passes are not in alignment with the passes of the previous layers. Another important point is that if it was solidification cracking, massive stress relaxation would occur before the others transverse cracks could be induced.

The cracks presented by Figure 109 and Figure 110 apparently propagate from the HAZ to the WM and are similar to liquation cracks presented in the literature [110].

The type of defects found in fusion lines (see Figure 87, Figure 88, Figure 98, Figure 99 and Figure 111 to Figure 113) are more difficult to associate with hydrogen and have been interpreted as lack of interrun fusion.

The defects found in the HAZ of test IIS1M0.325 (Figure 96 and Figure 97) seems to be associated with inclusions and did not revealed cracking propagating from them.

6.7.2 CONFIGURATION S3

The root pass test of consumable III (IIS3R0.325) revealed a crack with typical features of solidification crack (Figure 114), with large opening between the crack surfaces. However, it is not clear why the multipass weld for the same consumable and welding conditions (IIS3M0.325) did not present crack in any of the cut samples, as one should expect to find solidification cracking restricted to the root pass region.

The fact that the consumable IV has not revealed cracking either for root pass or multipass tests would suggest that the configuration S3 could discriminate the consumables III and IV, chosen in the extremities of the range of PCM values of 0.9 mm diameter consumables available.

6.7.3 CONFIGURATION S4

Single pass tests revealed that both consumables III (IIS4M0.325) and IV (IVS4M0.325) presented cracks with clear characteristics of solidification cracking, as can be seen in Figure 117 and Figure 121 respectively. These cracks differed in the way that they extended, since consumable III presented cracking propagating from the weld toe up to the bead surface while consumable IV presented only a small surface crack.

The nature of the cracks found in the multipass test for the consumable III (IIS4M0.325) is not so clear. As it is presented by Figure 118, in the region near the weld toe the crack reveals some change in direction perpendicular to the solidification direction which is not typical of solidification cracks (see also Figure 119). Regardless of the classification of the longitudinal crack presented above, typical HACC have also been found in this test (see Figure 120).

The multipass test of the consumable IV (IVS4M0.325) revealed a centre-line solidification crack restricted to the portion of weld metal placed inside the root gap (Figure 122). It was also found cracks in the third layer region (Figure 123 to Figure 126). Those cracks seem to be similar to those found in test IXS1M0.325 (see section 6.7.1).

6.7.4 CONFIGURATIONS S5 AND S6

The cracks found in test IXS6M0.325 (Figure 135, Figure 137 and Figure 138) were thought to be HACC as they are similar in shape and distribution to HACC found in the literature [17;110]. Cracks found in configurations S5 and S6 for welds IIS6M0.630

and IVS6M0.630 (Figure 129 to Figure 134) were also considered to be HACC, and the fact that they did not extend into the weld metal as those found in consumable IX could be attributed to the higher hydrogen content of this consumable.

6.8 MICROSTRUCTURE

Acicular ferrite was the predominant microstructural constituent found in the weld metal for the nine consumables in multipass tests and configuration S1 (Table 21).

For the tests studied, no relation could be established between cracking occurrence and the incidence of any particular microstructural constituent.

6.9 HARDNESS SURVEY

The results obtained in the hardness survey (see Table 22 and Figure 148 to Figure 150) were not found to reflect any particular trend in the cracking behaviour.

6.10 HYDROGEN CONTENT

Four solid wires and the metal cored wire (“consumable of control”) were tested for two values of heat input (0.3 and 6 kJ/mm).

The metal cored wire presented a decrease in hydrogen content with increased heat input (3.1 ml/100g to 2.3 ml/100 g). The solid wires presented diffusible hydrogen content in the range of 0 to 1 ml/100 g but no consistent change in hydrogen content due to increased heat input.

The difference in hydrogen content of the metal cored wire and the solid wires seems to explain the higher cracking susceptibility of the metal cored wire and is the reason it was chosen as consumable of control.

6.11 NEED FOR FURTHER STUDIES

Budget and time constraints prevented the test configuration developed in this work from being fully validated. It is thought that further studies are needed in order a wider range of materials and conditions can be tested. Such additional tests, together with instrumentation, hydrogen tests and microstructural evaluation, would allow more information on hydrogen distribution, microstructure, stress and temperature field along time to be gathered, which can be eventually compared to pipeline field data.

The main suggestions for further work are presented in section 8.

6.12 MAIN CONTRIBUTION

An intensity of restraint expression applicable to the WIC test was formulated by the author based upon a simplified one-dimensional contraction model and the compatibility of displacement concept.

Configurations of increased severity (S1 to S4) were obtained by adjusting the geometrical parameters indicated by the intensity of restraint model together with applying different groove geometries and a root gap.

Due to budget and time restrictions, not all the 9 consumables available were tested for the configurations and conditions studied. Consumables III and IV were normally employed to carry out the tests due to their CE and PCM values (higher and lower CE values in the range of consumables available, respectively). Consumable IX was chosen as the “consumable of control” because of its relatively higher hydrogen content.

Among those configurations (S1 to S4), it is thought that configuration S3 discriminated between consumables III and IV, while configuration S4 was considered too much severe. Configurations S1 and S2 generate cracking but with poor reproducibility.

It is worth mentioning that most of the cracks obtained in configurations S1 to S4 were longitudinal and that both hydrogen cracking and solidification cracking were produced by configuration S4.

In order that transverse cracking in the plane yz (typical of pipeline girth welding) were obtained, further geometrical adjustments were performed following previous work [29]. The moment of inertia in the plane yz (I_{yz}) was the main parameter adjusted (Table 20). Configuration S6 was considered the optimal configuration obtained in the limits of the present work as it manage to prevent longitudinal cracking and induced only transverse cracking in the plane yz (T_{yz}), typical of pipeline girth welding.

In the case of consumable IX, for 0.3 kJ/mm heat input, surface transverse cracks evenly distributed along the x direction were obtained. Those cracks presented a length of 9 mm in average, as measured in longitudinal cut samples. The effect of increased heat input (0.6 kJ/mm) prevented cracking, all the others conditions and parameters being kept.

Consumables III and IV presented a different behaviour regarded to heat input values adopted. No cracks were detected for heat input of 0.3 kJ/mm while increased heat input

value (0.6 kJ/mm) produced surface transverse cracks which sound could be heard since the second layer.

Hydrogen tests confirmed the relatively higher hydrogen content of the consumable of control, however further tests are needed to compare the diffusible hydrogen content of the consumables studied. Microstructure qualification and hardness survey did not reveal any particular trend in cracking occurrence.

The main outcomes of this research are thought to be:

- a) A simple test geometry that is sensitive to GMA welding consumables of very low hydrogen content ($< 5 \text{ ml/100g}$) was developed;
- b) The simplified one-dimensional model of intensity of restraint indicated satisfactorily the geometrical parameters to be adjusted in order increased severity configurations were obtained, together with the application of different groove geometries and of a root gap;
- c) The cross-sectional area of the test configuration in the plane yz proved to be relevant for inducing restraint in the x direction and to generate cracking typical of pipeline girth welding; and
- d) This work studied a range of heat input (0.3 to 0.6 kJ/mm) which is not very well documented in the literature. It was found that minimum values of heat input were not always the most critical for hydrogen cracking, which is consistent with previous work that studied different welding processes in a different range of heat input (1 to 3 kJ/mm) [17;111]. It is suggested that there may be significant differences in the residual stress (as a result of the weld heat input) and that these stresses also influence the onset of cracking.

7 CONCLUSIONS

1. Changes introduced in the geometry have shown that test configuration can be modified in order to improve the sensitivity of the cracking test. This can enable available consumables to be ranked more accurately in terms of possible susceptibility to HACC. The final test geometry has proved the most satisfactory for this, but further development should be possible.
2. The simplified model of intensity of restraint employed and the application of groove geometries of different stress intensity factors were satisfactory to indicate the geometrical parameters to be altered for test severity adjustment. Four test geometries were produced to verify the changes in severity. Most cracking was observed in the test geometries predicted to have the largest intensity of restraint factor.
3. Increased cross sectional area and moment of inertia in the plane yz (I_{yz}) of the test configuration proved to be effective for altering the stress field and for obtaining transverse cracking in the plane yz , typical of pipeline girth welding; and
4. Minimum values of heat input were not always found to be the most critical for hydrogen cracking. It is suggested that there may be significant differences in the residual stress (as a result of the weld heat input) and that these stresses also influence the onset of cracking.

8 FURTHER WORK

1. Study the effect of different X100 base plate compositions and different thickness on the diffusible hydrogen content and HACC susceptibility.
2. Instrument the test for determining the cooling obtained through the test together with measurement of residual stresses would provide more elements for comparison of test and field pipeline girth welding.
3. Extract samples for hydrogen determination from different positions in the weld joints by machining them under liquid nitrogen in order a hydrogen distribution can be established as a function of time.
4. Employ a technique to establish the time for cracking occurrence, as the acoustic emission technique, which would also help the establishment of a time for inspection and risk assessment.
5. Employ a water cooling system in the test in order the cooling rate can be reduced and controlled.
6. Add a notch to create preferential site for cracking occurrence in order to facilitate the cracking evaluation and the establishment of a crack index for ranking purpose.
7. Employ groove geometries typical of mechanised pipeline girth welding (narrow gap).

9 TABLES AND FIGURES

Table 1: Carbon equivalent formulae. After Yurioka [53].

Group	Formula
A	$CE_{IIIW} = C + \frac{Mn}{6} + \frac{Cu + Ni}{15} + \frac{Cr + Mo + V}{5} \quad [52]$ $CE_{WES} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{10}$
B	$CE_{DNC} = C + \frac{Si}{24} + \frac{Mn}{10} + \frac{Ni + Cu}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{10}$ $CE_T = C + \frac{Mn}{10} + \frac{Cu}{20} + \frac{Ni}{40} + \frac{Cr}{20} + \frac{Mo}{10} \quad [112]$
C	$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad [113]$ $CE_{PLS} = C + \frac{Si}{20} + \frac{Mn}{16} + \frac{Cu}{16} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{40} + \frac{V}{15} \quad [114]$ $CE_{HSLA} = C + \frac{Mn}{16} - \frac{Ni}{50} + \frac{Cr}{23} + \frac{Mo}{7} + \frac{Nb}{5} + \frac{V}{9}$
D	$CE_N = C + A(C) \cdot \left\{ \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr + Mo + Nb + V}{5} + 5B \right\}$ $A(C) = 0.75 + 0.25 \cdot \tanh\{20(C - 0.12)\}$

Table 2: Predictive methods for preventing HAZ HACC. Part I. Summarised after Yurioka [53]

Criterion	Formulae	Weldability test
Cooling time	$t_{100} > (t_{100})_{cr} = 1.4 \cdot 10^4 (P_w - 0.28)^2$, $P_w = P_{cm} + H_{GL} / 60 + R_F / 400000$	Tekken test
criterion	$H_{IIW} \cong H_{GC} = 1.26 H_{GL} + 2.19$	
	$t_{100} > (t_{100})_{cr} = \exp(68.05 Cl^3 - 181.77 Cl^2 + 163.80 Cl - 41.65)$	Tekken test
	$Cl = CE_N + 0.15 \log H_{GL} + 0.70 \log(0.0017 K_t \sigma_w)$	
	McParlan – Graville[46]	GBOP test
	$H_R = H_0 \exp(-\beta_0 \tau)$, $\tau = \int_{1500}^{T_R} D(t) dt = \Sigma D \Delta t$	
	$H_{cr} = H_0 \exp(-\beta_0 \tau_{cr}) \Rightarrow \log H_{cr} = \log H_0 - \beta \tau_{cr}$	
	$\beta = \beta_0 / 2.3$, $\beta \tau > \beta \tau_{cr} = 3.75(CE - 0.40) + \log H_0$	
	$\tau (T_R = 100^\circ C) = (0.76 t_{100} + 6.3 t_{200}) \cdot 10^5$	
Stress Criterion	Critical stress[116]	Implant test
	$\sigma_{imp} \leq (\sigma_{imp})_{cr} = -73 \log(H_R)_{cr} + 83$	
	$\beta \tau \geq \beta \tau_{cr} = 0.0137 \sigma \text{ (kgf/mm}^2\text{)} + \log H_0 - 1.14$	
Critical stress	$\Sigma_I = F_I \cdot m \cdot R_F$, $\Sigma_C = 785 - 1.2 H_v - 250 \log H_{R100}$	
severity[117]	$\Sigma_I < \Sigma_C$	
	t_{100}: Cooling time to 100°C after welding (s) H_{GL}: Weld metal hydrogen content, glycerine method (ml/100g) R_F: Intensity of restraint of the joint (N/mm²): H_{IIW}: Weld metal hydrogen content, mercury method (ml/100g) H_{GC}: Weld metal hydrogen content, gas chromatography method (ml/100g) CE, P_{cm}, CE_N: See Table 1	K_t: Stress concentration factor at the root or toe σ_w: Yield strength of weld metal (MPa) H_0: Weld metal initial hydrogen content H_R: Residual hydrogen H_{R100}: H_R at $T_R = 100^\circ C$ F_I: Stress severity parameter

Table 3: Predictive methods for preventing HAZ HACC. Part II. Summarised after Yurioka [53].

Criterion	Formulae	Weldability test
Directly predicting preheat	BS5135 [65] AWS [118] Mannesmann [114] CE _T [112] CE _N [119]	Graphical chart, function of CE _{IHW} , H ₀ , Q and d Tables, function of CE _{IHW} , C content, material thickness and SI SI = 12 P _{cm} + log H _{IHW} T _P (°C) = 764 log (100 CE _{PLS}) – 1064 For gas shielded arc welding, 2 < t _{8/5} (s) < 6 and H ₀ (ml/100g DM) = 3 T _P = 700 C _{ET} + 160tanh(d/35) + 62.H _{IHW} ^{0.35} + (53C _{ET} – 32) Q - 328 Graphical, function of H ₀ , Q, d, and C _{EN}
• H₀ : Weld metal initial hydrogen content • Q : Heat input • D : plate thickness • H_{IHW} : Weld metal hydrogen content, mercury method (ml/100g) • t_{8/5}: Cooling time from 800 °C to 500°C after welding (s) • CE_{IHW}, P_{cm}, CE_N, CE_T, CE_{PLS}: See Table 1		Tekken test and welding practice

Table 4: Predictive methods for preventing WM HACC. Summarised after Yurioka [53].

Criterion	Formulae	Weldability test
Cooling time criterion	McParlan – Graville[46] $H_R = H_0 \exp (-\beta_0 \tau) , \tau = \int_{1500}^{T_R} D(t) dt = \Sigma D \Delta t$ $H_{cr} = H_0 \exp (-\beta_0 \tau_{cr}) \Rightarrow \log H_{cr} = \log H_0 - \beta \tau_{cr}$ $\beta = \beta_0 / 2.3 , \beta \tau > \beta \tau_{cr} = 3.75 (CE - 0.40) + \log H_0$ $CE = C + \frac{Mn}{6} + \frac{Cr + Mo}{5} + \frac{Ni}{5}$	GBOP test
Directly predicting preheat	Hart[120] $T_P(^{\circ}C) = 188.4 CE_W - 108.3$ $CE_W = C + 0.378 Mn + 0.145 Ni + 0.468 Cr + 0.298 Mo - 0.012 t_{8/5} + 0.039 H_{IIW}$ For $15 \leq d_w \leq 30$ mm Nippon Steel[121] $T_P(^{\circ}C) = 120 + \log (H_{GL} / 3.5) + 5(d_w - 20) + 8(\sigma_{UTS} - 83)$ $\sigma_{UTS} (MPa) = 3.0 H_v + 22.3$ Okuda[89] $T_P(^{\circ}C) = 6.03 \sigma_{UTS} (kgf/mm^2) + 318.6 \log H_{GC} - 554.3$ $\sigma_{UTS} (MPa) = 3.0 H_v + 22.3$	GBOP test
• H_{GL}: weld metal hydrogen content, glycerine method (ml/100g) • H_{IIW}: weld metal hydrogen content, mercury method (ml/100g) • H_{GC}: weld metal hydrogen content, gas chromatography method (ml/100g) • σ_{UTS}: Tensile strength of weld metal • H_v: Vickers hardness • d: plate thickness • d_w (mm): height of weld metal • $d_w = d$ (V-groove and U-groove) • $d_w = \frac{1}{2} d$ (X-groove and K-groove)		

Table 5: Theoretical effect of A_S on intensity of restraint.

A (mm ²)	L (mm)	B (mm)	E (MPa)	h (mm)	r _f (mm)	h _w (mm)	e ₁ (mm)	e ₂ (mm)	γ ₁	γ ₂	K (MPa)	K _{e1} (MPa)	K _{e2} (MPa)	K _{em} (MPa)
2.0E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.08E+05	3.57E+04	6.43E+04	5.00E+04
2.5E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.16E+05	3.64E+04	6.69E+04	5.17E+04
3.0E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.21E+05	3.70E+04	6.87E+04	5.29E+04
3.5E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.26E+05	3.74E+04	7.01E+04	5.37E+04
4.0E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.29E+05	3.77E+04	7.12E+04	5.44E+04
4.5E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.32E+05	3.79E+04	7.20E+04	5.50E+04
5.0E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.34E+05	3.81E+04	7.27E+04	5.54E+04
6.0E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.38E+05	3.84E+04	7.38E+04	5.61E+04
6.5E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.39E+05	3.85E+04	7.42E+04	5.63E+04
7.0E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.41E+05	3.86E+04	7.45E+04	5.66E+04
8.5E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.44E+05	3.88E+04	7.54E+04	5.71E+04
9.0E+03	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.44E+05	3.89E+04	7.56E+04	5.72E+04
1.0E+04	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.46E+05	3.90E+04	7.60E+04	5.75E+04
1.0E+05	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.58E+05	3.98E+04	7.92E+04	5.95E+04
1.0E+06	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.59E+05	3.99E+04	7.95E+04	5.97E+04
1.0E+07	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.60E+05	3.99E+04	7.96E+04	5.97E+04
1.0E+08	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.60E+05	3.99E+04	7.96E+04	5.97E+04
1.0E+09	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.60E+05	3.99E+04	7.96E+04	5.97E+04
1.0E+10	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.60E+05	3.99E+04	7.96E+04	5.97E+04

Table 6: Theoretical effect of *L* on intensity of restraint.

A	L	B	E	h	r _f	h _w	e ₁	e ₂	γ ₁	γ ₂	K	K _{e1}	K _{e2}	K _{em}
(mm ²)	(mm)	(mm)	(MPa)	(mm)	(mm)	(mm)	(mm)	(mm)			(MPa)	(MPa)	(MPa)	(MPa)
6900	1	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	3.51E+06	2.97E+06	3.29E+06	3.13E+06
6900	5	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	7.01E+05	5.93E+05	6.58E+05	6.26E+05
6900	10	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	3.51E+05	2.97E+05	3.29E+05	3.13E+05
6900	15	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	2.34E+05	1.98E+05	2.19E+05	2.09E+05
6900	20	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	1.75E+05	1.48E+05	1.65E+05	1.56E+05
6900	25	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	1.40E+05	1.19E+05	1.32E+05	1.25E+05
6900	30	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	1.17E+05	9.89E+04	1.10E+05	1.04E+05
6900	35	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	1.00E+05	8.47E+04	9.40E+04	8.94E+04
6900	40	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	8.77E+04	7.41E+04	8.23E+04	7.82E+04
6900	45	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	7.79E+04	6.59E+04	7.31E+04	6.95E+04
6900	50	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	7.01E+04	5.93E+04	6.58E+04	6.26E+04
6900	60	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	5.85E+04	4.94E+04	5.48E+04	5.21E+04
6900	70	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	5.01E+04	4.24E+04	4.70E+04	4.47E+04
6900	80	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	4.38E+04	3.71E+04	4.11E+04	3.91E+04
6900	90	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	3.90E+04	3.30E+04	3.66E+04	3.48E+04
6900	100	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	3.51E+04	2.97E+04	3.29E+04	3.13E+04

Table 7: Theoretical effect of *B* on intensity of restraint

A (mm ²)	L (mm)	B (mm)	E (MPa)	h (mm)	r _f (mm)	h _w (mm)	e ₁ (mm)	e ₂ (mm)	γ ₁	γ ₂	K (MPa)	K _{e1} (MPa)	K _{e2} (MPa)	K _{em} (MPa)
6900	25	5	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.57E+05	3.98E+04	7.90E+04	5.94E+04
6900	25	10	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.55E+05	3.96E+04	7.85E+04	5.91E+04
6900	25	15	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.53E+05	3.95E+04	7.80E+04	5.87E+04
6900	25	20	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.51E+05	3.94E+04	7.75E+04	5.84E+04
6900	25	25	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.49E+05	3.92E+04	7.69E+04	5.81E+04
6900	25	30	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.47E+05	3.91E+04	7.64E+04	5.78E+04
6900	25	35	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.46E+05	3.90E+04	7.59E+04	5.74E+04
6900	25	40	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.44E+05	3.88E+04	7.54E+04	5.71E+04
6900	25	45	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.42E+05	3.87E+04	7.49E+04	5.68E+04
6900	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.40E+05	3.86E+04	7.45E+04	5.65E+04
6900	25	55	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.39E+05	3.84E+04	7.40E+04	5.62E+04
6900	25	60	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.37E+05	3.83E+04	7.35E+04	5.59E+04
6900	25	65	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.35E+05	3.82E+04	7.31E+04	5.56E+04
6900	25	70	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.34E+05	3.81E+04	7.26E+04	5.53E+04
6900	25	75	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.32E+05	3.79E+04	7.21E+04	5.50E+04
6900	25	80	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.31E+05	3.78E+04	7.17E+04	5.48E+04
6900	25	85	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.29E+05	3.77E+04	7.13E+04	5.45E+04
6900	25	90	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.28E+05	3.76E+04	7.08E+04	5.42E+04
6900	25	95	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.27E+05	3.75E+04	7.04E+04	5.39E+04
6900	25	100	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.25E+05	3.73E+04	7.00E+04	5.37E+04

Table 8: Theoretical effect of *h* on intensity of restraint.

A (mm ²)	L (mm)	B (mm)	E (MPa)	h (mm)	r _f (mm)	h _w (mm)	e ₁ (mm)	e ₂ (mm)	γ ₁	γ ₂	K (MPa)	K _{e1} (MPa)	K _{e2} (MPa)	K _{em} (MPa)
6900	25	50	2.10E+05	10	2.00	4.00	5.00	1.00	1.00	0.20	7.83E+04	2.06E+04	7.04E+04	4.55E+04
6900	25	50	2.10E+05	12	2.00	4.00	6.00	2.00	1.00	0.33	9.27E+04	2.47E+04	7.10E+04	4.78E+04
6900	25	50	2.10E+05	14	2.00	4.00	7.00	3.00	1.00	0.43	1.07E+05	2.87E+04	7.12E+04	4.99E+04
6900	25	50	2.10E+05	16	2.00	4.00	8.00	4.00	1.00	0.50	1.20E+05	3.27E+04	7.20E+04	5.23E+04
6900	25	50	2.10E+05	18	2.00	4.00	9.00	5.00	1.00	0.56	1.34E+05	3.66E+04	7.35E+04	5.51E+04
6900	25	50	2.10E+05	20	2.00	4.00	10.00	6.00	1.00	0.60	1.47E+05	4.05E+04	7.55E+04	5.80E+04
6900	25	50	2.10E+05	25	2.00	4.00	12.50	8.50	1.00	0.68	1.78E+05	5.02E+04	8.18E+04	6.60E+04
6900	25	50	2.10E+05	30	2.00	4.00	15.00	11.00	1.00	0.73	2.07E+05	5.98E+04	8.90E+04	7.44E+04
6900	25	50	2.10E+05	35	2.00	4.00	17.50	13.50	1.00	0.77	2.35E+05	6.91E+04	9.67E+04	8.29E+04
6900	25	50	2.10E+05	40	2.00	4.00	20.00	16.00	1.00	0.80	2.60E+05	7.83E+04	1.05E+05	9.15E+04
6900	25	50	2.10E+05	45	2.00	4.00	22.50	18.50	1.00	0.82	2.85E+05	8.74E+04	1.13E+05	1.00E+05
6900	25	50	2.10E+05	50	2.00	4.00	25.00	21.00	1.00	0.84	3.08E+05	9.63E+04	1.21E+05	1.08E+05

Table 9: Theoretical effect of r_f on intensity of restraint.

A (mm ²)	L (mm)	B (mm)	E (MPa)	h (mm)	r _f (mm)	h _w (mm)	e ₁ (mm)	e ₂ (mm)	γ ₁	γ ₂	K (MPa)	K _{e1} (MPa)	K _{e2} (MPa)	K _{em} (MPa)
6900	25	50	2.10E+05	19	2.00	4.00	9.50	5.50	1.00	0.58	1.40E+05	3.86E+04	7.45E+04	5.65E+04
6900	25	50	2.10E+05	19	3.00	4.00	8.50	4.50	0.89	0.47	1.40E+05	4.51E+04	8.81E+04	6.66E+04
6900	25	50	2.10E+05	19	4.00	4.00	7.50	3.50	0.79	0.37	1.40E+05	5.31E+04	1.03E+05	7.82E+04
6900	25	50	2.10E+05	19	5.00	4.00	6.50	2.50	0.68	0.26	1.40E+05	6.28E+04	1.19E+05	9.07E+04
6900	25	50	2.10E+05	19	6.00	4.00	5.50	1.50	0.58	0.16	1.40E+05	7.45E+04	1.32E+05	1.03E+05
6900	25	50	2.10E+05	19	7.00	4.00	4.50	0.50	0.47	0.05	1.40E+05	8.81E+04	1.39E+05	1.14E+05
6900	25	50	2.10E+05	19	8.00	4.00	3.50	-0.50	0.37	-0.05	1.40E+05	1.03E+05	1.39E+05	1.21E+05
6900	25	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	1.40E+05	1.19E+05	1.32E+05	1.25E+05
6900	25	50	2.10E+05	19	10.00	4.00	-1.50	2.50	-0.16	0.26	1.40E+05	1.32E+05	1.19E+05	1.25E+05
6900	25	50	2.10E+05	19	11.00	4.00	-0.50	3.50	-0.05	0.37	1.40E+05	1.39E+05	1.03E+05	1.21E+05
6900	25	50	2.10E+05	19	12.00	4.00	0.50	4.50	0.05	0.47	1.40E+05	1.39E+05	8.81E+04	1.14E+05
6900	25	50	2.10E+05	19	16.00	4.00	4.50	8.50	0.47	0.89	1.40E+05	8.81E+04	4.51E+04	6.66E+04

Table 10: Theoretical effect of h_w on intensity of restraint

A (mm ²)	L (mm)	B (mm)	E (MPa)	h (mm)	r _f (mm)	h _w (mm)	e ₁ (mm)	e ₂ (mm)	γ ₁	γ ₂	K (MPa)	K _{e1} (MPa)	K _{e2} (MPa)	K _{em} (MPa)
6900	10	50	2.10E+05	19	9.00	2.00	1.50	-0.50	0.16	-0.05	3.51E+05	3.29E+05	3.48E+05	3.39E+05
6900	10	50	2.10E+05	19	9.00	2.50	1.75	-0.75	0.18	-0.08	3.51E+05	3.22E+05	3.45E+05	3.33E+05
6900	10	50	2.10E+05	19	9.00	3.00	2.00	-1.00	0.21	-0.11	3.51E+05	3.14E+05	3.41E+05	3.27E+05
6900	10	50	2.10E+05	19	9.00	3.50	2.25	-1.25	0.24	-0.13	3.51E+05	3.06E+05	3.35E+05	3.20E+05
6900	10	50	2.10E+05	19	9.00	4.00	2.50	-1.50	0.26	-0.16	3.51E+05	2.97E+05	3.29E+05	3.13E+05
6900	10	50	2.10E+05	19	9.00	4.50	2.75	-1.75	0.29	-0.18	3.51E+05	2.87E+05	3.22E+05	3.05E+05
6900	10	50	2.10E+05	19	9.00	5.00	3.00	-2.00	0.32	-0.21	3.51E+05	2.78E+05	3.14E+05	2.96E+05
6900	10	50	2.10E+05	19	9.00	5.50	3.25	-2.25	0.34	-0.24	3.51E+05	2.68E+05	3.06E+05	2.87E+05
6900	10	50	2.10E+05	19	9.00	6.00	3.50	-2.50	0.37	-0.26	3.51E+05	2.58E+05	2.97E+05	2.77E+05
6900	10	50	2.10E+05	19	9.00	6.50	3.75	-2.75	0.39	-0.29	3.51E+05	2.49E+05	2.87E+05	2.68E+05
6900	10	50	2.10E+05	19	9.00	7.00	4.00	-3.00	0.42	-0.32	3.51E+05	2.39E+05	2.78E+05	2.58E+05

Table 11: Effect of the influencing parameters on intensity of restraint.

Parameter studied	Others parameters values						Range of parameter applied		Range of intensity of restraint obtained (MPa)		Average value (MPa)	Percentage variation ¹ (%)
	h (mm)	B (mm)	h _w (mm)	r _r (mm)	A _s (mm ²)	L (mm)						
h (mm)	X	50	4	2	6900	25	10	50	4.55E+04	1.08E+05	7.70E+04	41
B (mm)	19	X	4	2	6900	25	5	100	5.94E+04	5.37E+04	5.65E+04	5
h _w (mm)	19	50	X	9	6900	10	2	7	3.39E+05	2.58E+05	2.98E+05	14
r _r (mm)	19	50	4	X	6900	25	2	16	5.65E+04	1.26E+05	9.11E+04	38
A _s (mm ²)	19	50	4	2	X	25	2000	10000	5.00E+04	5.75E+04	5.37E+04	7
L (mm)	19	50	4	9	6900	X	10	100	3.13E+05	3.13E+04	1.72E+05	82

¹ [(Maximum value – Average value)/Average value]x 100

Table 12: Test configurations - intensity of restraint assessment.

Configuration	Axz (mm2)	Ixz (mm4)	Ayz (mm2)	Iyz (mm4)	L (mm)	B (mm)	r _f (mm)	K _{e1} (MPa)	K _{e2} (MPa)	K _{wmed} (MPa)
1 – WIC test [94]	3500	1.30E+07	7500	3.91E+05	100	50	2.00	9.3411E+03	1.7523E+04	1.34E+04
2 – “	3500	1.30E+07	7500	3.91E+05	50	50	2.00	1.8682E+04	3.5047E+04	2.69E+04
3 – “	3500	1.30E+07	7500	3.91E+05	25	50	2.00	3.7365E+04	7.0094E+04	5.37E+04
4 – WIC Patchett [96]	8500	4.55E+07	6000	2.00E+05	50	50	2.00	1.9408E+04	3.7689E+04	2.85E+04
5 – “	8500	4.55E+07	6000	2.00E+05	25	50	2.00	3.8815E+04	7.5379E+04	5.71E+04
6 – Wang LRC [29]	4375	2.28E+05	7500	2.60E+05	60	150	2.00	1.4297E+04	2.5029E+04	1.97E+04
7 – “	4375	2.28E+05	7500	2.60E+05	25	150	2.00	3.4312E+04	6.0069E+04	4.72E+04
8 – “	4375	2.28E+05	7500	2.60E+05	10	150	2.00	8.5780E+04	1.5017E+05	1.18E+05
9 – S1 (Figure 71)	4500	1.30E+07	7500	4.69E+06	25	75	2.00	3.6973E+04	6.8728E+04	5.29E+04
10 – S2 (Figure 72)	4500	1.30E+07	7500	4.69E+06	10	75	2.00	9.2432E+04	1.7182E+05	1.32E+05
11 – S3 (Figure 73)	7000	5.22E+07	7500	4.69E+06	10	50	9.00	2.9699E+05	3.2961E+05	3.13E+05
12 – S4 (Figure 74)	7000	5.22E+07	7500	4.69E+06	10	50	9.00	2.9699E+05	3.2961E+05	3.13E+05
13 – S5 (Figure 75)	3500	1.40E+06	6500	5.72E+06	50	150	2.00	1.6576E+04	2.8300E+04	2.24E+04
14 – S5 A	3500	1.40E+06	6500	5.72E+06	25	150	2.00	3.3151E+04	5.6599E+04	4.49E+04
15 – S5 B	3500	1.40E+06	6500	5.72E+06	10	150	2.00	8.2879E+04	1.4150E+05	1.12E+05
16 – S5 C	3500	1.40E+06	6500	5.72E+06	10	150	6.00	1.4150E+05	2.1122E+05	1.76E+05
17 – S6 (Figure 76)	3500	1.40E+06	7750	8.51E+06	50	150	2.00	1.6576E+04	2.8300E+04	2.24E+04
18 – S6 A	3500	1.40E+06	7750	8.51E+06	25	150	2.00	3.3151E+04	5.6599E+04	4.49E+04
19 – S6 B	3500	1.40E+06	7750	8.51E+06	10	150	2.00	8.2878E+04	1.4150E+05	1.12E+05
20 – S6 C	3500	1.40E+06	7750	8.51E+06	10	150	6.00	1.4150E+05	2.1122E+05	1.76E+05

Table 13: X100 plate chemistry and properties.

Nominal 0.4 Cr – 0.5Ni – 0.4 Mo – 0.5 Cu – V – Nb – Ti		
	Analysis*	
	ESAB	Supplier
C	0.025	0.027
Mn	1.98	1.95
P	0.006	0.005
S	<0.005	0.0024
Si	0.20	0.20
Cr	0.42	0.41
Ni	0.48	0.47
Mo	0.43	0.42
Cu	0.46	0.46
Al	0.006	0.002
V	0.07	0.063
Nb	0.05	0.046
Ti	0.015	0.013
O	38	-
N	50	53
B	<5	2
P_{CM}	0.219	0.218
CE_{IIW}	0.602	0.593
* Values in wt %, except for O, N and B, expressed in ppm		

Table 14: Wires employed.

I	ESAB SPOOLARC120, 0.9 mm, R20, AWS 5.28ER120S-1
II	BOHLER NiMo1-1G, 0.9 mm, R10, AWS 5.28 ER90S-G
III	THYSSEN, UNION NiMoCr, 0.9 mm, R14, AWS5.28ER100S-1
IV	THYSSEN, K-NOVA, 0.9 mm, R2, AWS5.18ER70S-6
V	OERLIKON, CARBOFIL HT, 1.0 mm, R12, AWS 5.28 ER100S-G
VI	BOHLER, X-90-1G, 1.0 mm, R2, AWS5.28ER120S-G
VII	THYSSEN UNION MoNi, 1.0 mm, R9, AWS5.28ER90S-G
VIII	THYSSEN UNION X85, 1.0 mm, R19, AWS5.28ER110S-G
IX	ESAB OKTUBROD 1406

Table 15: Wires chemistries.

Name	Spoolarc 120	NiMo1-1G	Union NiMoCr	K-Nova	Carbofil HT	Union NiMo80	Union X85	X90-IG	OKTubrod 14.06
Diameter(mm)	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.2
Code	R20	R10	R14	R2	R12	R9	R19	R21	
Class. AWS	5.28ER120S-G	5.28ER90S-G	5.28ER100S-1	5.18ER70S-6	5.28ER100S-G	5.28 ER90S-G	5.28 ER110S-G	5.28 ER120S-G	
Manufacturer	ESAB	Bohler	Thyssen	Thyssen	Oerlikon	Thyssen	Thyssen	Bohler	ESAB
Analysis	ESAB UK	ESAB UK	ESAB UK	ESAB UK	ESAB UK	ESAB UK	ESAB UK	Bohler	
C	0.057	0.072	0.096	0.06	0.072	0.099	0.094	0.088	
Mn	1.55	1.69	1.61	1.49	1.36	1.55	1.59	1.79	
Si	0.4	0.61	0.6	0.82	0.76	0.63	0.71	0.80	
S	0.005	0.011	0.008	0.009	0.011	0.016	0.016	0.015	
P	0.007	0.011	0.01	0.01	0.009	0.01	0.01	0.010	
Ni	2.28	0.88	1.43	0.03	0.47	1.07	1.68	2.27	
Mo	0.5	0.29	0.49	0.005	0.46	0.41	0.55	0.57	
Cr	0.28	0.03	0.17	0.04	0.48	0.03	0.32	0.35	
Cu	0.08	0.1	0.26	0.14	0.15	0.09	0.1	0.01	
Al	0.012	0.007	0.007	0.009	0.005	0.008	0.009	0.009	
Nb	0.006	0.005	0.005	0.005	0.006	0.005	0.006	0.000	
V	0.006	0.007	0.007	0.006	0.006	0.007	0.007	0.003	
B	0.0007	0.0006	0.0005	0.0005	0.0005	-	-	-	
Ti	0.02	0.1	0.04	0.07	0.005	0.07	0.06	0.05	
O ₂	58	46	43	65	145	30	54	-	
N ₂	61	64	66	52	98	106	62	65	
PCM	0.24	0.22	0.28	0.17	0.24	0.25	0.28	0.30	
CE _{HW}	0.63	0.48	0.61	0.33	0.53	0.52	0.65	0.72	

*Values in wt %, except for O₂ and N₂ expressed in ppm

Table 16: Welding conditions employed – Solid wires of 0.9 mm diameter.

Polarity:	DC+	Transfer mode:	DIP	Shieldin g gas:	CO ₂	Gas flow:	10 l/min
	Stickout (mm)	WFS (m/min)	v (mm/min)	V(v)	VR(v)	IR(a)	h (kJ/mm)
	13	9	750	26.5	25.1	144	0.29
I	ESAB SPOOLARC120, 0.9 mm, R20, AWS 5.28ER120S-1						
II	BOHLER NiMo1-1G, 0.9 mm, R10, AWS 5.28 ER90S-G						
III	THYSSEN, UNION NiMoCr, 0.9 mm, R14, AWS5.28ER100S-1						
IV	THYSSEN, K-NOVA, 0.9 mm, R2, AWS5.18ER70S-6						

Table 17: Welding conditions employed – Solid wires of 1.0 mm diameter.

Polarity:	DC+	Transfer mode:	DIP	Shieldin g gas:	CO ₂	Gas flow:	10 l/min
	Stickout (mm)	WFS (m/min)	v (mm/min)	V(v)	VR(v)	IR(a)	h (kJ/mm)
	12	9	890	27	25.6	173	0.30
V	OERLIKON, CARBOFIL HT, 1.0 mm, R12, AWS 5.28 ER100S-G						
VI	Bohler, X-90-1G, 1.0 mm, R2, AWS5.28ER120S-G						
VII	THYSSEN UNION MoNi, 1.0 mm, R9, AWS5.28ER90S-G						
VIII	THYSSEN UNION X85, 1.0 mm, R19, AWS5.28ER110S-G						

Table 18: Welding conditions employed – Metal cored wire.

Polarity:	DC+	Transfer mode:	DIP	Shieldin g gas:	CO ₂	Gas flow:	10 l/min
	Stickout (mm)	WFS (m/min)	v (mm/min)	V(v)	VR(v)	IR(a)	h (kJ/mm)
	16	6	950	26.5			0.30
IX	ESAB OK Tubtod 14.06						

Table 19: Test development welds.

	Consumable	Test configuration	Multi or root pass	Heat input (kJ/mm)	Pre-heat, interpass T (°C)	
1	I	S1	M	0.3	25	
2	II	S1	M	0.3	25	
3	III	S1	M	0.3	25	a
4	III	S1	M	0.3	25	b
5	III	S1	M	0.3	25	c
6	IV	S1	M	0.3	25	
7	IX	S1	M	0.3	25	
8	V	S1	M	0.3	25	
9	VI	S1	M	0.3	25	
10	VI	S1	M	0.3	25	
11	VII	S1	M	0.3	25	
12	VIII	S1	M	0.3	25	
13	III	S1	R	0.3	25	
14	III	S2	M	0.3	25	
15	VI	S2	M	0.3	25	
16	III	S2	R	0.3	25	
17	III	S3	M	0.3	25	
18	IV	S3	M	0.3	25	
19	III	S3	R	0.3	25	
20	IV	S3	R	0.3	25	
21	I	S4	M	0.3	25	
22	III	S4	M	0.3	25	
23	IV	S4	M	0.3	25	
24	IV	S4	M	0.3	25	
25	IX	S4	M	0.3	25	
26	I	S4	R	0.3	25	
27	III	S4	R	0.3	25	
28	IV	S4	R	0.3	25	
29	IV	S4	M	0.6	25	
30	III	S4	R	0.6	25	
31	IV	S4	R	0.6	25	
32	III	S5	M	0.3	25	
33	IV	S5	M	0.3	25	
34	III	S6	M	0.3	25	
35	IX	S6	M	0.3	25	
36	III	S6	M	0.6	30	
37	IV	S6	M	0.6	30	
38	IX	S6	M	0.6	30	

Table 20: Test configurations - intensity of restraint assessment.

Configu ration	A _{xz} (mm2)	I _{xz} (mm4)	A _{yz} (mm2)	I _{yz} (mm4)	L (mm)	B (mm)	r _f (mm)	K _{ened} (MPa)	Consumables tested	Crack description
S1	4500	1.30E+07	7500	4.69E+06	25	75	2.00	5.29E+04	I to IX	I to VIII – few cases of Lxz and Tyz, poor reproducibility X – extensive Lxz and Tyz cracks VI – Tyz III – NC III – Lxz in single-pass, NC in multipass IV – NC
S2	4500	1.30E+07	7500	4.69E+06	10	75	2.00	1.32E+05	III and VI	
S3	7000	5.22E+07	7500	4.69E+06	10	50	9.00	3.13E+05	III and IV	
S4	7000	5.22E+07	7500	4.69E+06	10	50	9.00	3.13E+05	I, III, IV and IX	I, III, IV – Extensive Lxz in single pass, mainly solidification cracking III, IV – Solidification and hydrogen cracks in multipass tests Increased heat input (0.3 to 0.6 kJ/mm) was beneficial for consumable IV but not prevent cracks for consumable III (both for single and multipass tests) IX – Dismissed due to excessive grinding
S5	3500	1.40E+06	6500	5.72E+06	50	150	2.00	2.24E+04	III and IV	NC
S6	3500	1.40E+06	7750	8.51E+06	50	150	2.00	2.24E+04	III, IV and IX	III, IV – NC for multipass tests and 0.3 kJ/mm heat input but in 0.6 kJ/mm tests, “cracking sound” for every bead since the second layer, shallow superficial transverse cracks Tyz IX – In 0.3 kJ/mm tests, Tyz detected by surface examination, 8 to 10 mm length measured in longitudinally cut samples. Heat input of 0.6 kJ/mm prevented cracking.
L _{xz} – Longitudinal cracking, plane xz T _{yz} – Transverse cracking, plane yz										
T _{xy} – Transverse cracking, plane xy NC – No cracking										

Table 21: Microstructure quantification results.

WELD	REGION	PF	FSA	FSN	FS	M	FC	AF
IS1M0325	RP	9.8	3.4	7.5	10.9	3.0	0.4	75.9
	CAP	6.0	0.8	4.5	5.3	0.8	0.0	87.9
IIS1M0325	RP	6.0	3.0	2.6	5.6	4.5	0.8	83.1
	CAP	8.6	13.9	0.0	13.9	4.5	0.8	72.2
IIIS1M0325	RP	4.4	4.4	7.6	12.0	0.0	0.0	83.6
	CAP	2.7	7.6	2.7	10.2	0.0	0.0	87.1
IVS1M0325	RP	4.4	5.3	8.0	13.3	0.0	0.0	82.2
	CAP	5.8	3.6	1.8	5.3	12.4	0.0	76.4
VS1M0325	RP	5.6	4.5	10.9	15.4	2.6	1.9	74.4
	CAP	7.1	15.4	11.7	27.1	0.0	0.0	65.8
VIS1M0325	RP	0.8	1.8	10.5	12.3	0.0	0.0	87.0
	CAP	7.4	13.3	15.3	28.6	0.0	0.0	63.9
VIIS1M0325	RP	7.5	6.0	0.8	6.8	0.0	0.0	85.7
	CAP	3.8	4.2	0.8	4.9	0.0	0.0	91.3
VIIIS1M0325	RP	7.3	2.3	1.5	3.8	0.0	0.0	88.8
	CAP	9.0	1.5	0.8	2.3	0.0	0.0	88.7
IXS1M0325	RP	2.0	0.0	0.0	0.0	0.0	0.0	98.0
	CAP	3.5	0.0	0.0	0.0	0.0	0.0	96.5

Table 22: Hardness survey results.

IS1M0.325 / ESAB Spoolarc 120											
WM	(1)	303	(6)	355	(7)	355	(12)	407	(13)	331	
HAZ	(2)	293	(4)	303	(8)	305	(10)	325	(14)	325	(16) 318
PM	(3)	252	(5)	253	(9)	265	(11)	266	(15)	273	(17) 257
IIS1M0.325 / Bohler NiMo1-1G											
WM	(1)	330	(6)	288	(7)	329	(12)	282	(13)	336	
HAZ	(2)	290	(4)	289	(8)	279	(10)	309	(14)	309	(16) 311
PM	(3)	273	(5)	263	(9)	257	(11)	268	(15)	278	(17) 274
IIIS1M0.325 / Thyssen Union NiMoCr											
WM	(1)	340	(6)	345	(7)	270	(12)	355	(13)	375	
HAZ	(2)	295	(4)	300	(8)	293	(10)	290	(14)	315	(16) 300
PM	(3)	257	(5)	276	(9)	254	(11)	270	(15)	286	(17) 264
IVS1M0.325 / Thyssen K-Nova											
WM	(1)	276	(6)	248	(7)	270	(12)	243	(13)	280	
HAZ	(2)	286	(4)	283	(8)	297	(10)	274	(14)	327	(16) 300
PM	(3)	266	(5)	261	(9)	266	(11)	243	(15)	266	(17) 261
VS1M0.325 / Oerlikon Carbofil HT											
WM	(1)	339	(6)	384	(7)	372	(12)	365	(13)	318	
HAZ	(2)	303	(4)	309	(8)	339	(10)	314	(14)	345	(16) 336
PM	(3)	273	(5)	266	(9)	273	(11)	266	(15)	273	(17) 293
VIS1M0.325 / Bohler X90-1G											
WM	(1)	396	(6)	363	(7)	409	(12)	367	(13)	359	
HAZ	(2)	301	(4)	309	(8)	294	(10)	313	(14)	321	(16) 316
PM	(3)	264	(5)	270	(9)	263	(11)	274	(15)	295	(17) 282
VIIS1M0.325 / Thyssen Union MoNi											
WM	(1)	324	(6)	301	(7)	363	(12)	302	(13)	309	
HAZ	(2)	279	(4)	303	(8)	307	(10)	303	(14)	312	(16) 322
PM	(3)	263	(5)	265	(9)	291	(11)	270	(15)	266	(17) 263
VIIIS1M0.325 / Thyssen Union X85											
WM	(1)	402	(6)	388	(7)	340	(12)	360	(13)	432	
HAZ	(2)	293	(4)	291	(8)	309	(10)	305	(14)	316	(16) 325
PM	(3)	251	(5)	251	(9)	267	(11)	266	(15)	266	(17) 253
IXS1M0.325 / ESAB OKTubrod 14.06											
WM	(1)	339	(6)	279	(7)	358	(12)	317	(13)	373	
HAZ	(2)	261	(4)	260	(8)	283	(10)	260	(14)	299	(16) 305
PM	(3)	246	(5)	297	(9)	237	(11)	315	(15)	254	(17) 250

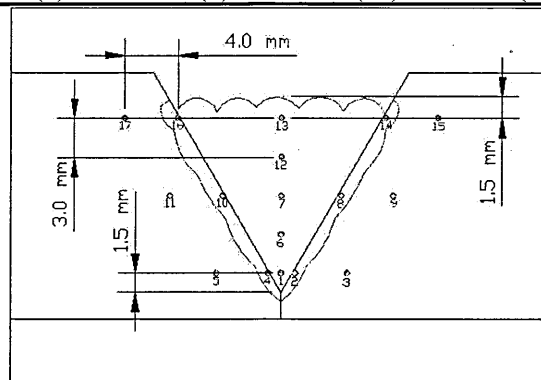


Table 23: Hydrogen determination tests.

Consumable	Gas	I(A)	V(V)	St (mm)	WFS (m/min)	WI (mm)	TS (mm/min)	Wt (s)	h (kJ/mm)	Te/te	H (ml/100g)	OBS
UNION NiMoCr	CO ₂	143	25.7	12	9	75	750	6	0.30	400/20	0.1	
K-NOVA	CO ₂	148	26.5	12	9	75	750	6	0.30	400/20	1.1	
CARBOFIL HT	CO ₂	169	26.1	12	9	75	890	5	0.30	400/20	0.8	
X-90-1G	CO ₂	176	25.3	12	9	75	890	5	0.30	400/20	0.4	
OKTUBROD 1406	Ar+CO ₂	142	30.5	16	6	75	950	5	0.29	400/20	3.1	DC -ve
UNION NiMoCr	CO ₂	140	27.4	12	9	75	380	12	0.62	400/20	0.2	
K-NOVA	CO ₂	151	25.1	12	9	75	380	12	0.60	400/20	0.6	
CARBOFIL HT	CO ₂	164	28.4	12	9	75	450	10	0.62	400/20	0	
X-90-1G	CO ₂	175	26.4	12	9	75	450	10	0.62	400/20	0.4	
OKTUBROD 1406	Ar+CO ₂	142	30.5	16	6	75	200	22.5	1.42	400/20	2.3	DC -ve
X-90-1G	CO ₂	178	24.9	12	9	75	450	10	0.62	800/20	0.2	
SPOOLARC120	CO ₂	140	25.4	13	9	139	190	43.7	0.94	400/20	1.6	ESAB
OKTUBROD 1406	Ar+CO ₂	140	24.8	16	6	140	205	41	1.49	400/20	3.8	ESAB
OKTUBROD 1406	Ar+CO ₂	142	30.5	20	6	142	356	23.9	1.36	400/20	5.4	ESAB
St: Stick-out		TS: Travel speed				Te/te: Temperature / time for hot H: Diffusible hydrogen						
WFS : Wire feed speed		Wt: Welding time				content						
WI: Weld length												

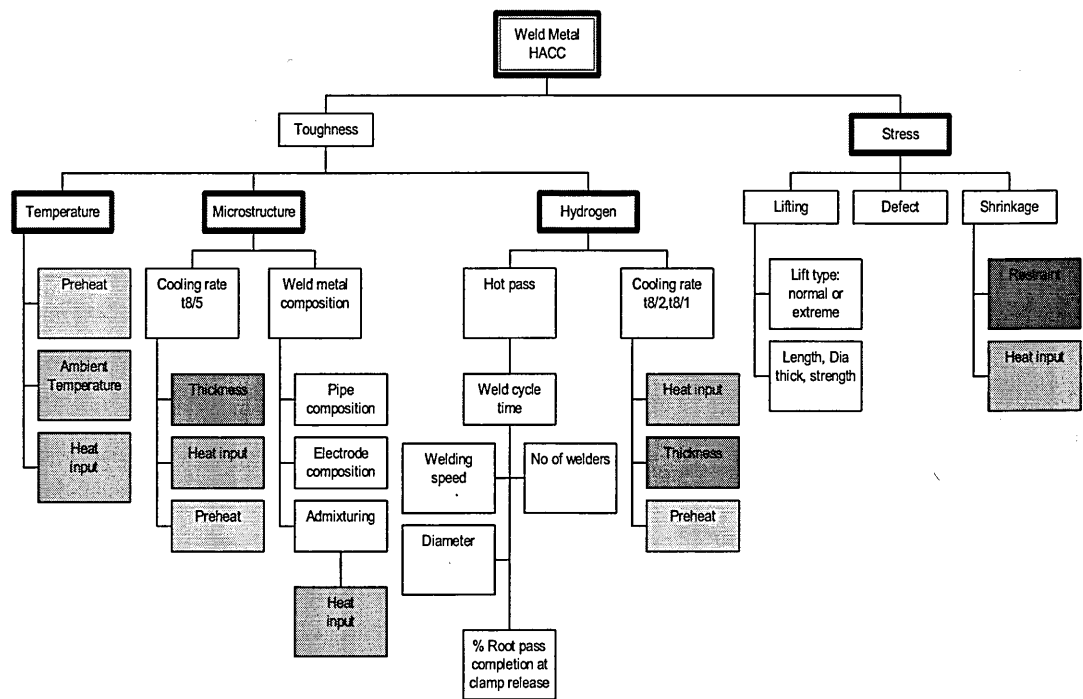
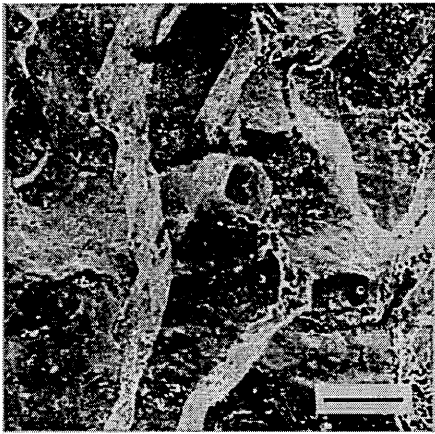


Figure 1: HACC causal factors. Adapted from Fletcher and Yurioka [25].



a)



b)



c)

a) An intergranular hydrogen assisted crack in weld metal b) A weld metal solidification crack c) A HAZ liquation crack. Obs: The scale bars are 20 μm .

Figure 2: Crack surface morphology. After Davidson [32].

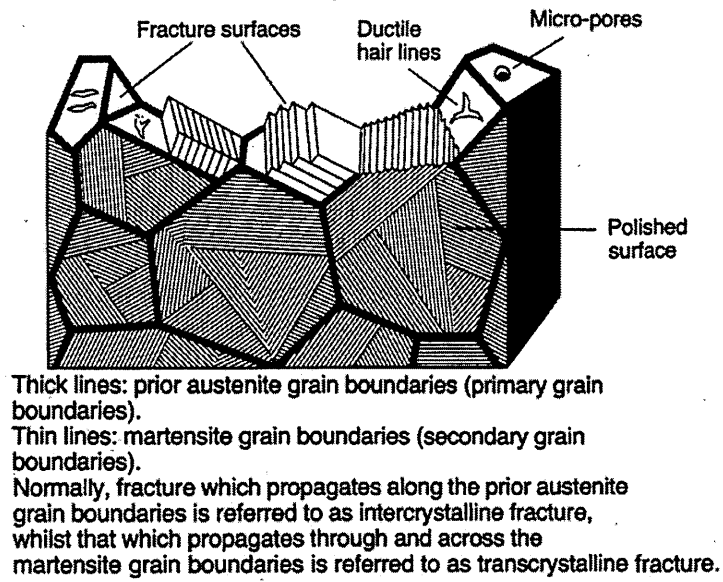


Figure 3: Fracture formation in steels caused by hydrogen embrittlement. Extracted from Engel [33].

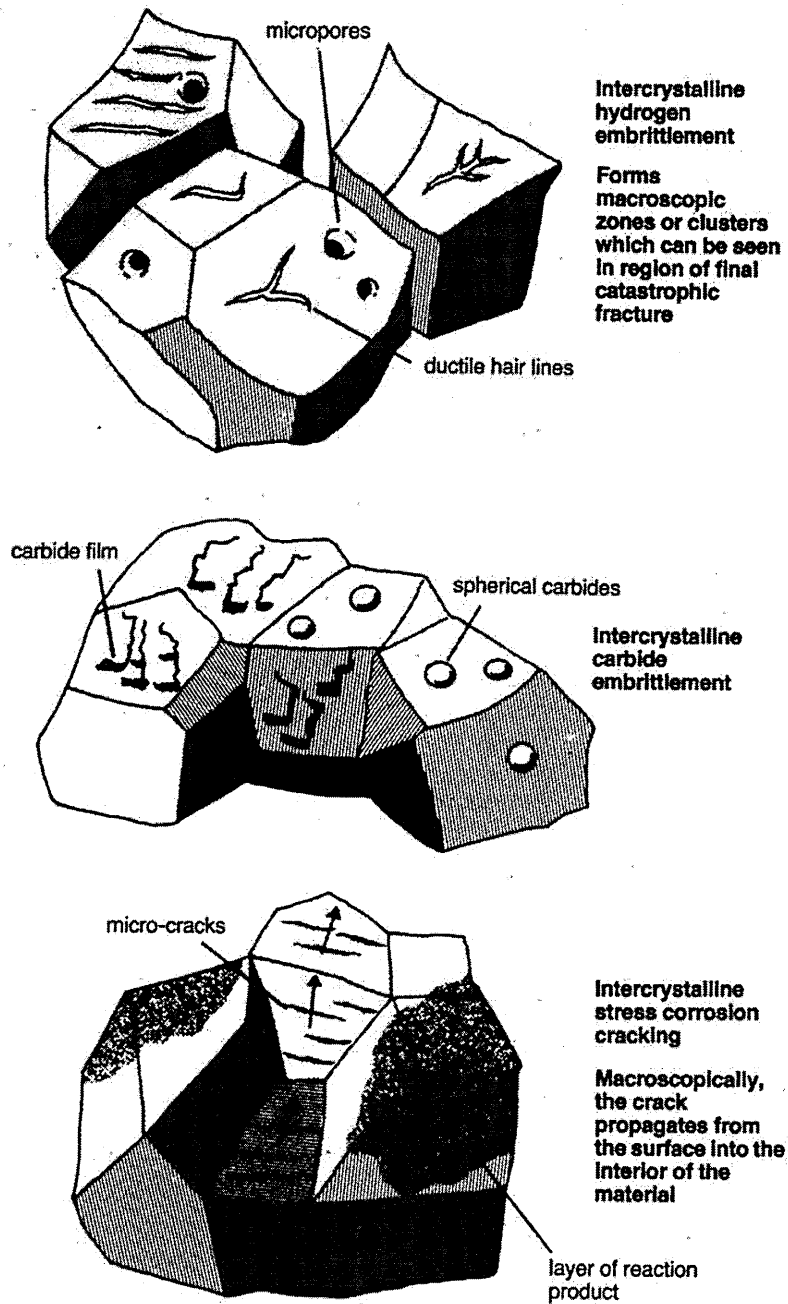


Figure 4: Schematic representation of three cases of intercrystalline fracture. Extracted from Engel [33].

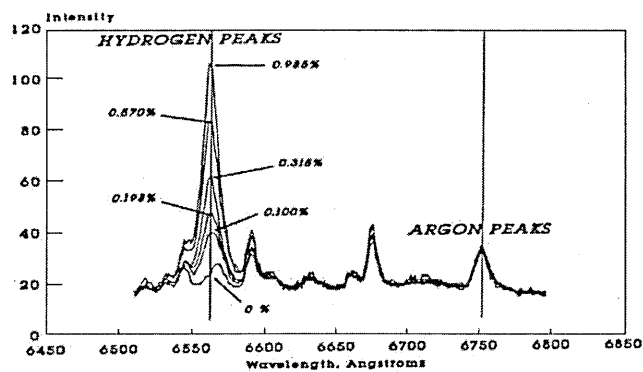


Figure 5: Spectra showing the hydrogen and argon peaks for various levels of shielding gas hydrogen. After Wong [38].

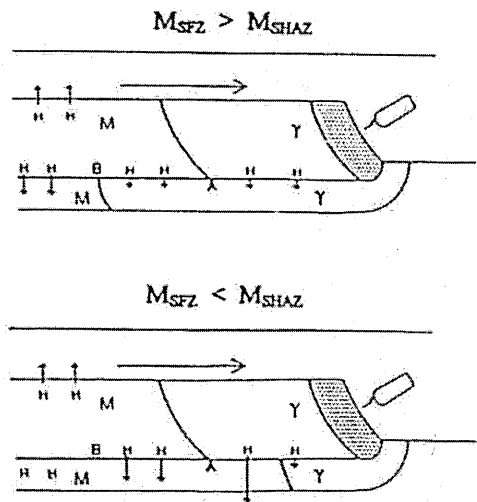


Figure 6: Effect of relative martensite start temperatures of weld metal and HAZ on hydrogen transport. After Olson [35].

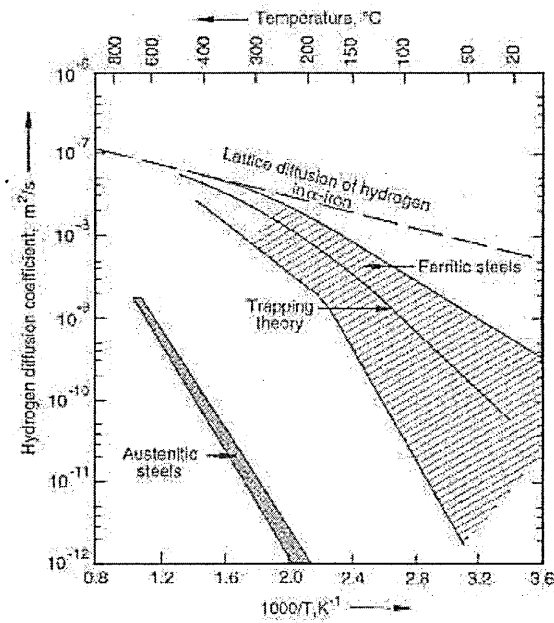


Figure 7: Diffusion coefficients of hydrogen in iron and steel. After Grong [12].

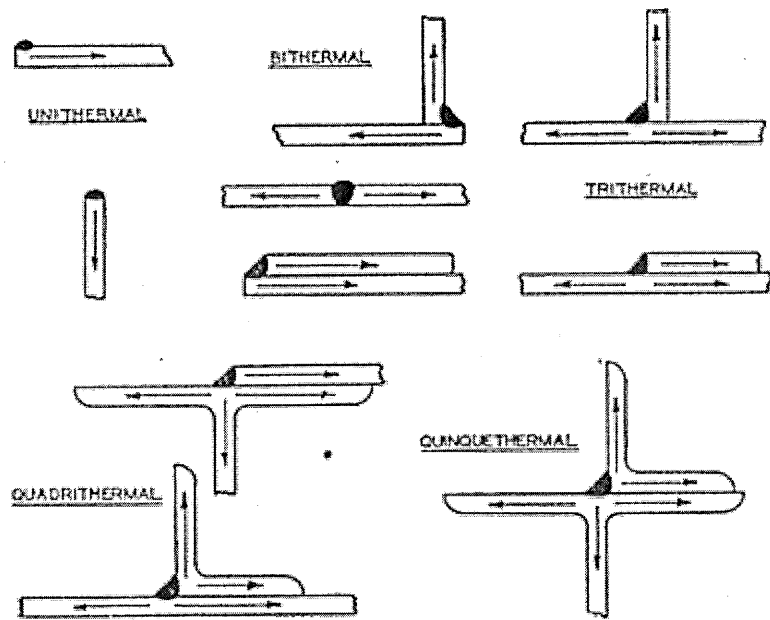


Figure 8: Heat flow conditions related to joint geometry. After Cottrell [51].

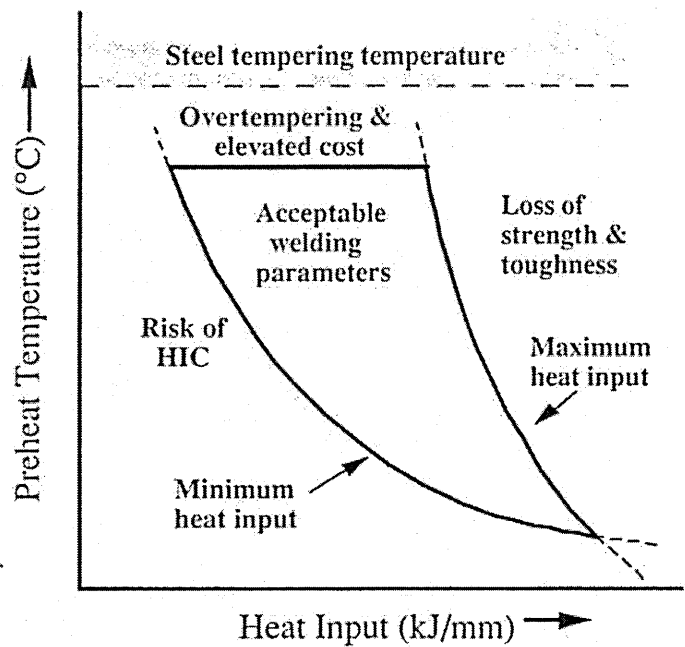


Figure 9: Control of heating input for avoiding the risk of HACC. After Davidson [32].

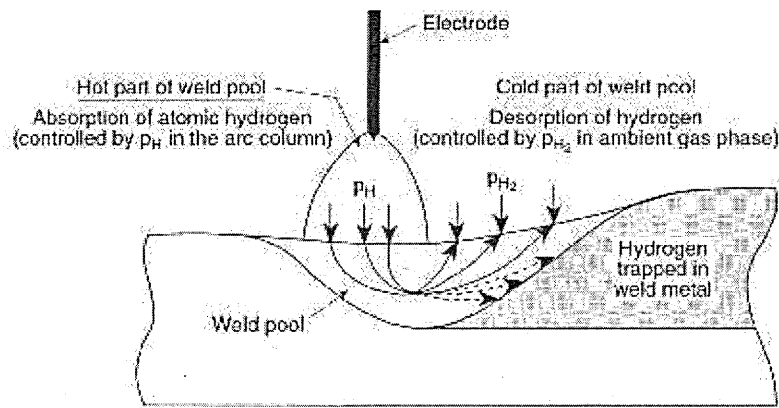


Figure 10: Idealised reaction model for hydrogen pick-up in arc welding. After Grong [12].

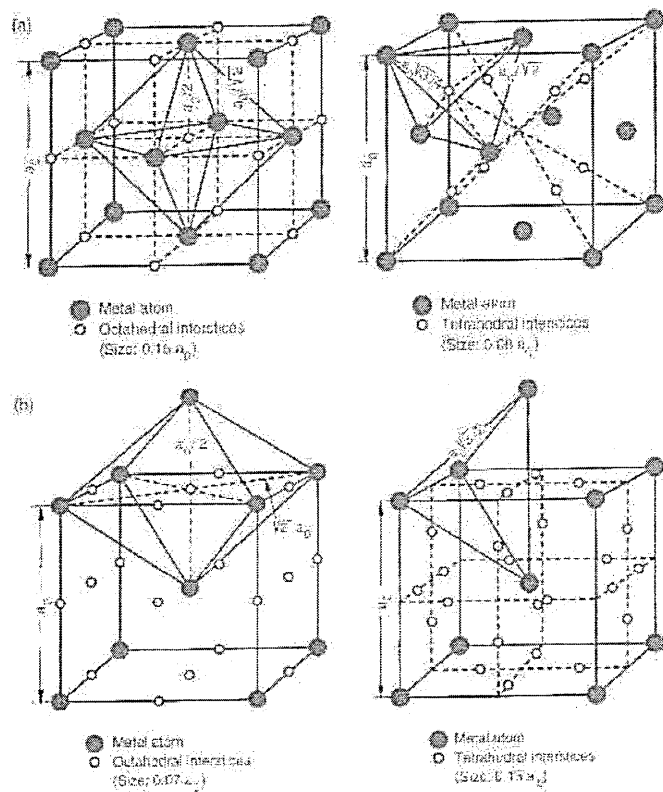


Figure 11: Schematic representation of octahedral and tetrahedral lattice sites in different crystal structures; a) face-centred cubic (fcc) structures, b) body-centred cubic (bcc) structures. After Grong [12].

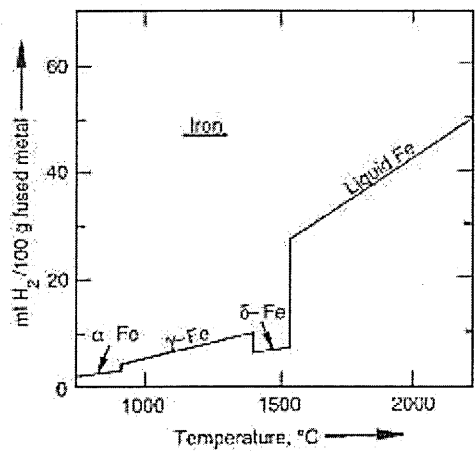


Figure 12: Solubility of hydrogen in Iron. After Grong [12].

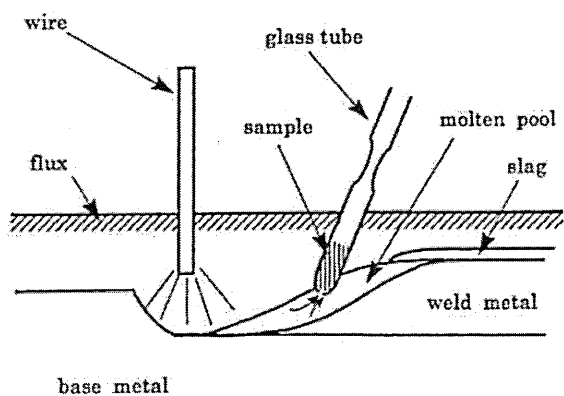


Figure 13: Method for obtaining sample from the weld pool for hydrogen determination. After Kasuya [60].

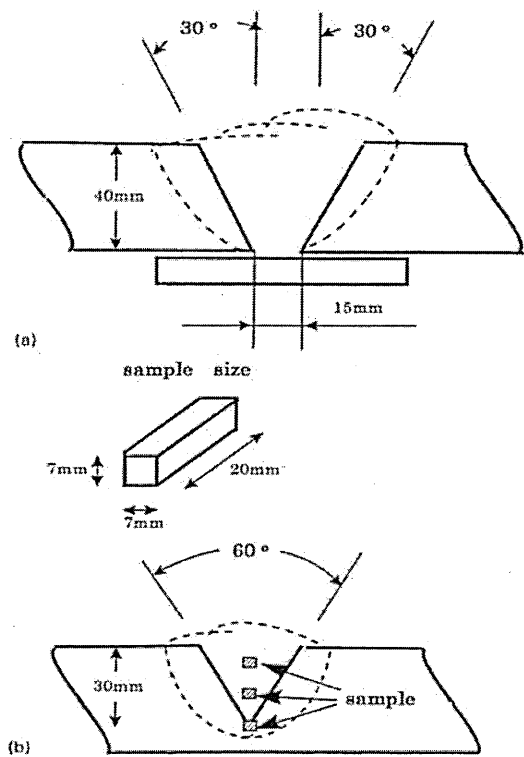
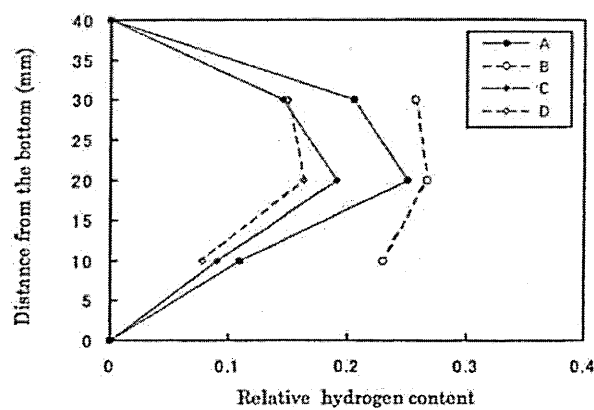


Figure 14: Shapes and dimensions of grooves and test pieces used by Kasuya [60] for transient hydrogen distribution determination.



A and C are calculated results for three and seven days after completion of welding, respectively, and B and D are experimental results for three and seven days after completion of welding, respectively.

Figure 15: Hydrogen distributions in weld metal of a SAW. After Kasuya [60].

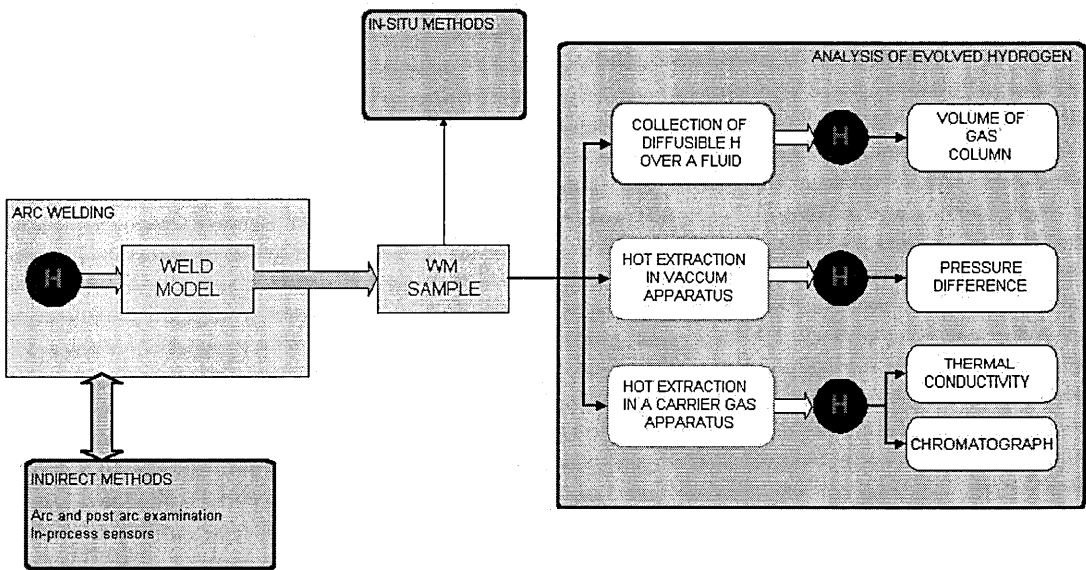
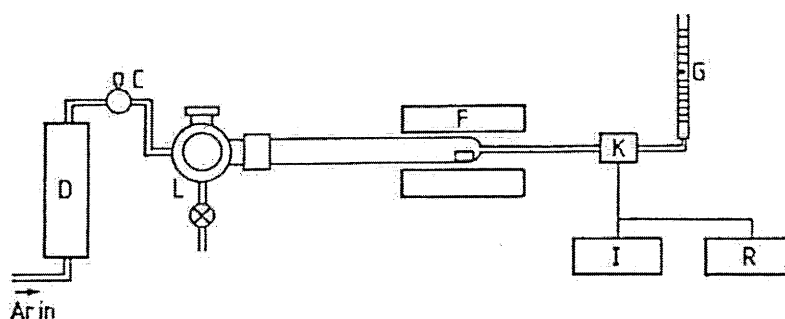
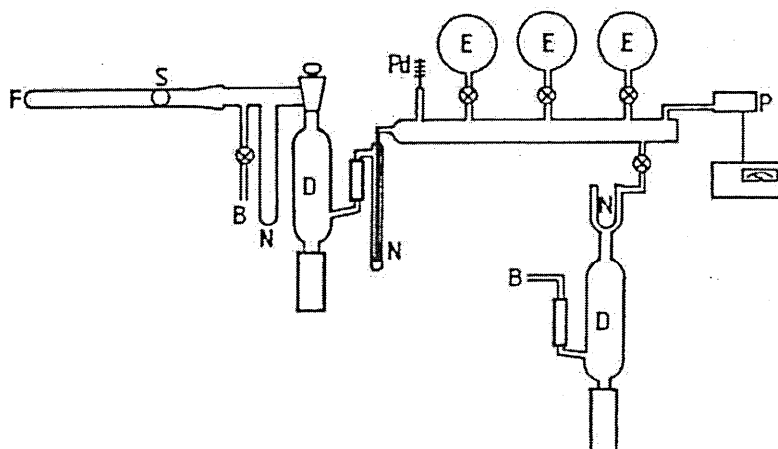


Figure 16: Hydrogen determination in steel weld metals.



D – Molecular sieve drier; C – gas flow controller; L – loading dock;
F – furnace; G – gas flow indicator; I – integrator; R - recorder

Figure 17: Schematic diagram of the TWI-built vacuum hot extraction apparatus. After Jenkins [69].



F – furnace tube; S – sample inlet; B – backing line; N – liquid nitrogen cold trap; D – mercury diffusion pump; Pd – palladium tube; E – expansion volume; P – pressure gauge.

Figure 18: Schematic diagram of the TWI-built carrier gas equipment. After Jenkins [69].

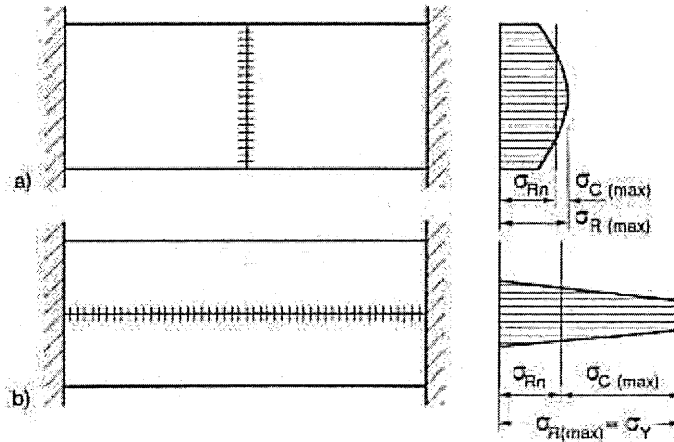


Figure 19: Constraint stresses, σ_c , and reaction stresses, σ_{Rn} , as consequence of plate edges being restrained. a) transverse weld b) longitudinal weld. After Radaj [72].

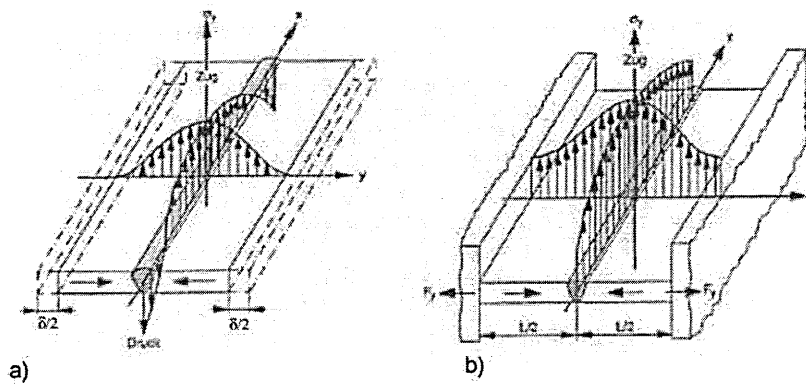


Figure 20: Schematic illustration of stress transverse to the welding direction at free shrinkage (a) and shrinkage restraint (b). After Boellinghaus [122].

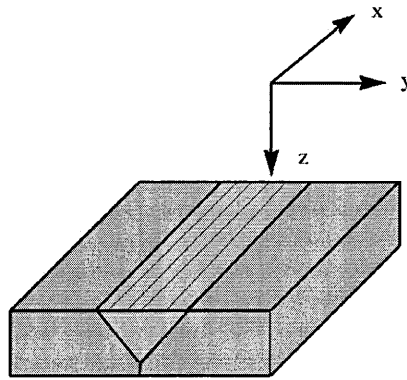


Figure 21: Convention of orthogonal directions in the butt weld joint.

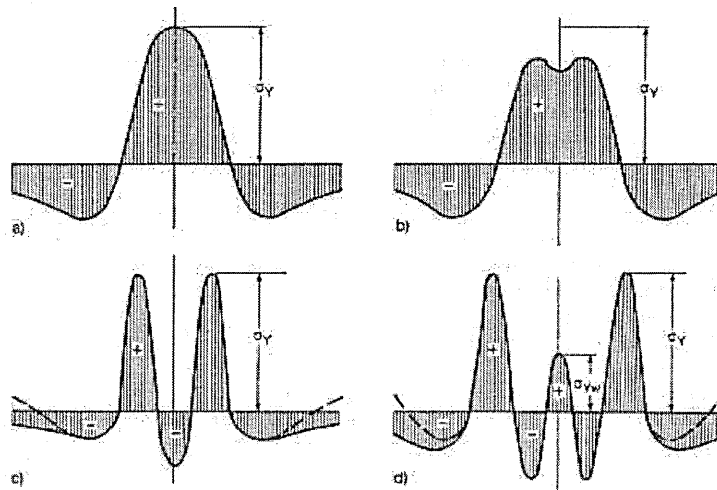


Figure 22: Weld longitudinal residual stresses, stress profile variants: mild steel and low alloy steel a), aluminium alloy b), high-alloy structural steel with ferritic c) and austenitic d) filler metal. After Radaj [72].

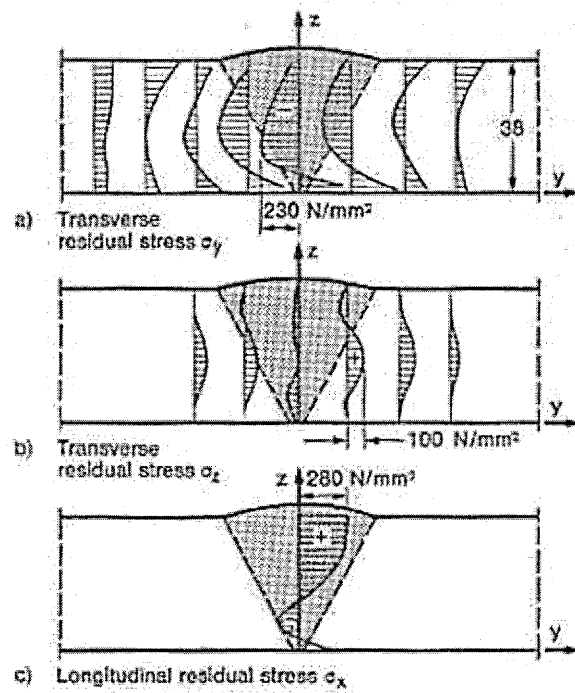


Figure 23: Residual stresses measured in a restrained multipass butt weld. After Radaj [72].

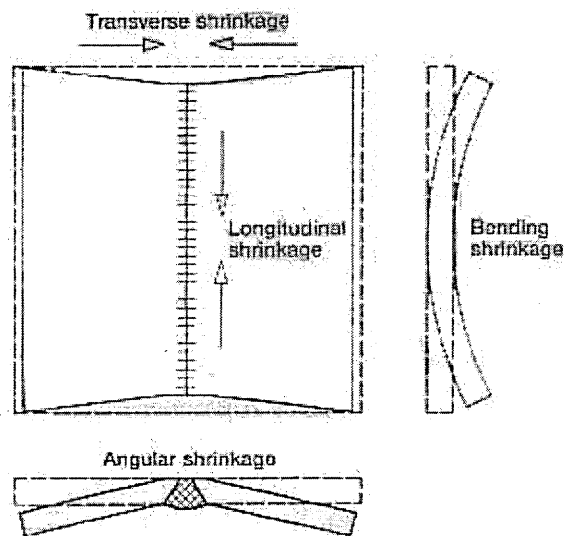


Figure 24: Longitudinal, transverse, angular and bending shrinkage of rectangular plate with single-side welded centric jointing seam After Radaj [72].

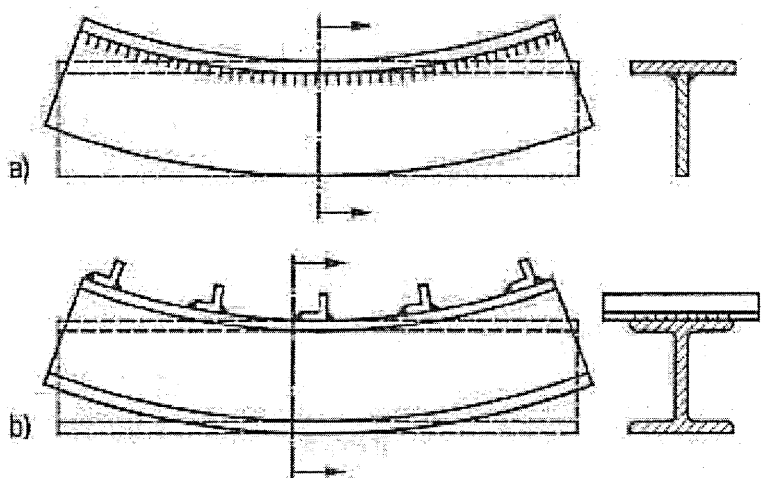


Figure 25: Bending deformation of girders with eccentric welds. a) longitudinal weld b) transverse weld. After Radaj [72].

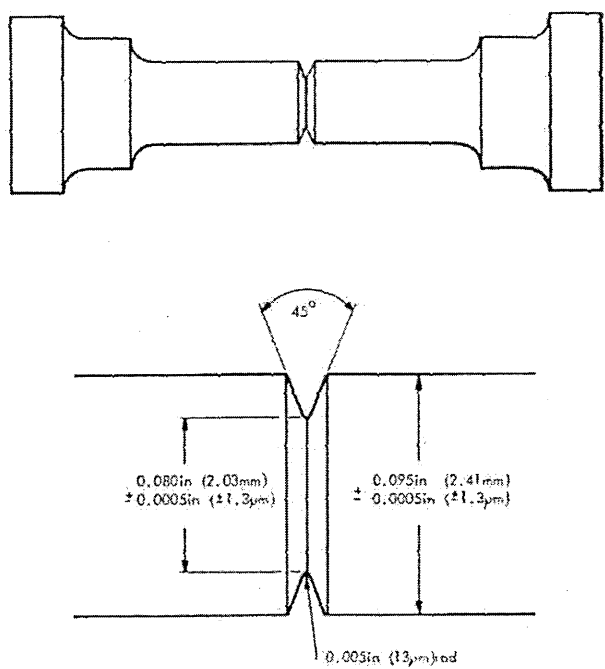


Figure 26: Notch tensile specimen used for the CLR test. After Boniszewski [44].

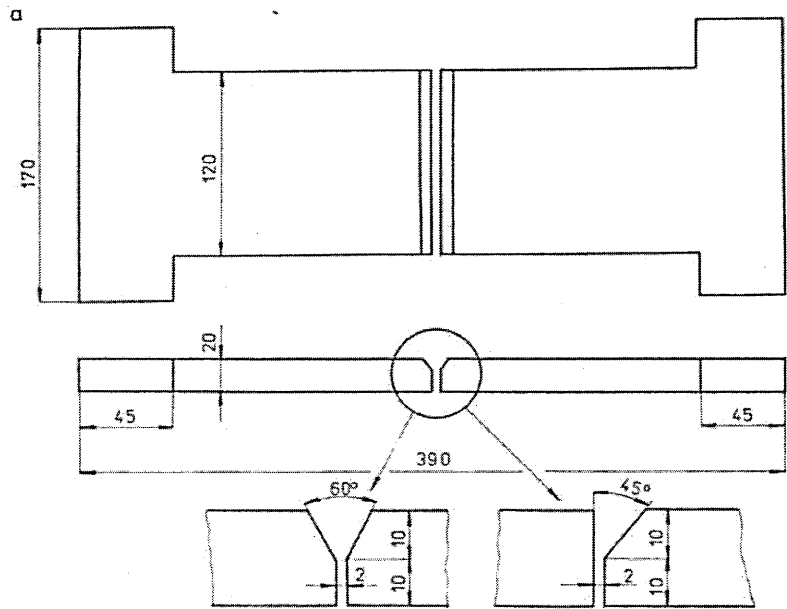


Figure 27: Schematic of TRC test. After Hrivnak [9].

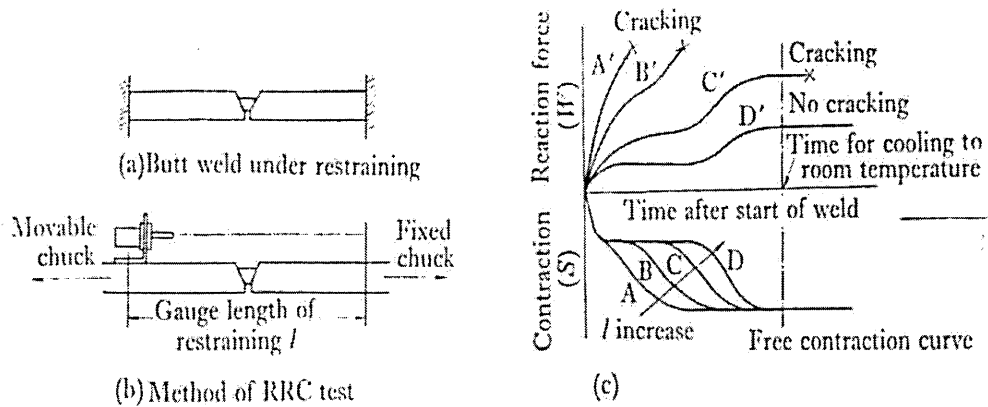


Figure 28: Rigid restraint cracking RRC test. After Satoh [77].

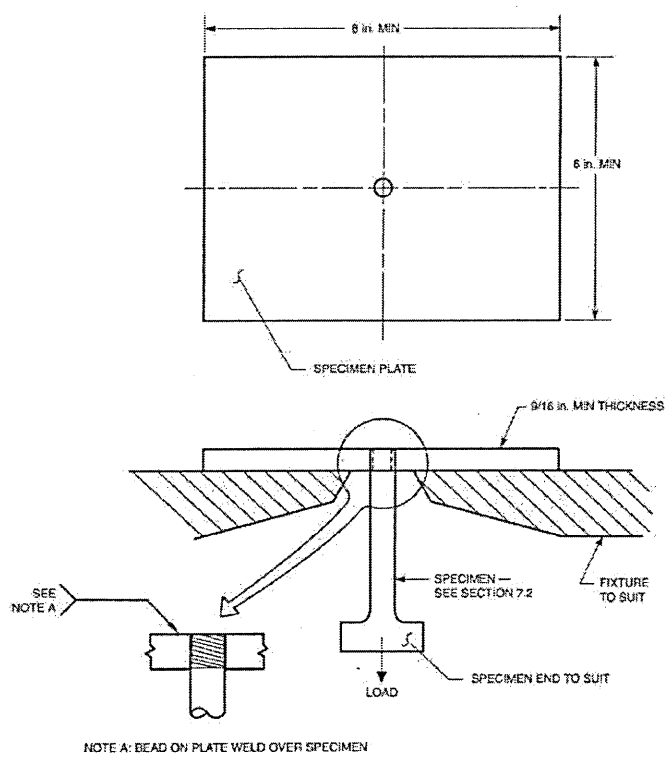


Figure 29: Implant test. After AWS [81].

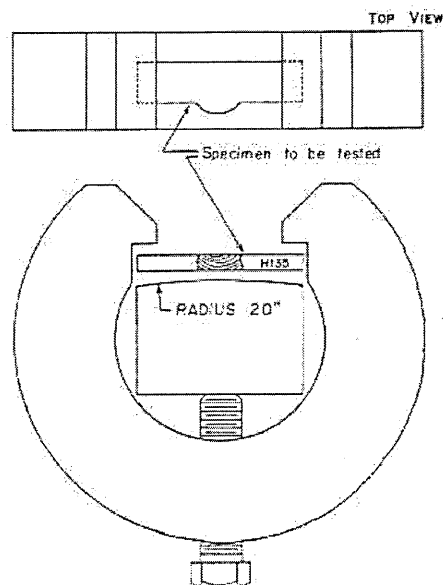


Figure 30: Augmented-strain cracking test fixture. After Savage [49].

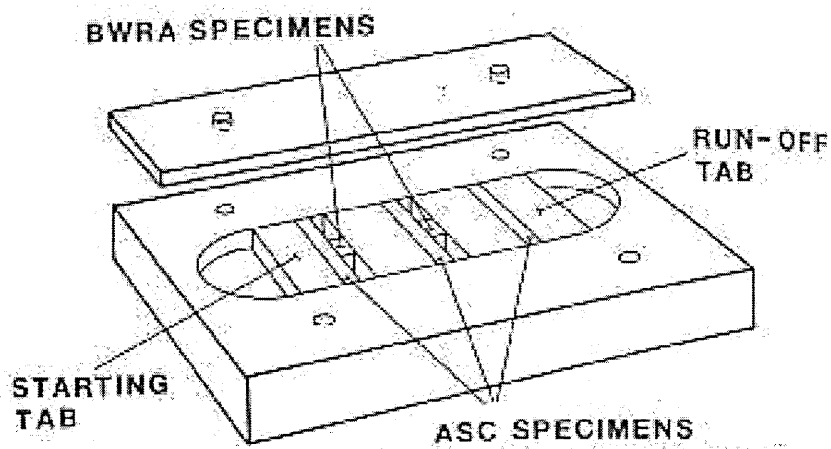


Figure 31: Samples preparation for ASC test. After Savage [79].

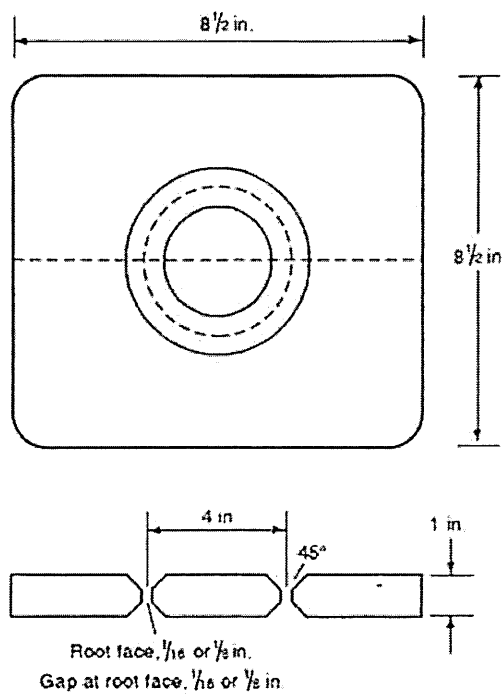


Figure 32: Plate specifications for circular patch test. After Stout [123].

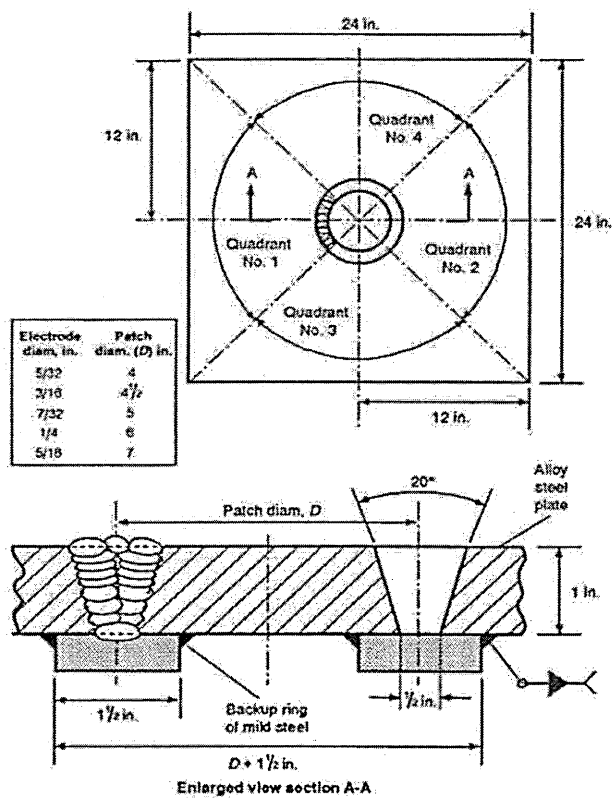


Figure 33: Plate requirements for Navy circular patch test. After Stout [123].

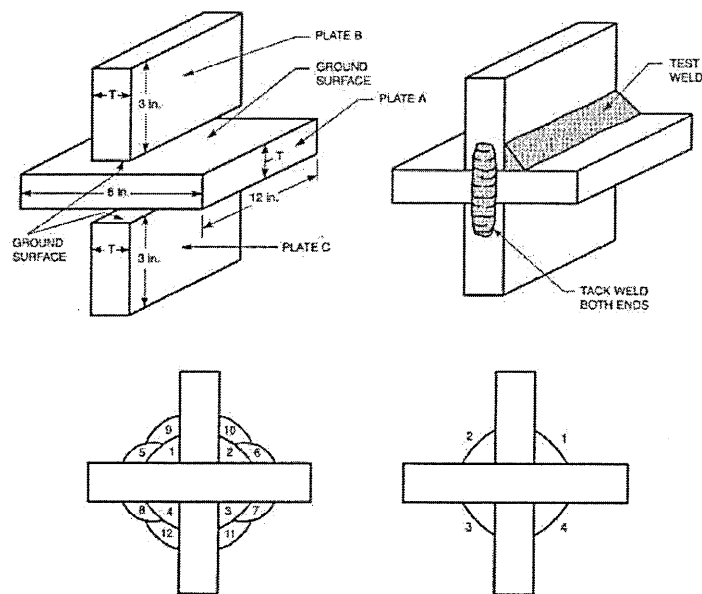


Figure 34: Specifications for cruciform cracking test specimens. After AWS [81].

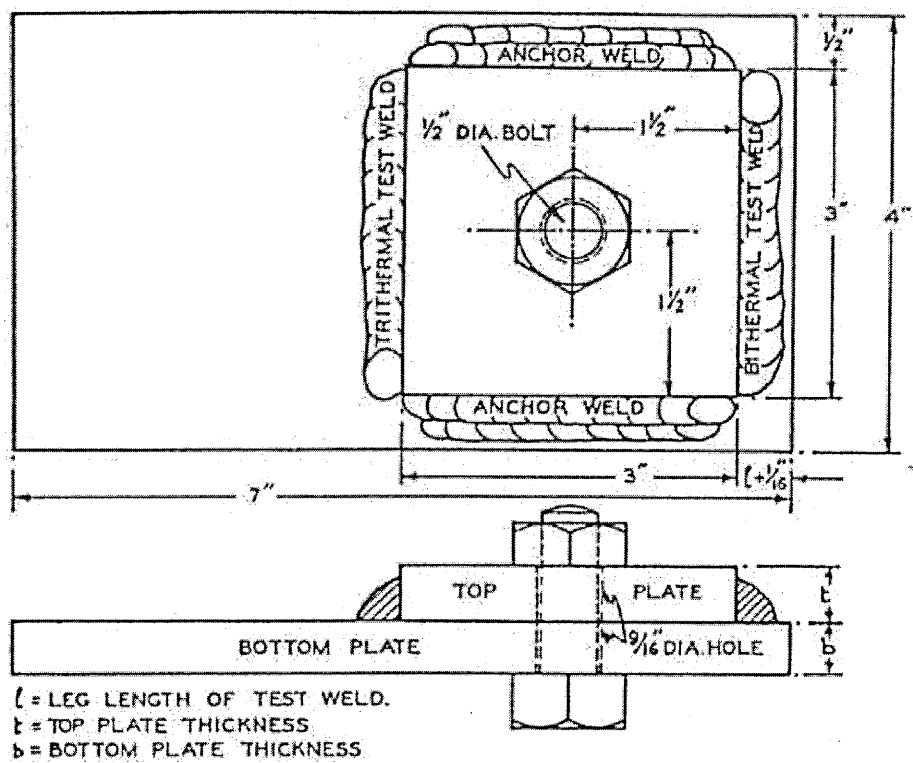


Figure 35: CTS weldability test assembly for alloy steel. After Cottrell [51].

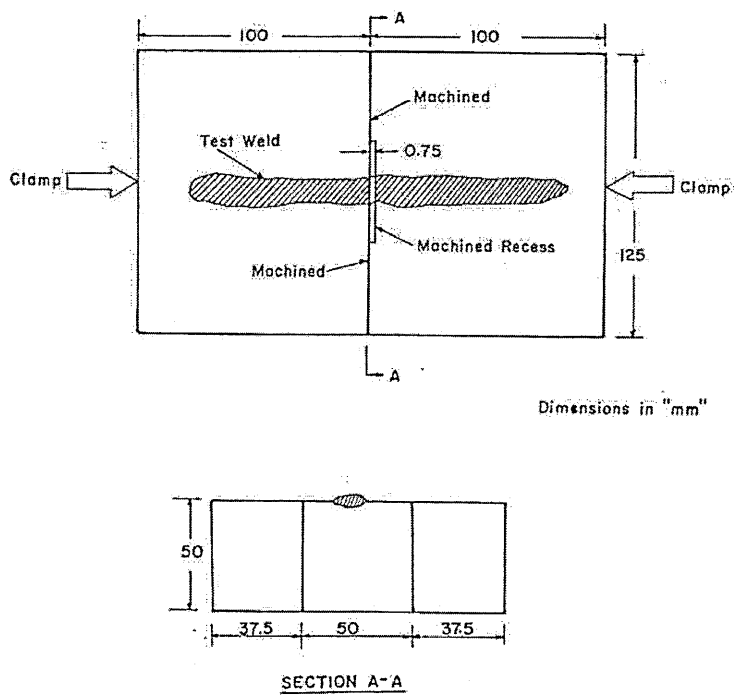


Figure 36: Standard G-BOP test. After Graville [46].

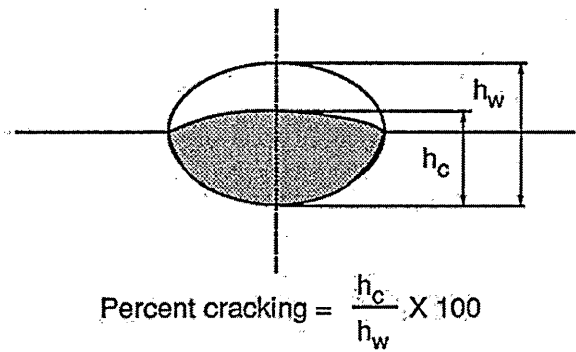


Figure 37: G-BOP measurement of percentage cracking. After Graville [5].

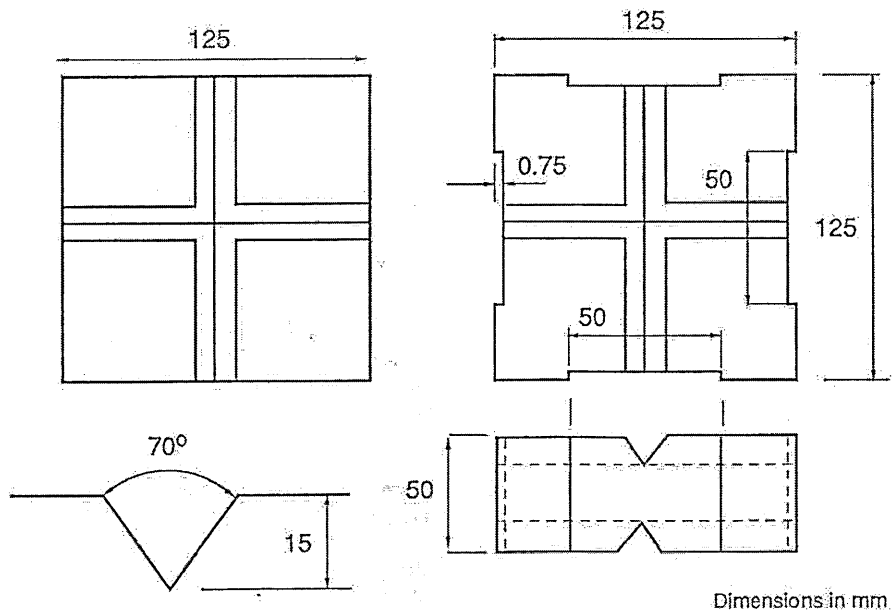


Figure 38: G-BOP test modified for multipass welds. After Graville [5].

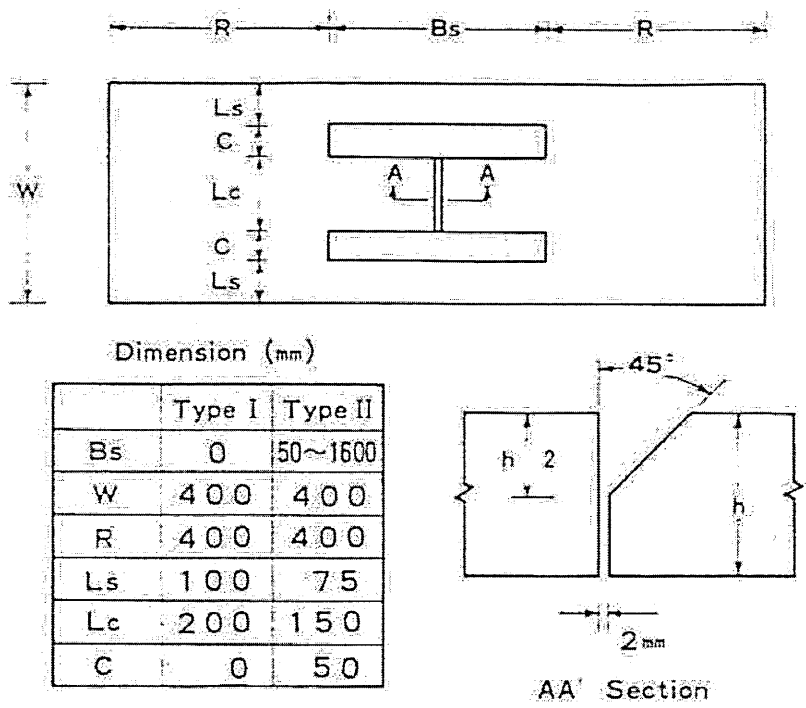


Figure 39: H slit test configuration. After Yurioka [88].

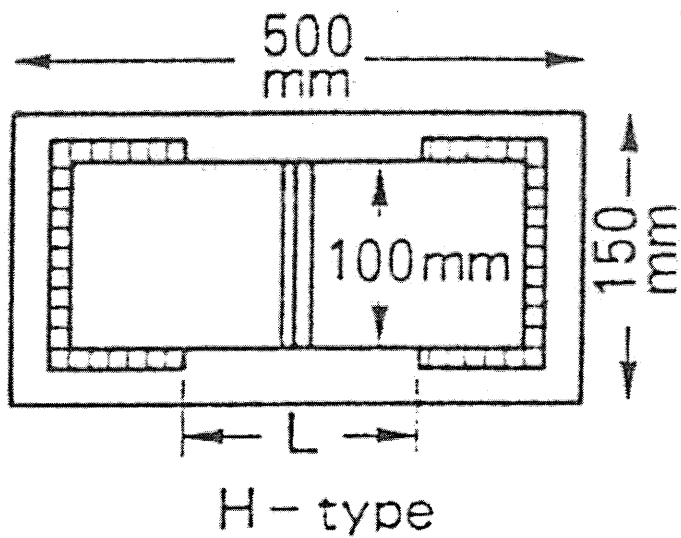


Figure 40: H type restraint cracking test. After Yurioka [26].

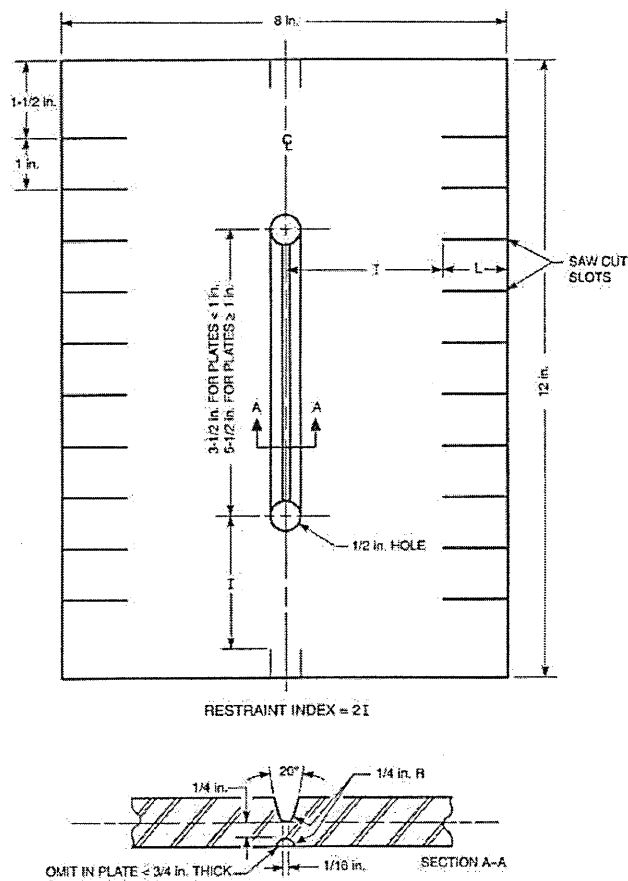


Figure 4.1: Lehigh Restraint Test. After AWS [81].

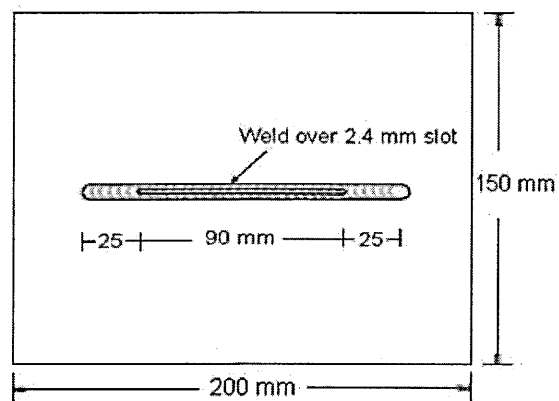


Figure 42: Slot weld test design. After Stout [86].

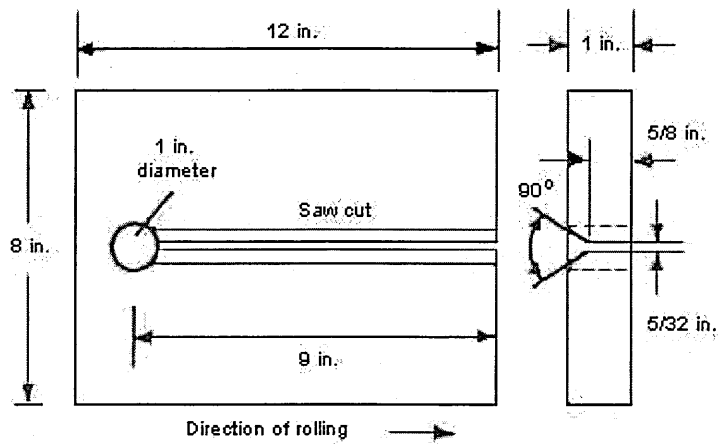


Figure 43: Plate specifications for NRL keyhole restraint test. After Campbell [80].

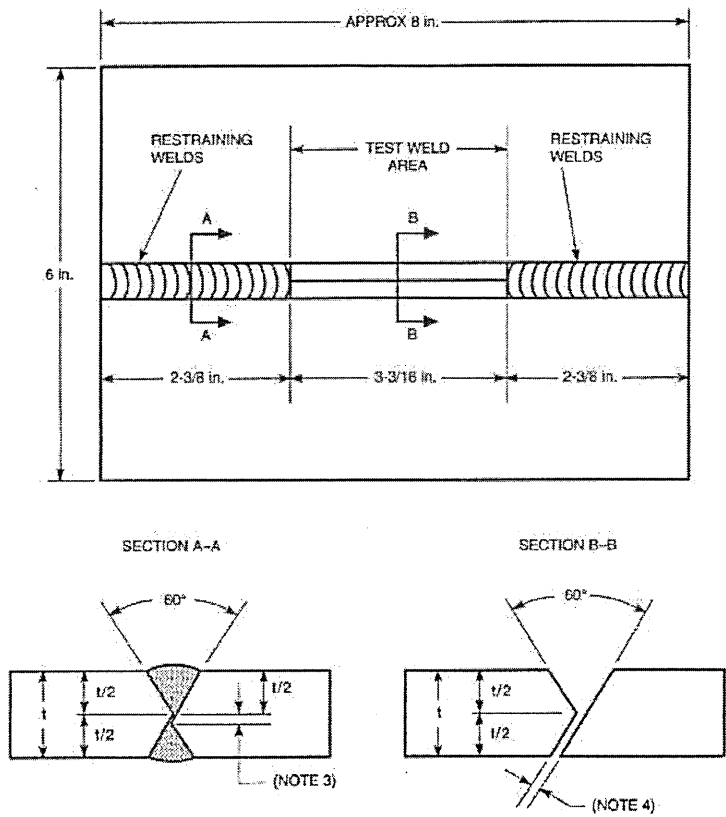


Figure 44: Tekken test. After AWS [81].

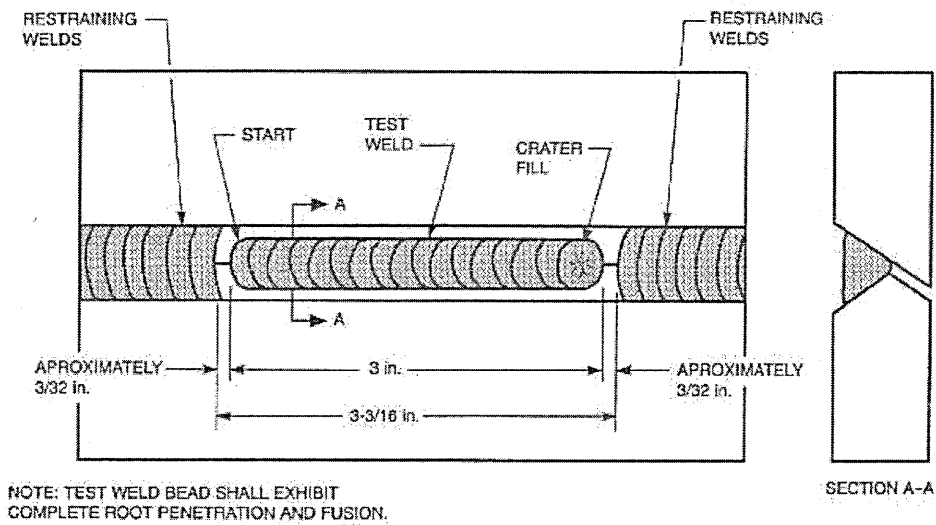


Figure 45: Tekken test. After AWS [81].

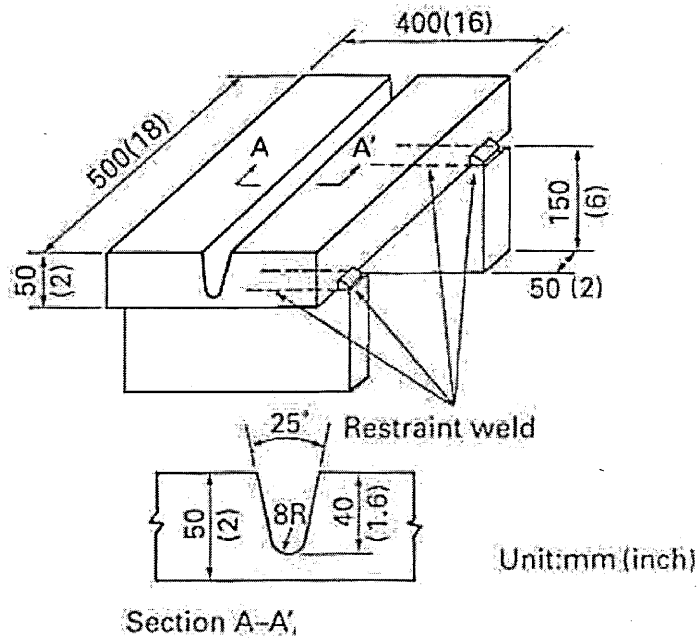


Figure 46: Multipass U – groove cracking test. After Vuik [124].

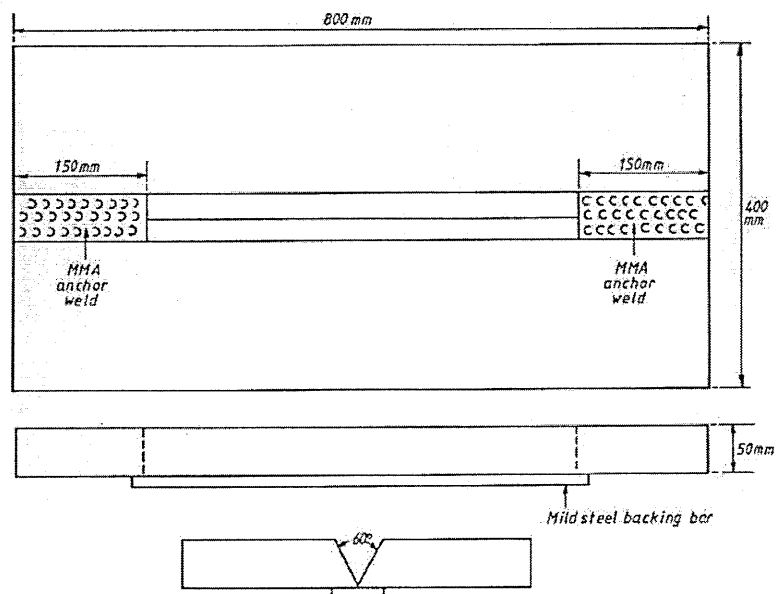


Figure 47: Flat plate HACC susceptibility test adopted by Jones [90]

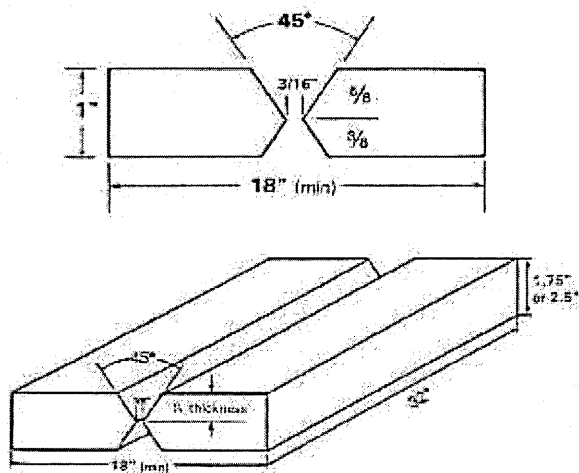


Figure 48: Flat plate HACC susceptibility test adopted by Devletian [91].

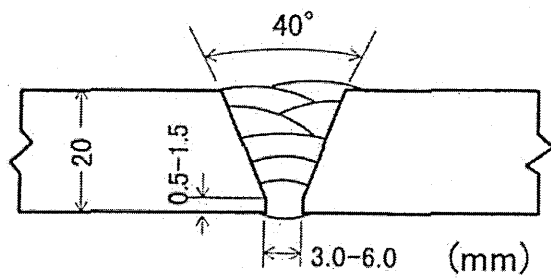


Figure 49: Japanese groove preparation for pipeline girth conventional GMAW. After Ushio [125].

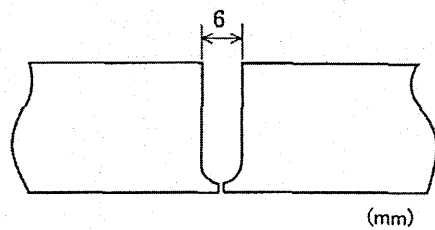


Figure 50: Japanese groove preparation for pipeline narrow gap GMAW. After Ushio [125].

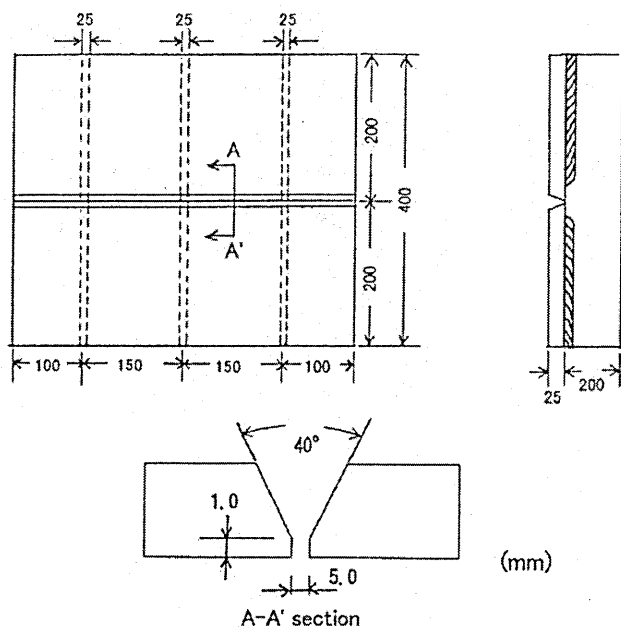


Figure 51: Test plate assembly for a restraint multiple-layer cracking test. After Ushio [125].

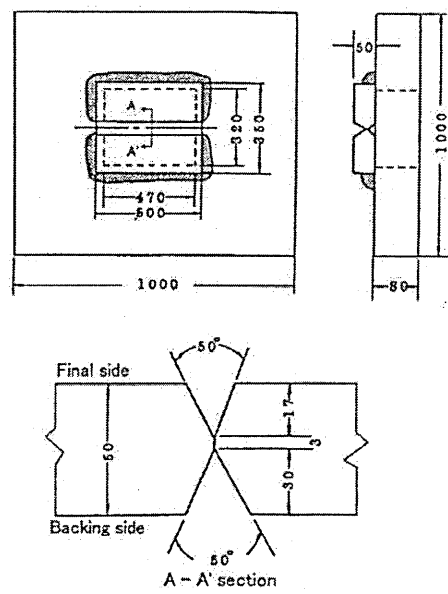


Figure 52: Test plate assembly for the window-type restraint multiple-layer cracking test. Ushio[125].

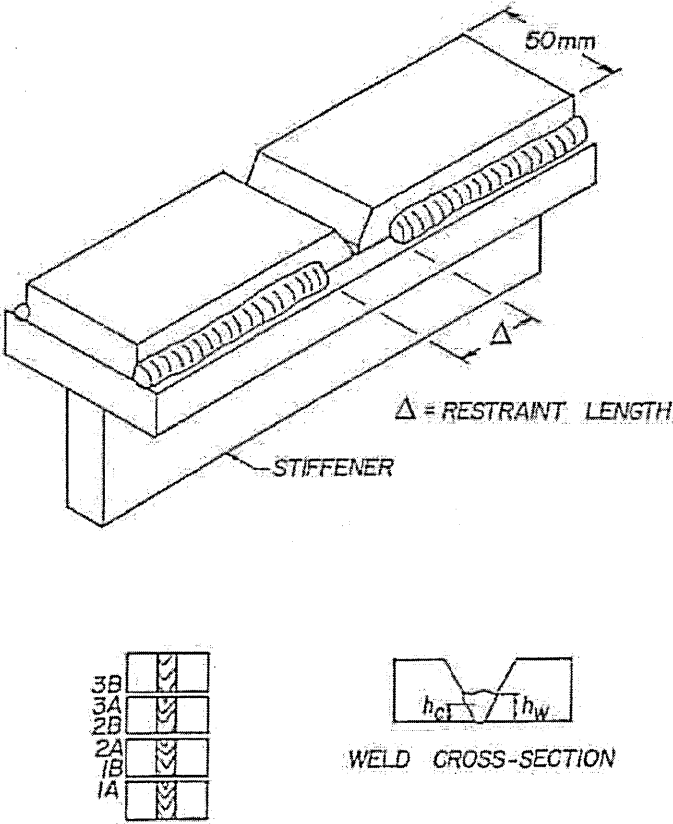


Figure 53: Drawing of the WIC test set ($\Delta = L$). After Lazor [94].

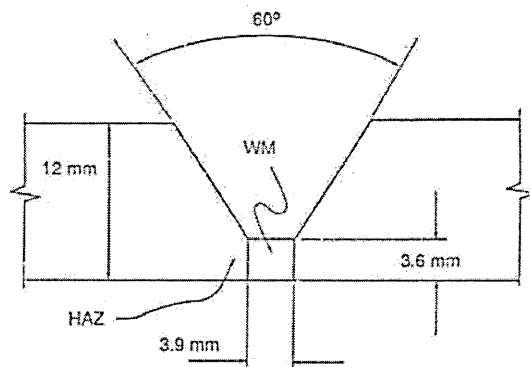


Figure 54: WIC test transverse section. After Graville [97].

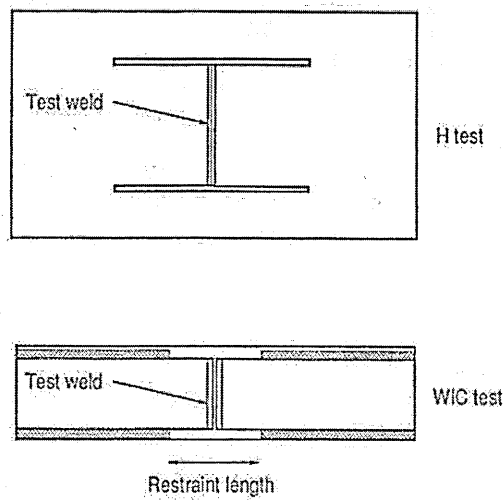


Figure 55: WIC test x H slit test. After Graville [5].

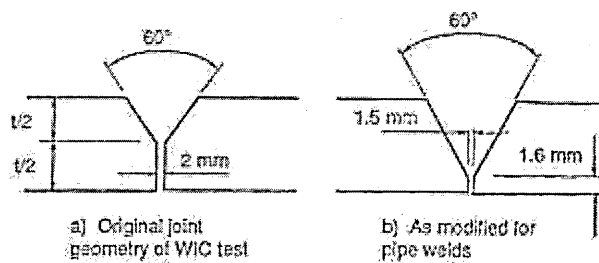


Figure 56: WIC test geometry change for pipeline girth weld. After Graville [5].

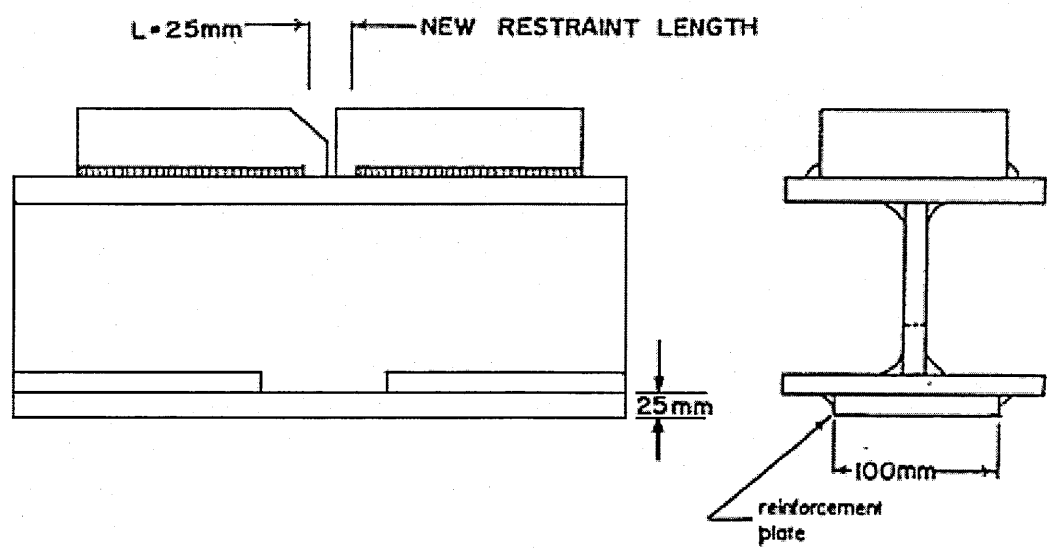


Figure 57: WIC test variation. After Patchett [96].

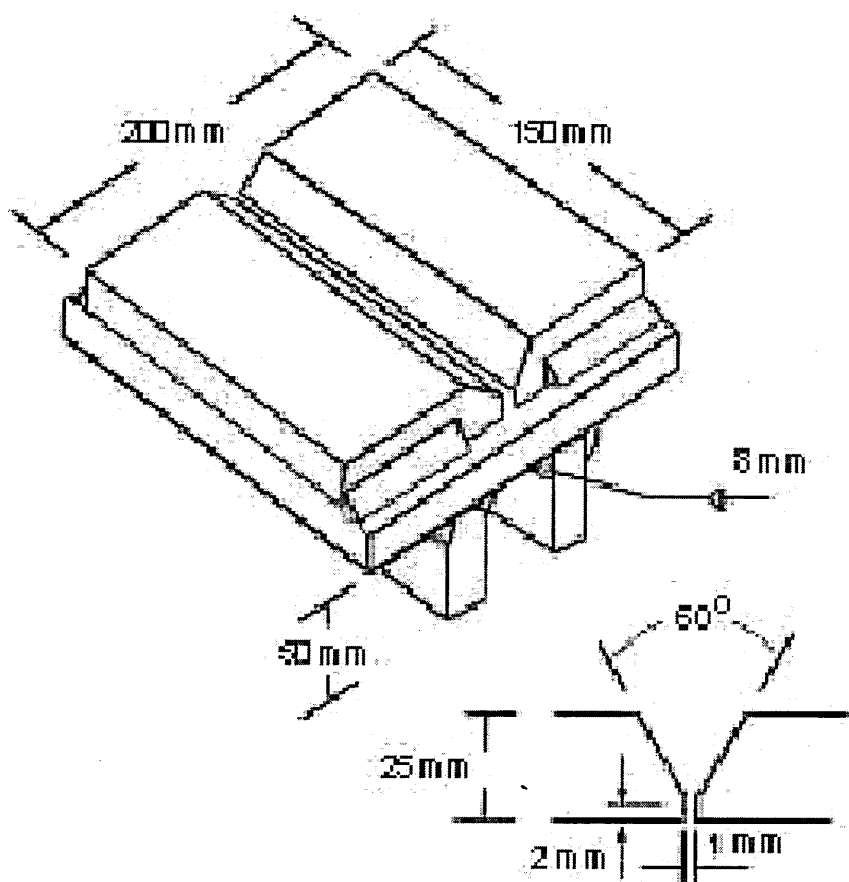


Figure 58: LRC test created by Wang [29].

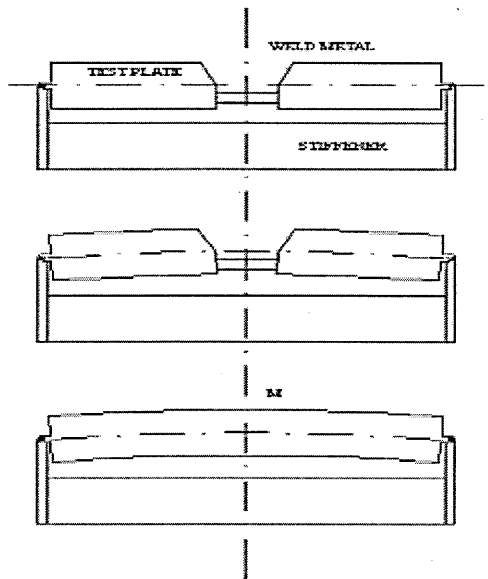


Figure 59: Model adopted for the compatibility of displacement.

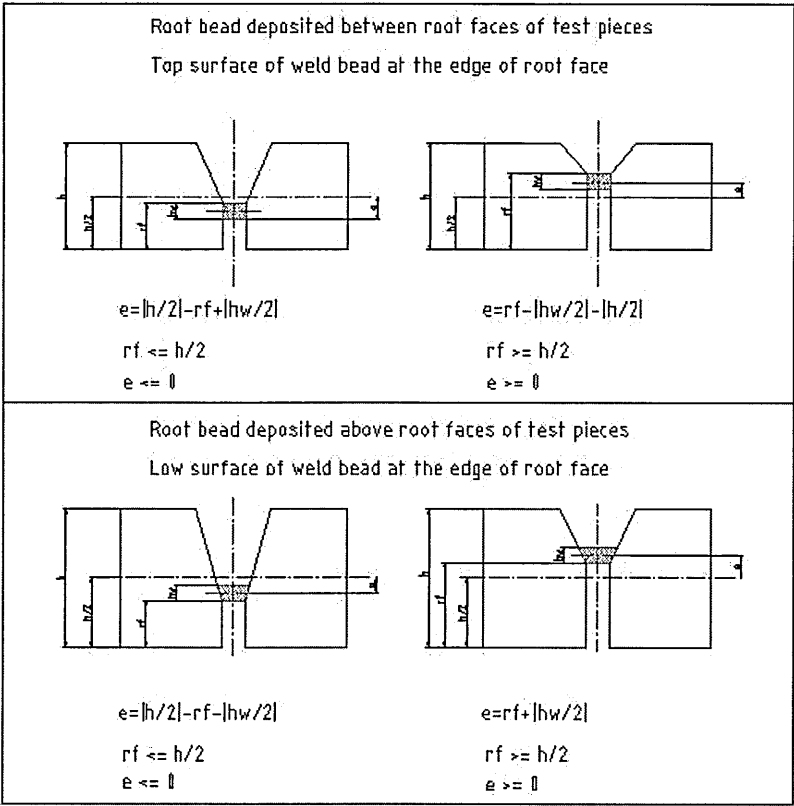


Figure 60: Eccentricity diagrams.

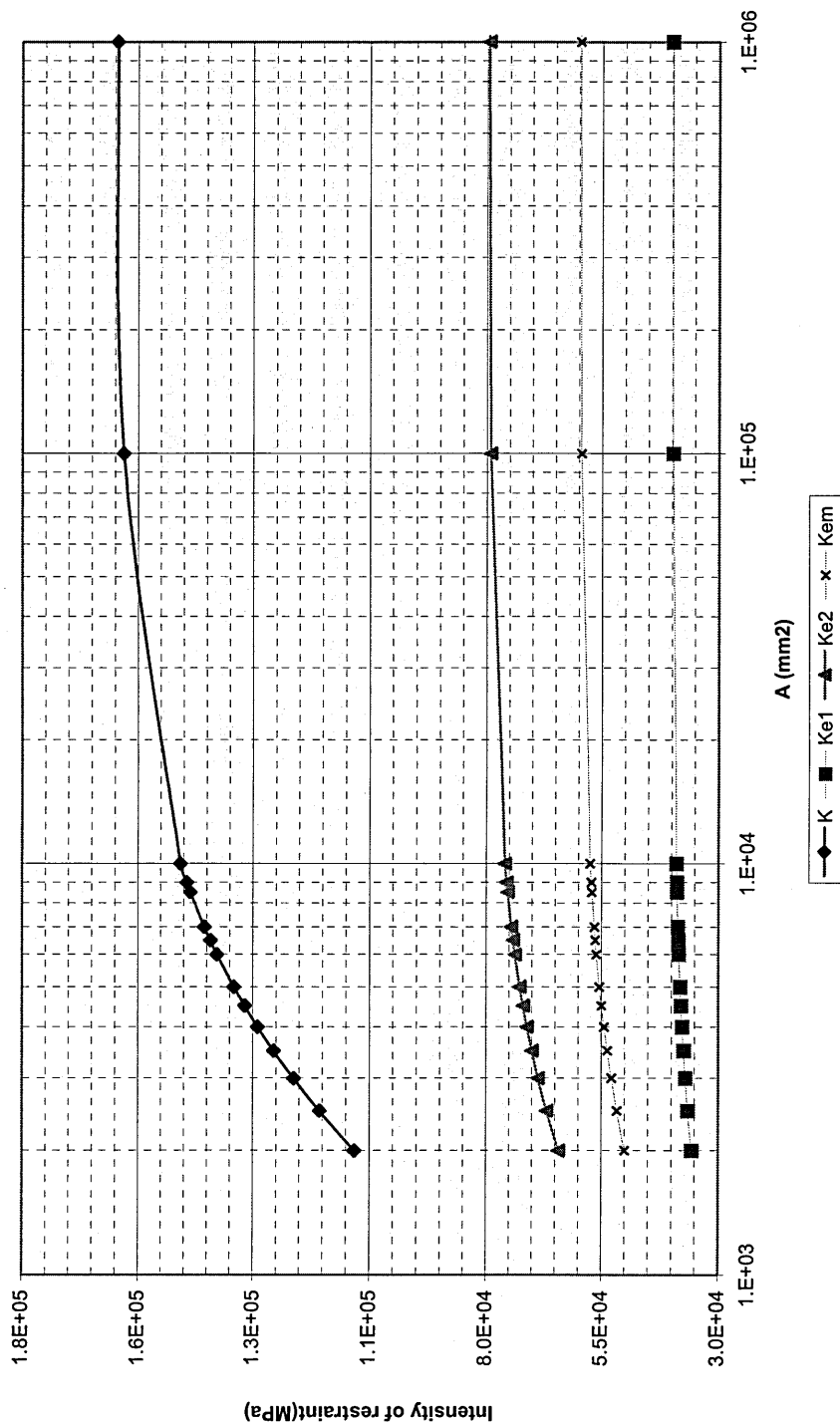


Figure 61: Analytical assessment - effect of A_S on intensity of restraint. See

Table 5.

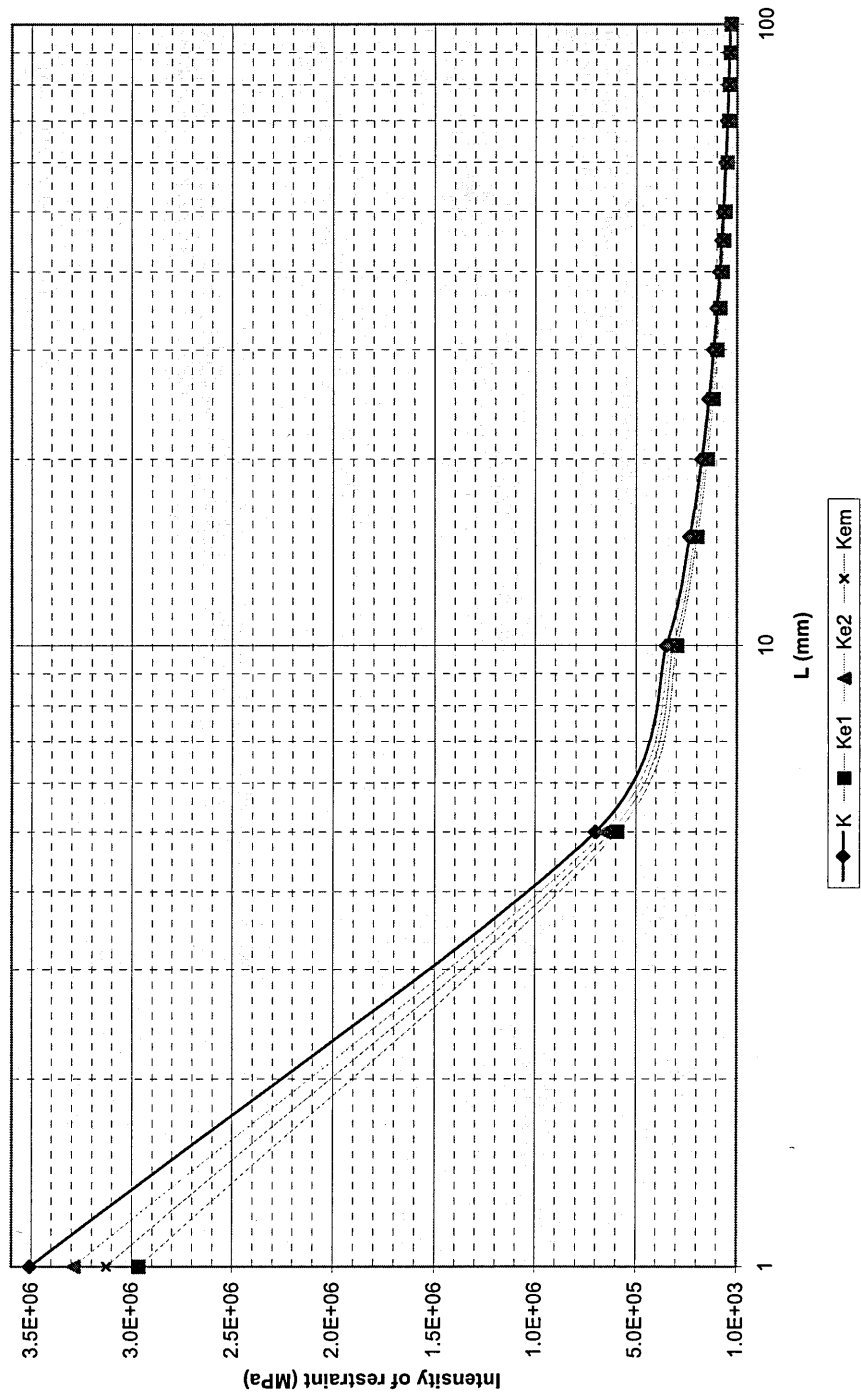


Figure 62: Analytical assessment - effect of L on intensity of restraint. See Table 6.

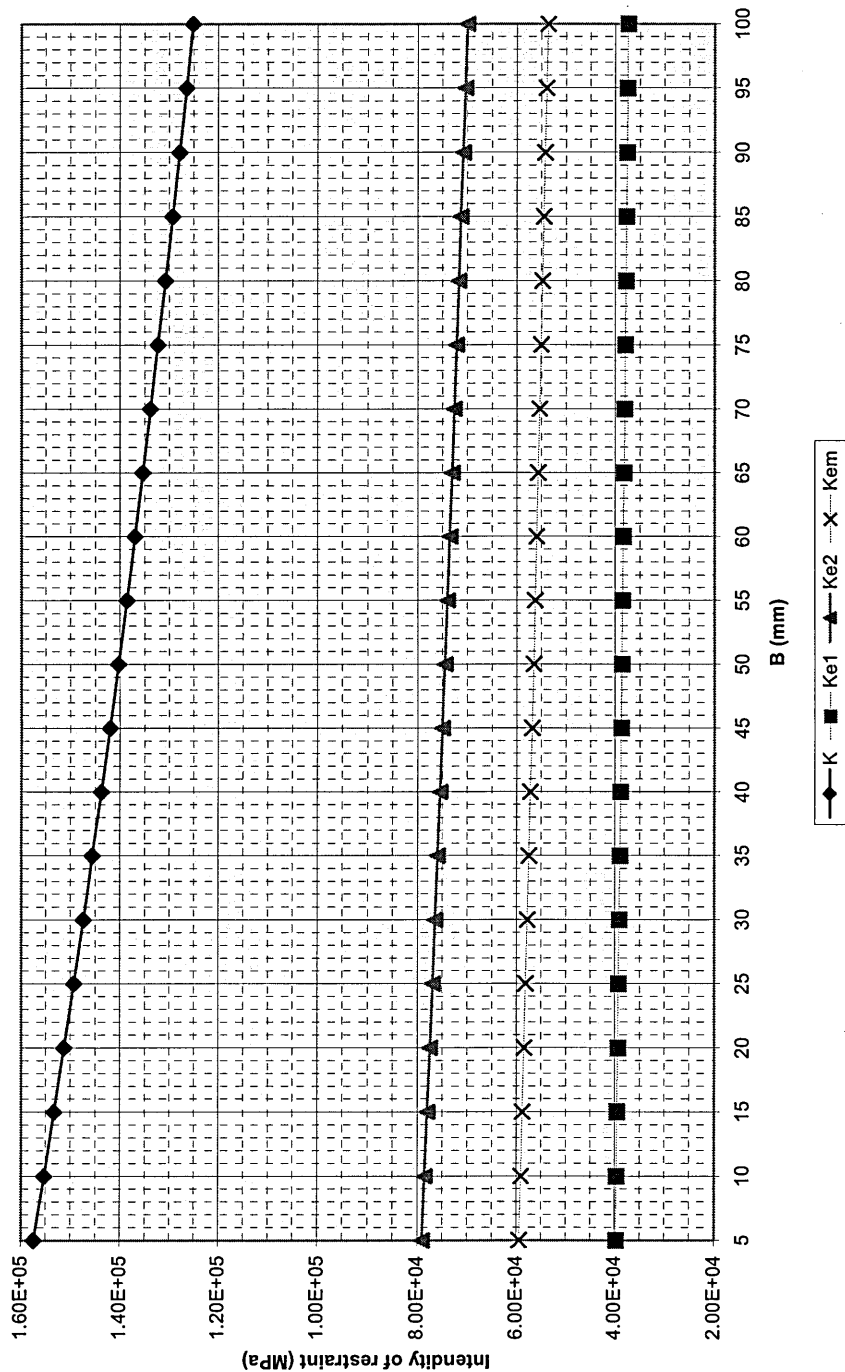


Figure 63: Analytical assessment - effect of B on intensity of restraint. See Table 7.

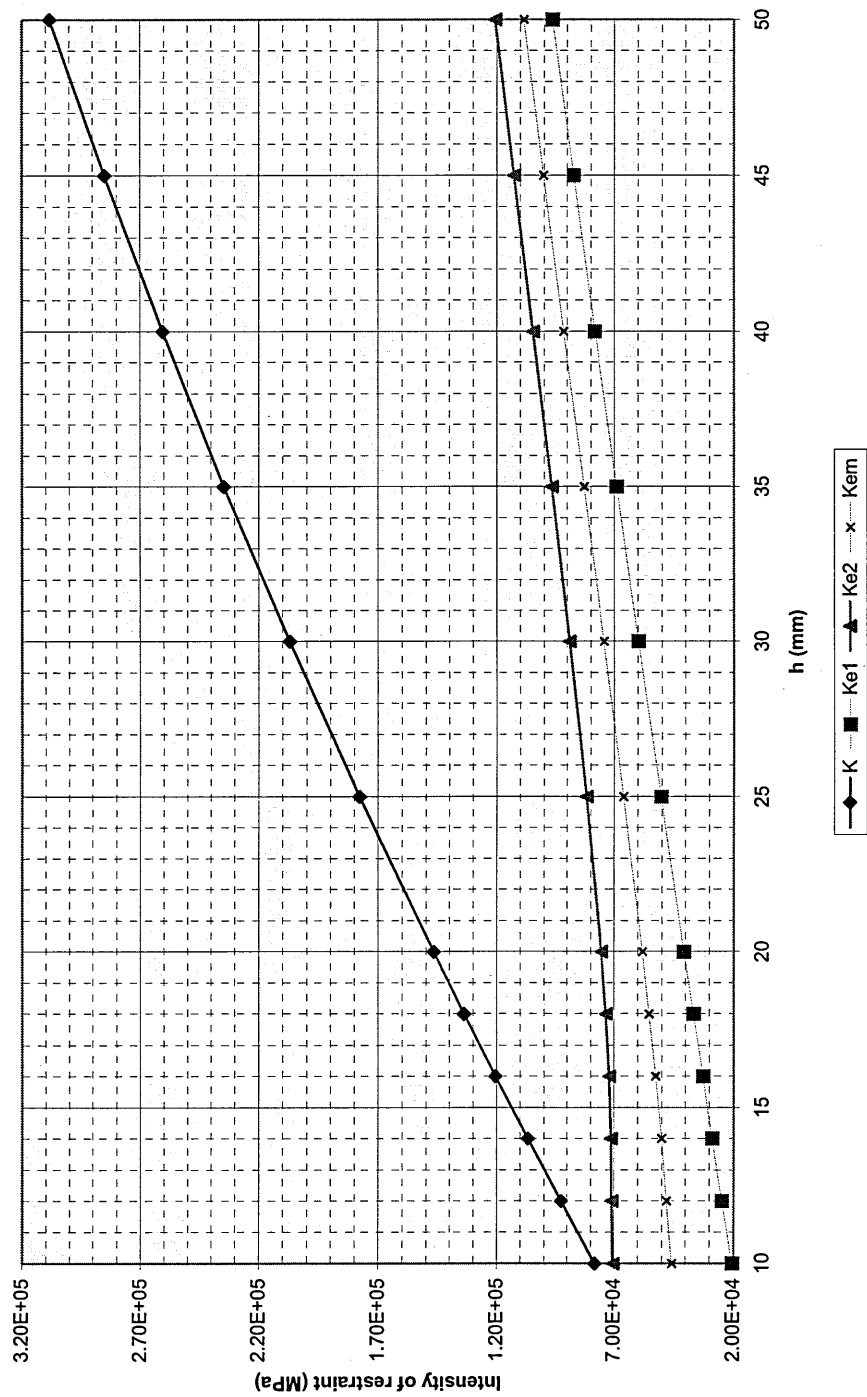


Figure 64: Analytical assessment - effect of h on intensity of restraint. See Table 8.

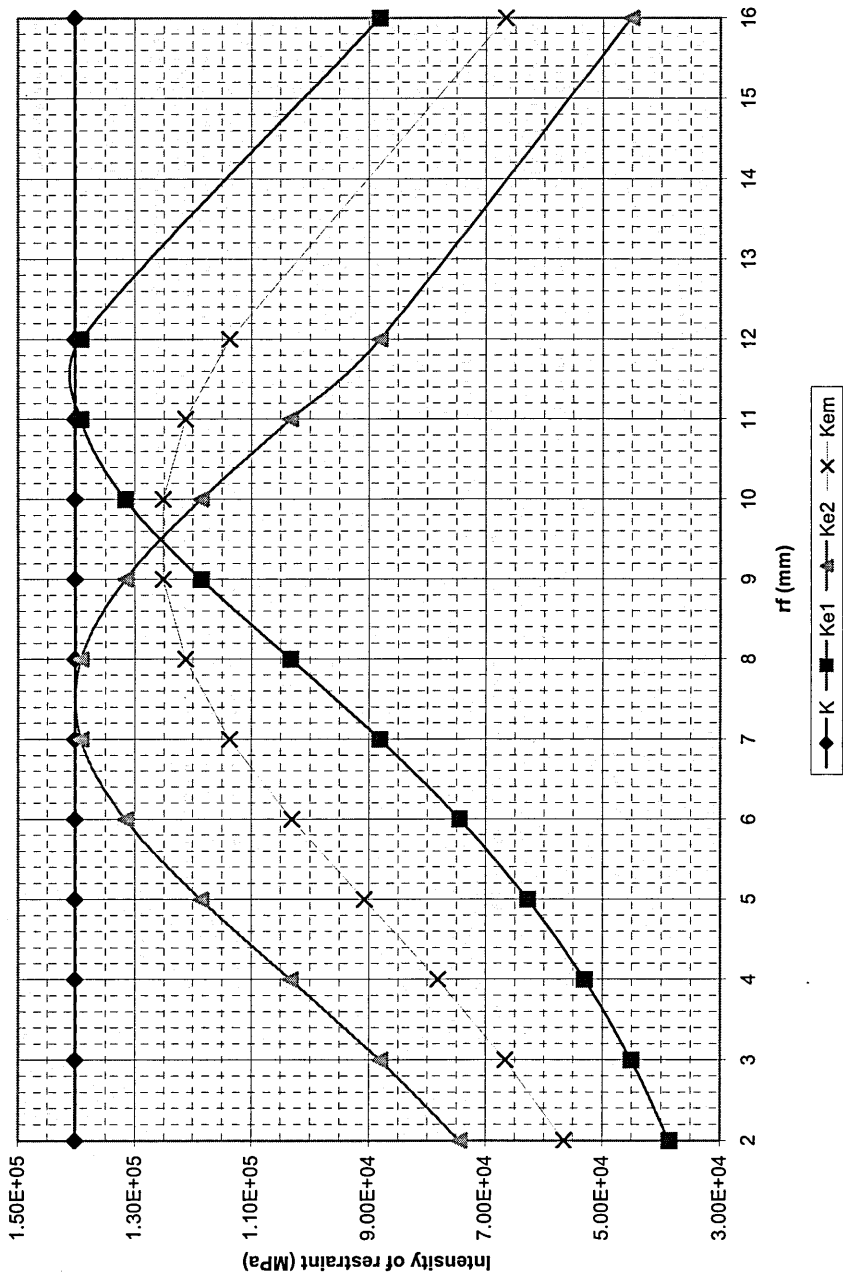


Figure 65: Analytical assessment - effect of rf on intensity of restraint. See Table 9.

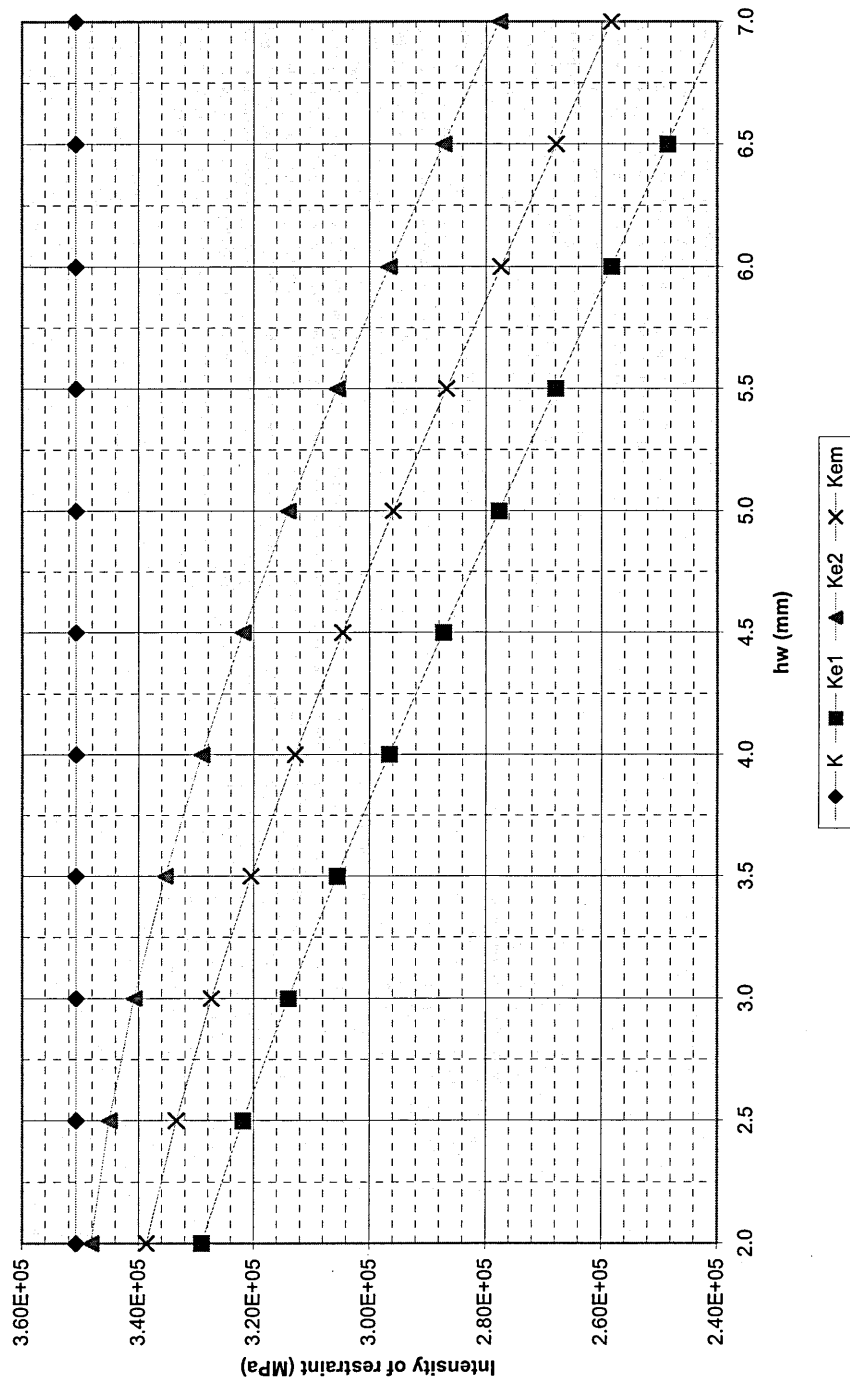


Figure 66: Analytical assessment - effect of h_w on intensity of restraint. See Table 10.

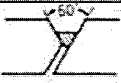
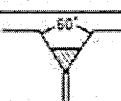
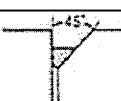
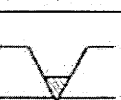
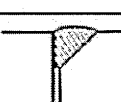
Groove type		Kt
y (root)		4
Double-Vee (root)		3.5
Y (root)		4~5
Single-bevel (root)		6~8
V (root)		1.5
y, x, Y, V, U (toe)		1.5

Figure 67: Stress concentration factors at welds. After Yurioka [88].

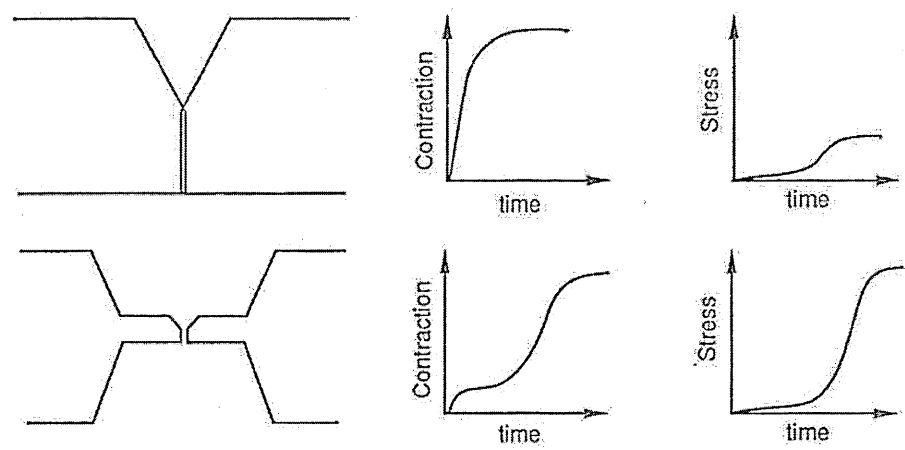


Figure 68: Effect of joint geometry on contraction and reaction stress during cooling. After Graville [5].

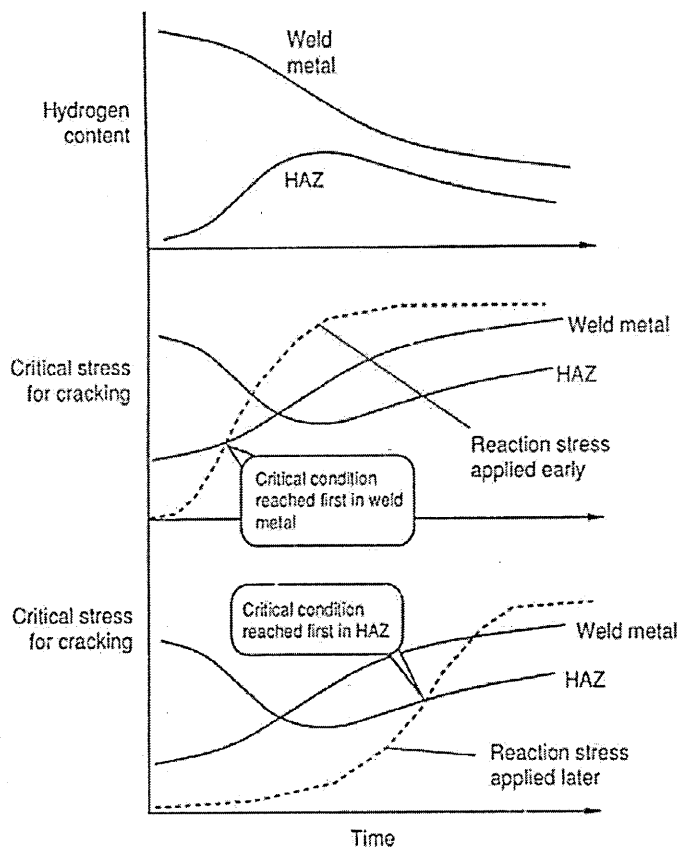


Figure 69: Reaction stress effect on WM and HAZ cracking. After Matsuda [102]

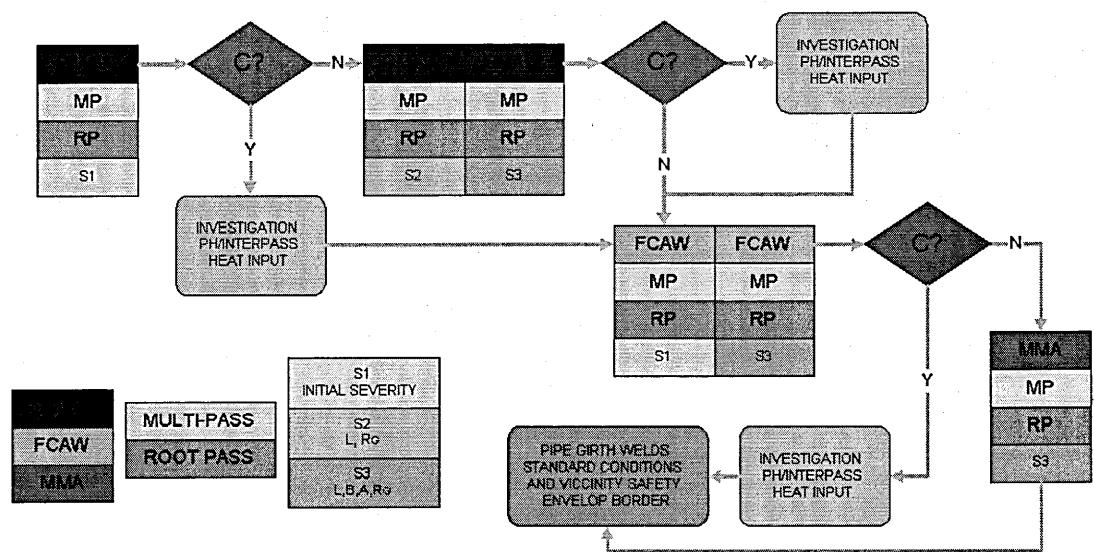
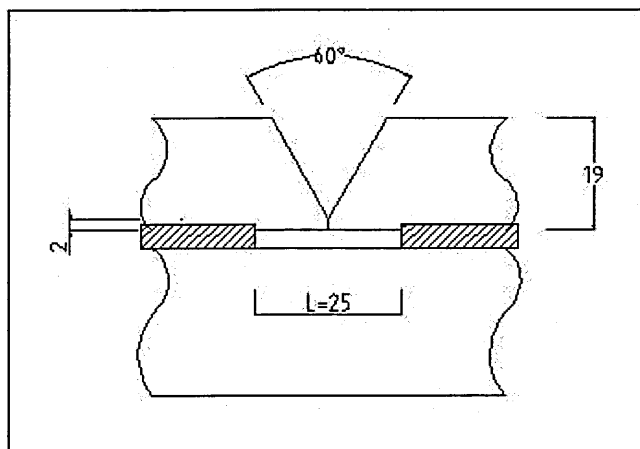
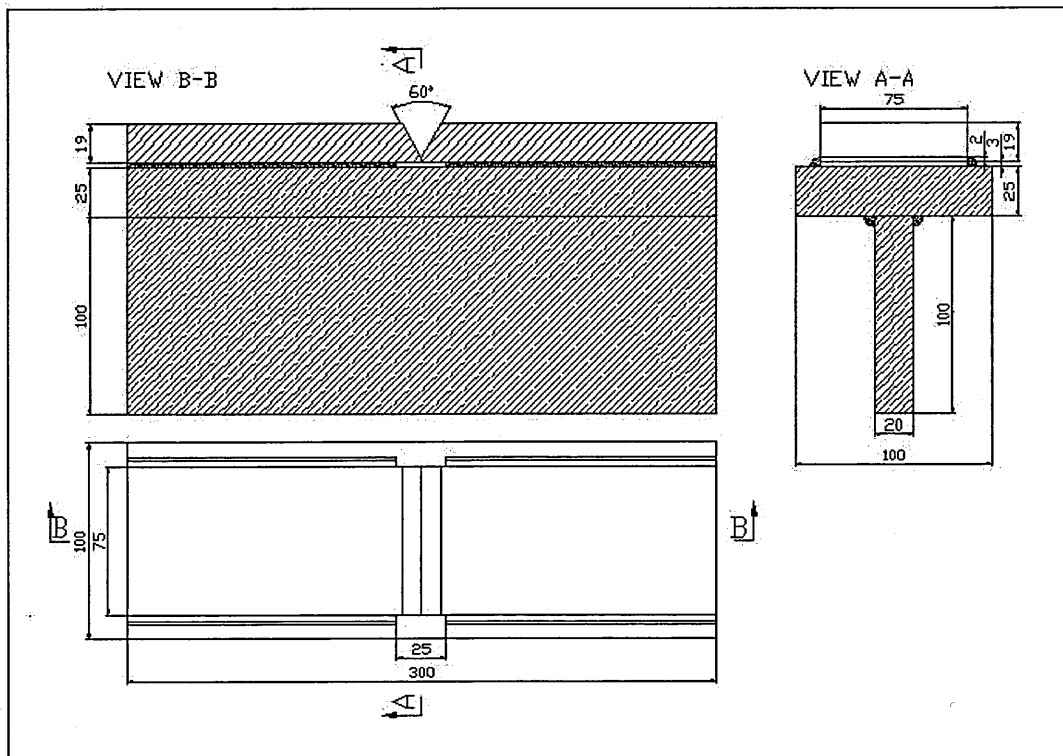


Figure 70: The logic of the experimentation process.

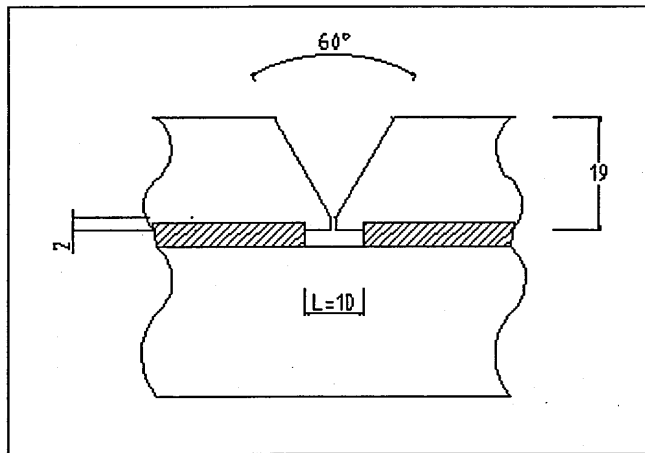
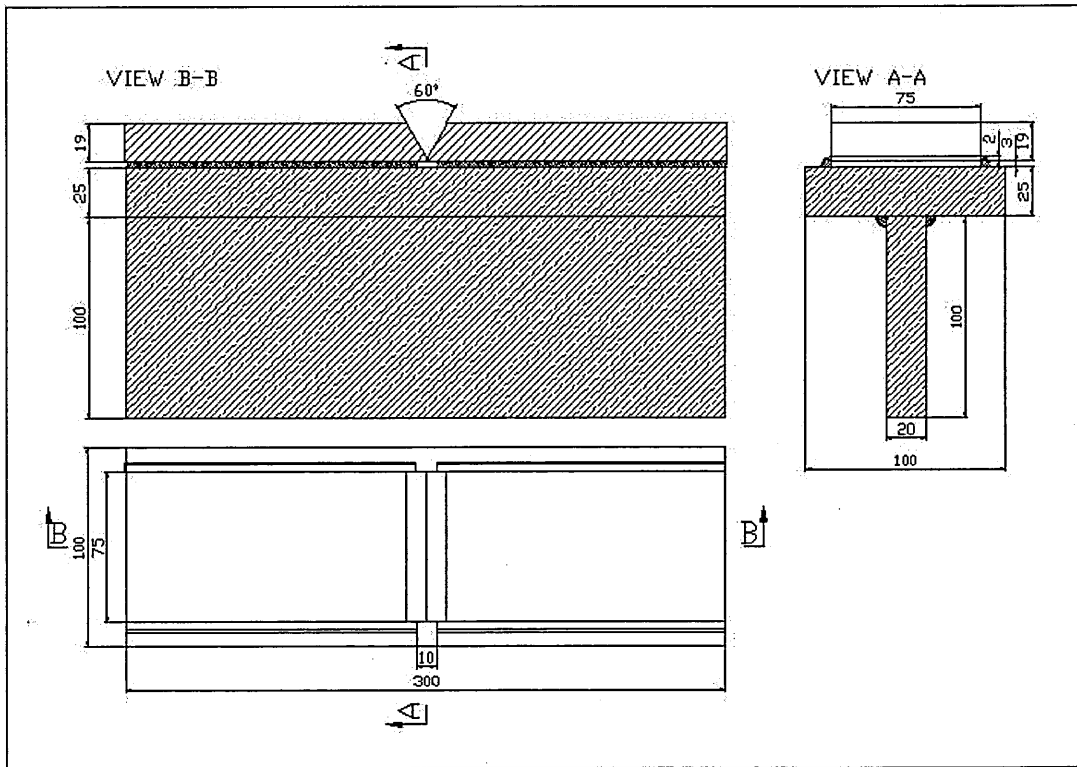


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 4500 \text{ mm}^2$

Root gap, $RG = 0 \text{ mm}$

Figure 71: S1 configuration - dimensional drawing.

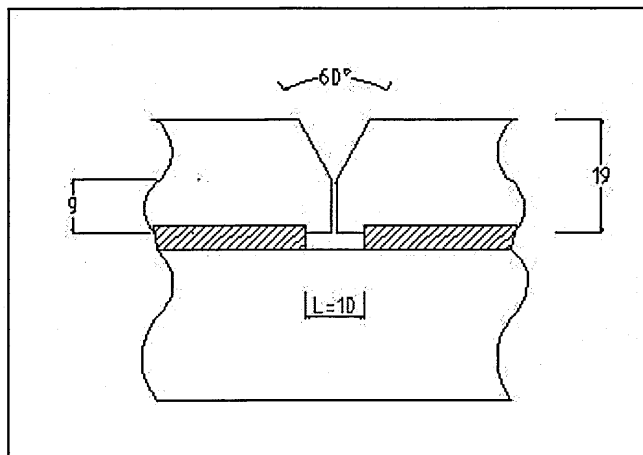
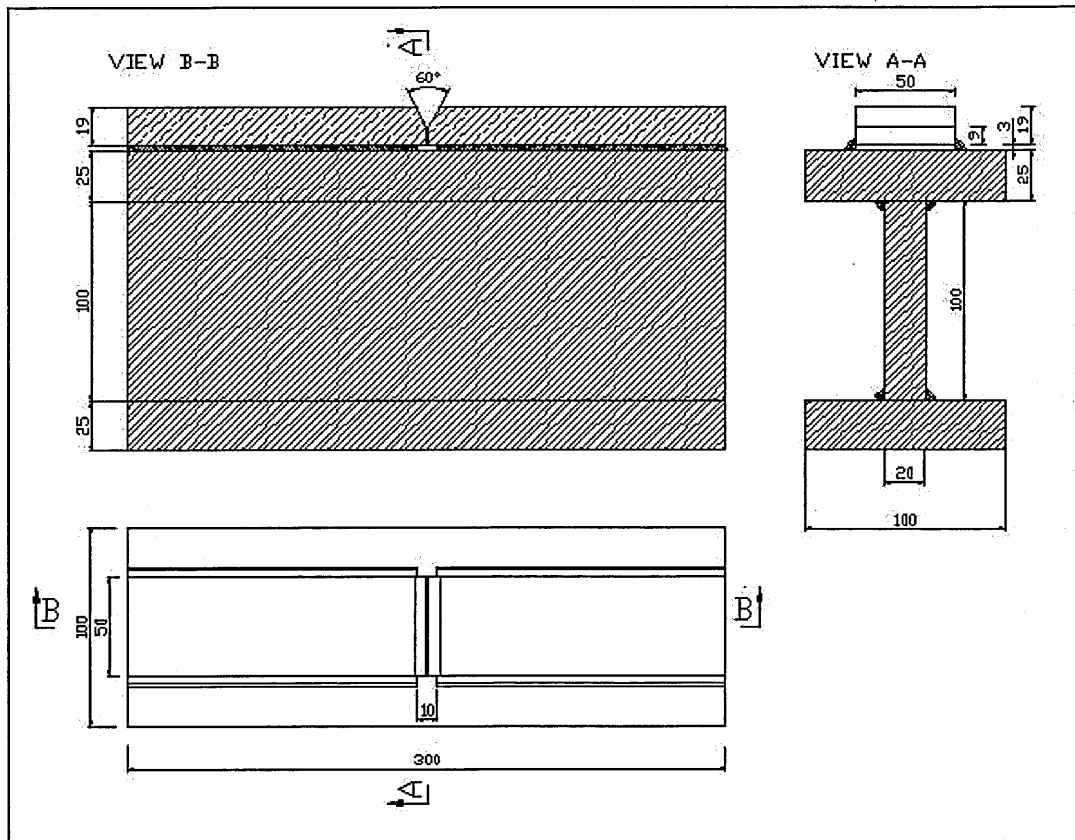


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 4500 \text{ mm}^2$

Root gap, $RG = 1 \text{ mm}$

Figure 72: S2 configuration - dimensional drawing.

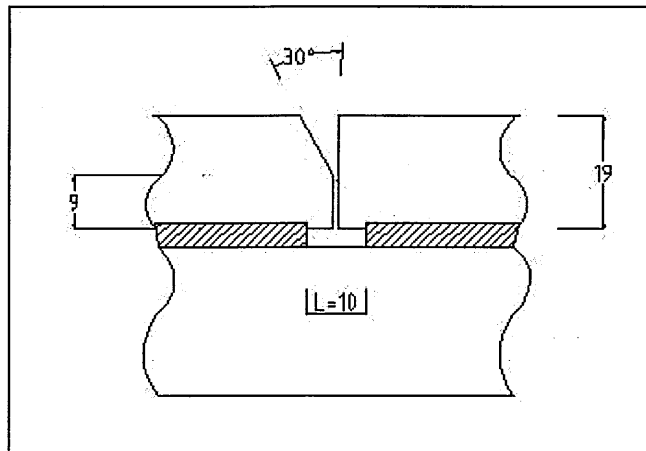
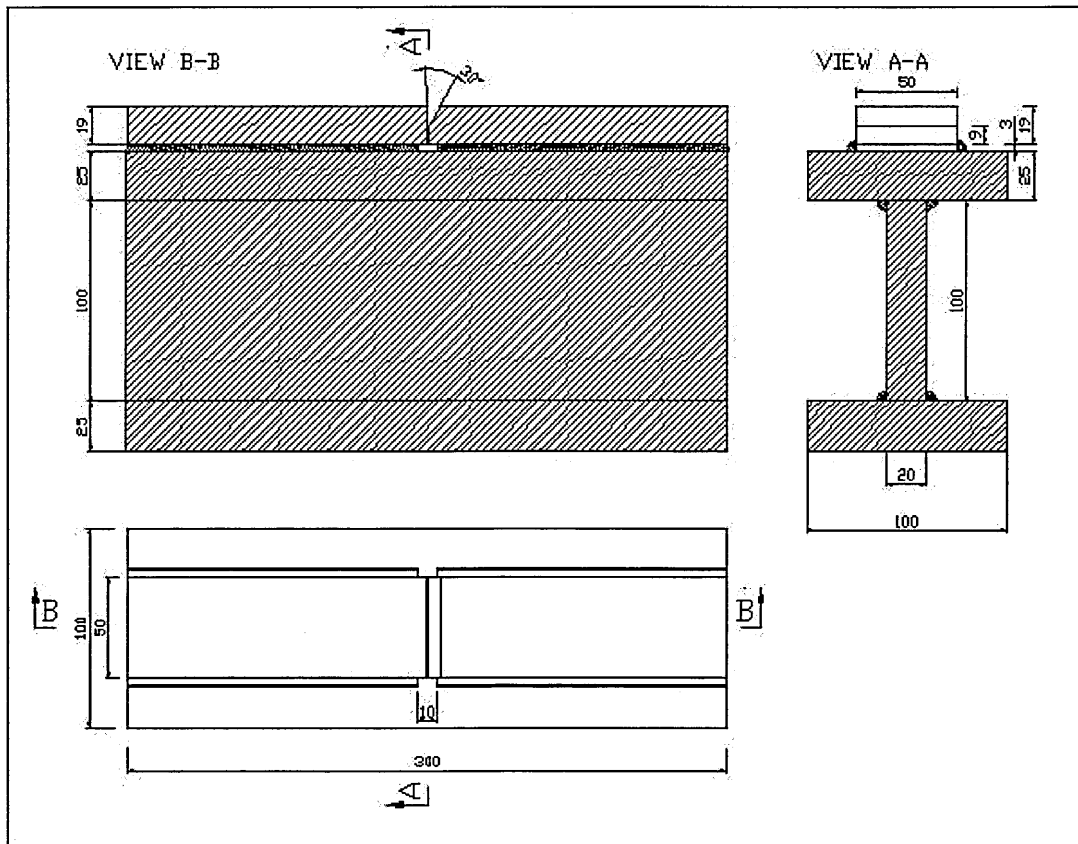


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 6900 \text{ mm}^2$

Root gap, $RG = 1 \text{ mm}$

Figure 73: S3 configuration - dimensional drawing.

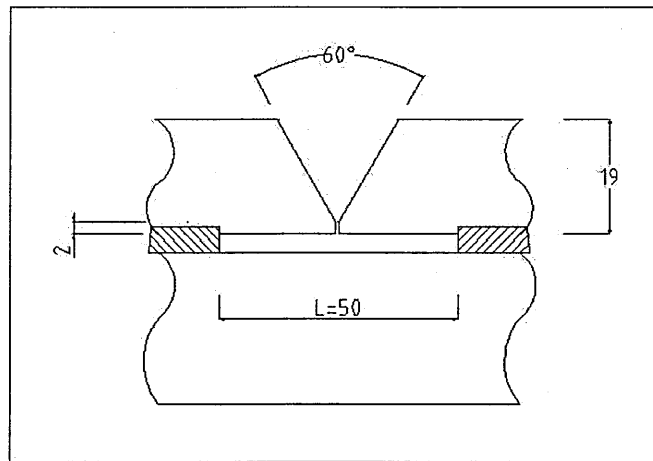
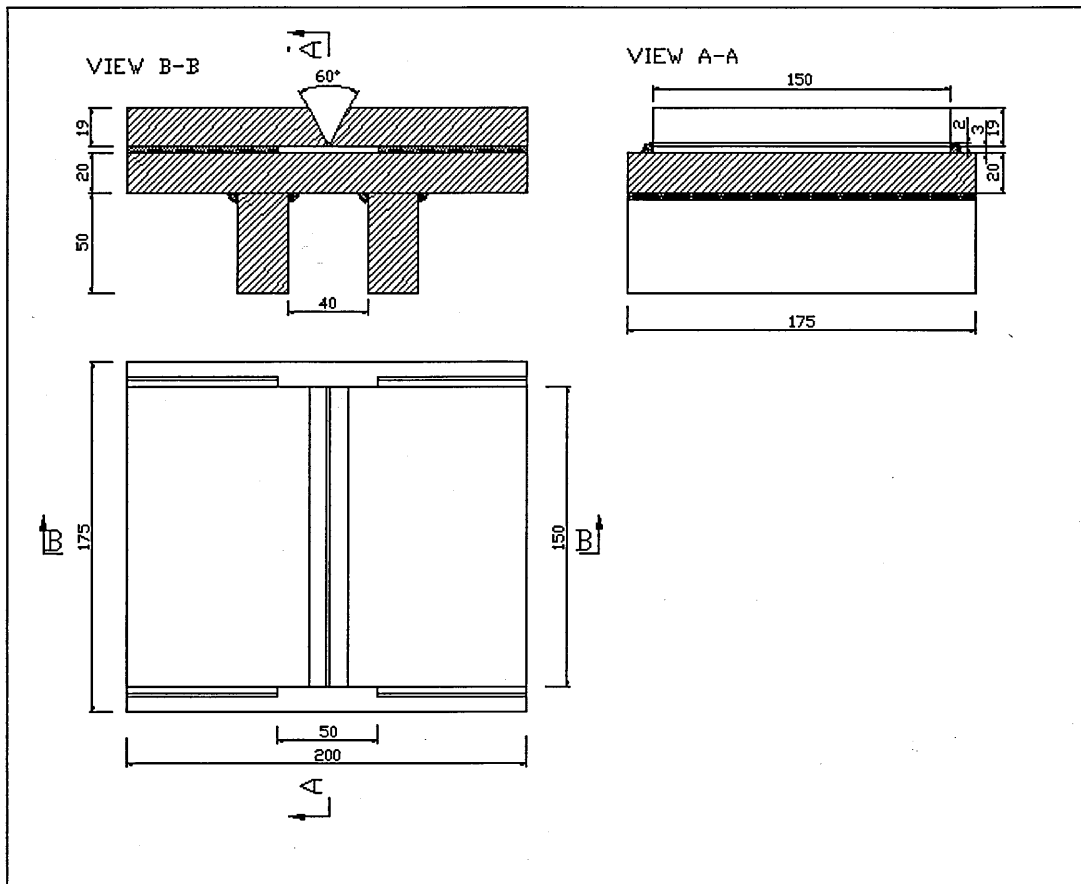


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 6900 \text{ mm}^2$

Root gap, $RG = 1 \text{ mm}$

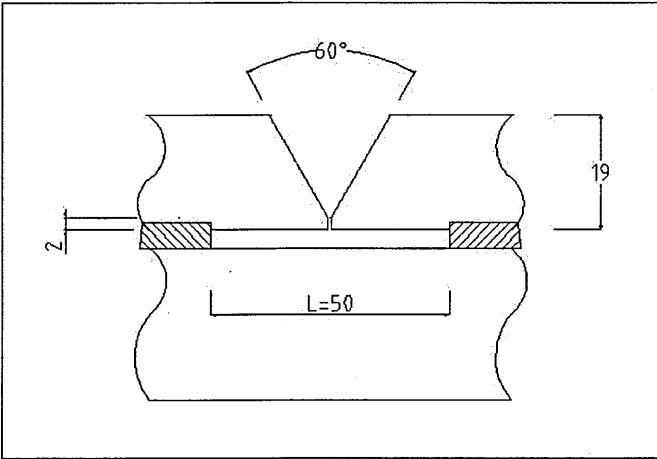
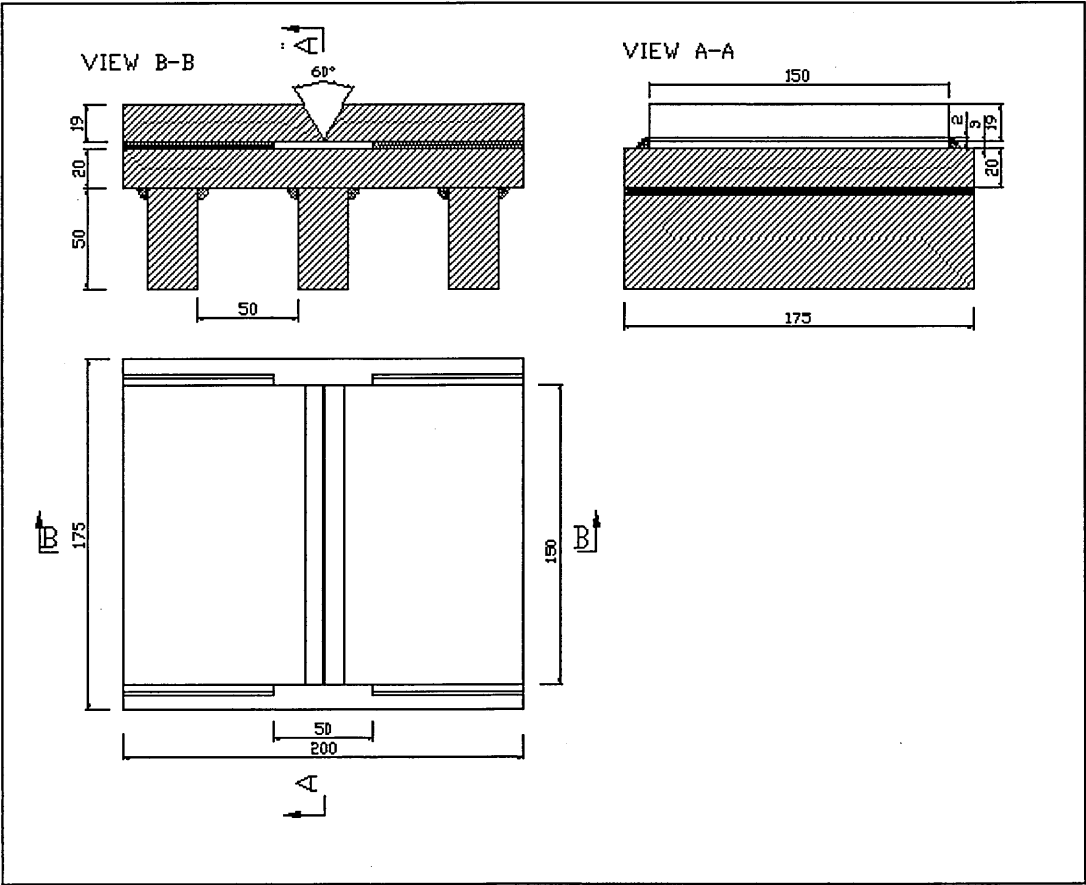
Figure 74: S4 configuration - dimensional drawing.



Dimensions in mm, not to scale.

Root gap, $RG = 1 \text{ mm}$

Figure 75: S5 configuration. Dimensional drawing. Adapted from Wang [29].



Dimensions in mm, not to scale.

Root gap, $RG = 0.5$ mm

Figure 76: S6 configuration. Dimensional drawing.

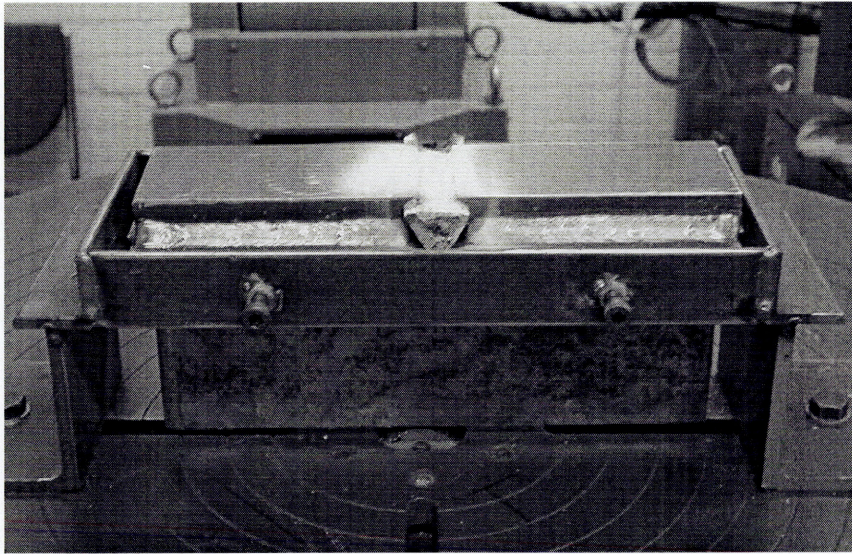


Figure 77: Test configuration S1 in the jig after welding.

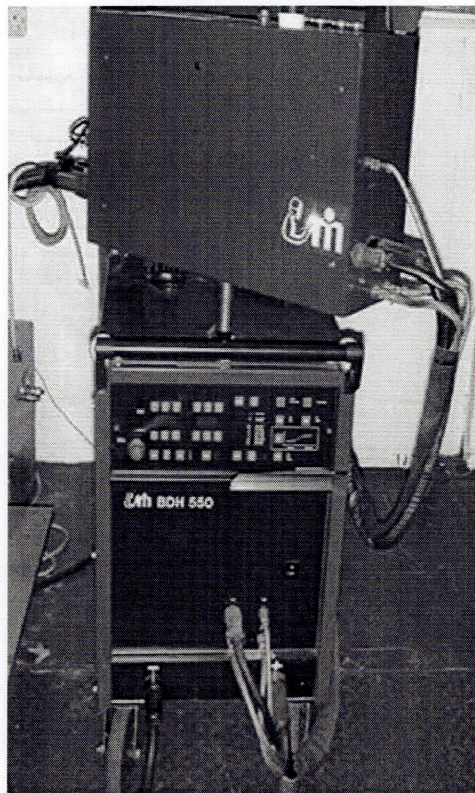


Figure 78: Migatronic

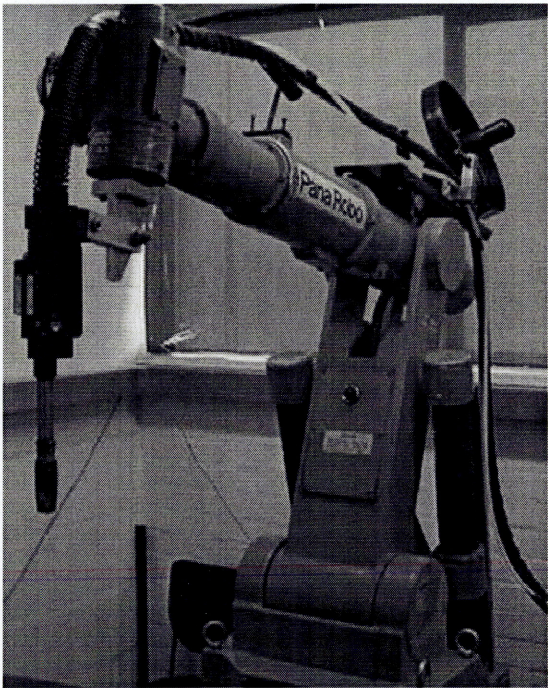


Figure 79: Pana Robo

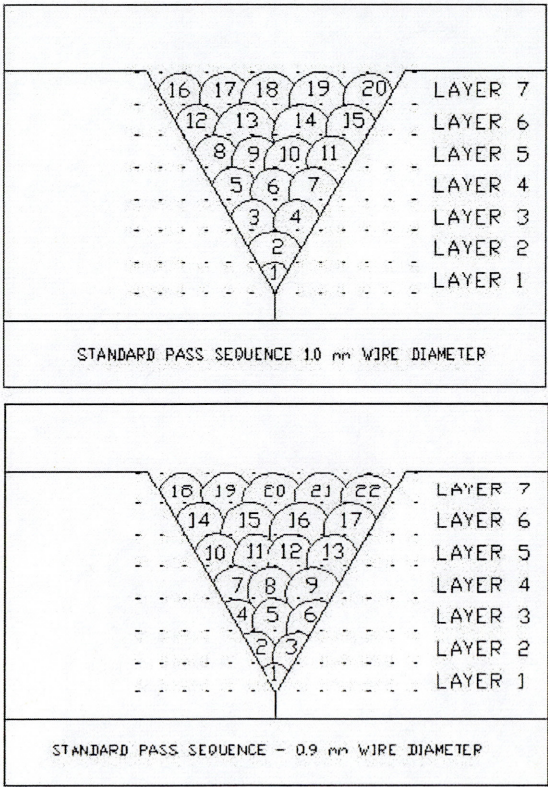


Figure 80: Standard pass sequence.

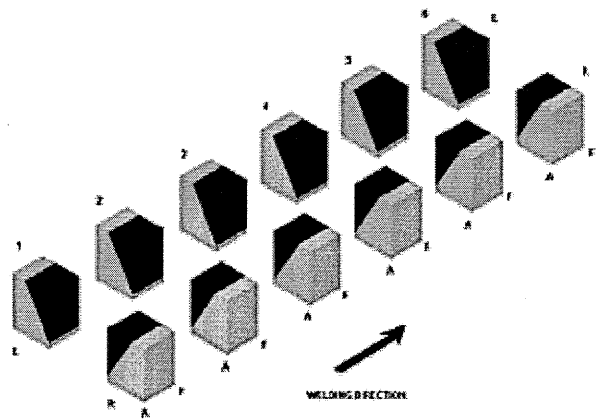


Figure 81: Samples cutting and numbering.

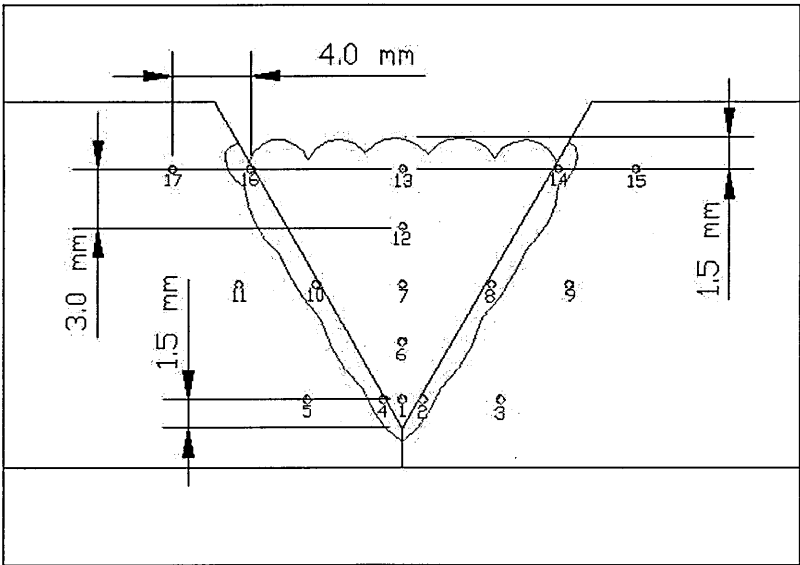


Figure 82: Distribution of points for hardness survey.

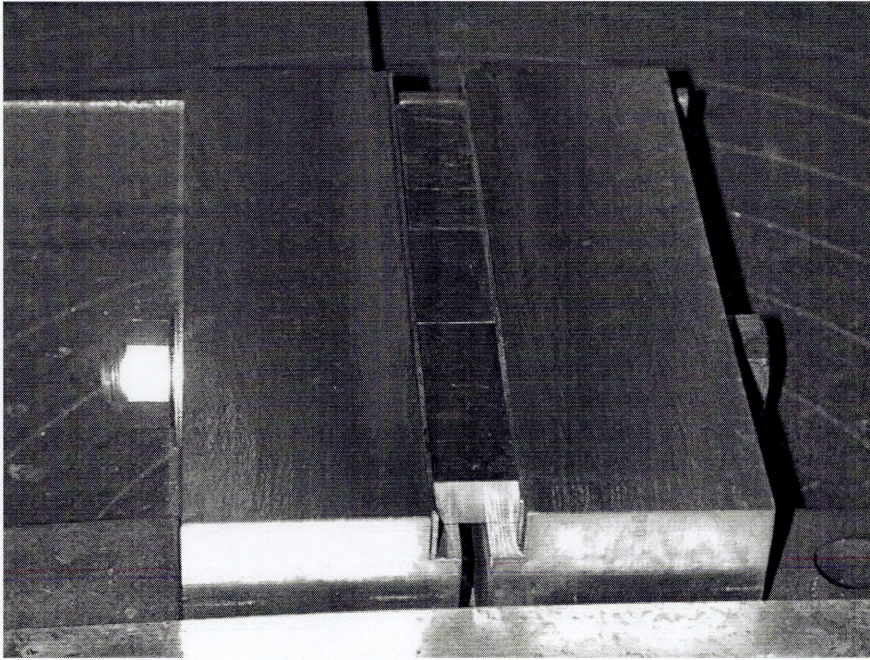


Figure 83: JIG for welds up to 2 kJ/mm with sample and tabs for hydrogen determination.

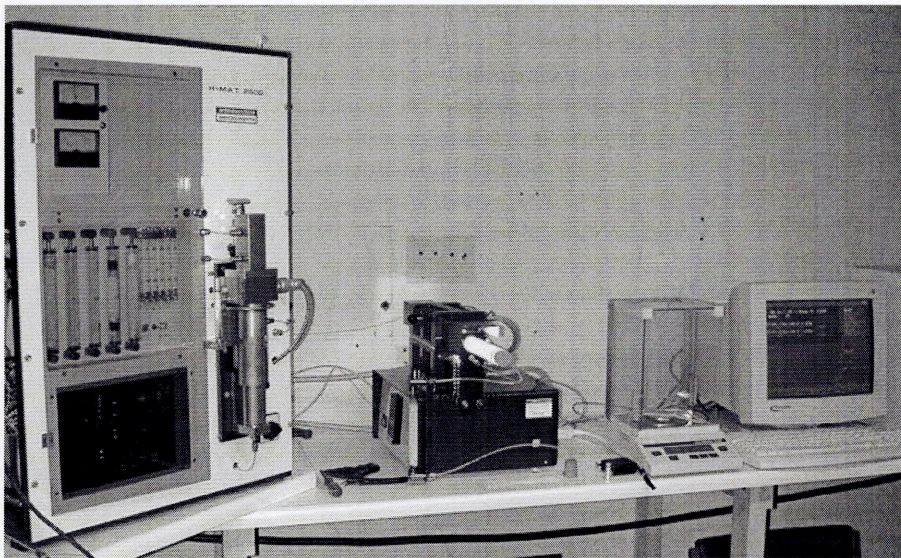


Figure 84: Hydrogen analyser device during calibration. Cranfield University laboratory.

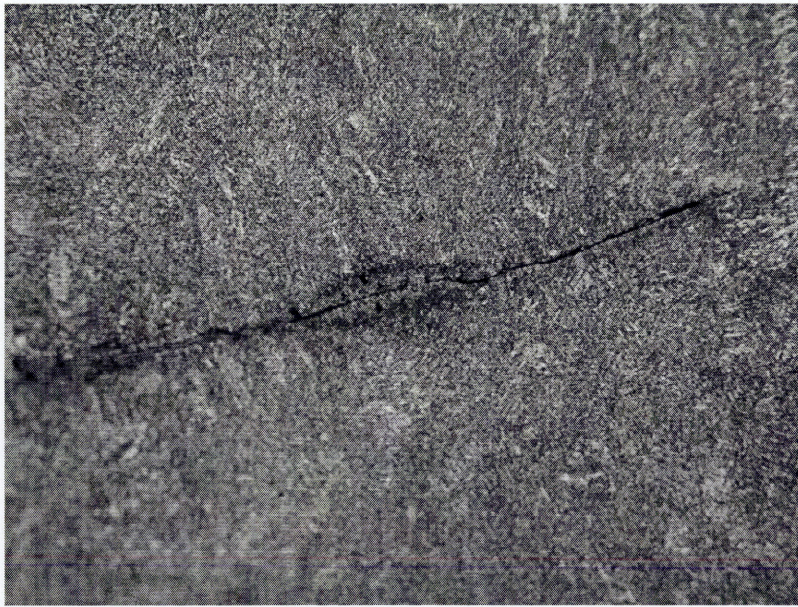


Figure 85: IS1M0325. Longitudinal defect.100X

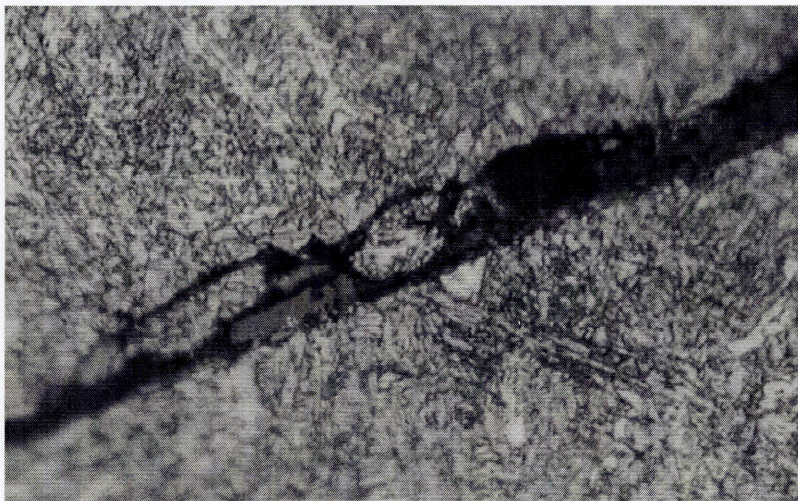


Figure 86: IS1M0325PROTO. Defect detail.



Figure 87: IIS1M0325. Sample 3F. 5X.



Figure 88: VIS1M0325. Weld metal defect.

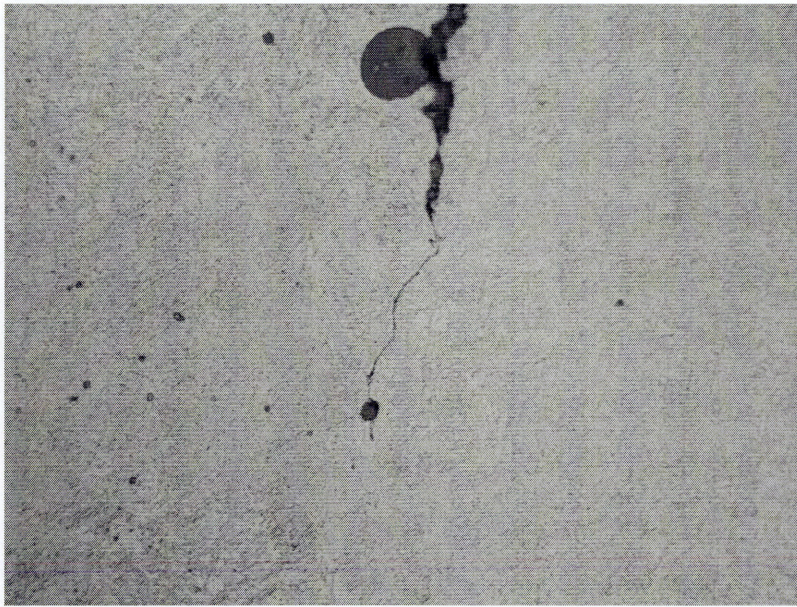


Figure 89: IIS1M0325. Crack propagating from side-wall defect. 500x.

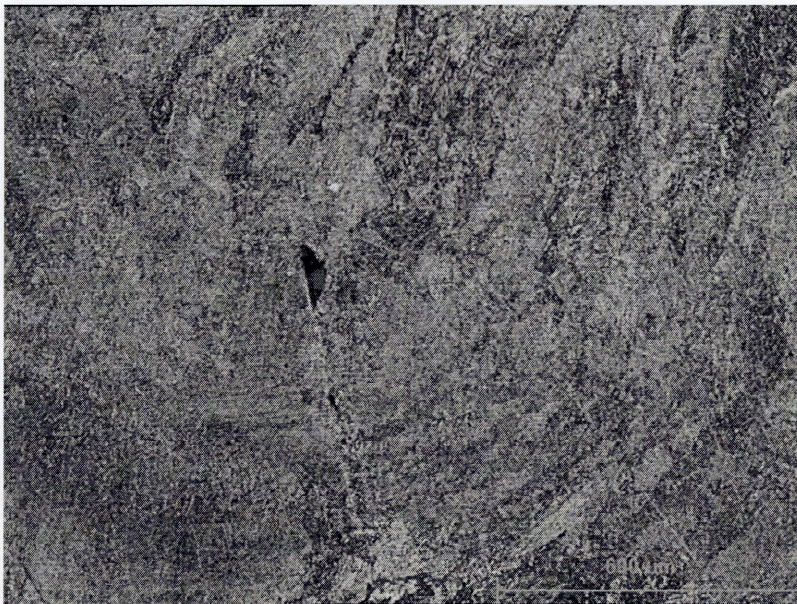


Figure 90: VS1M0325. Sample2F. Weld metal defect at mid-thickness.

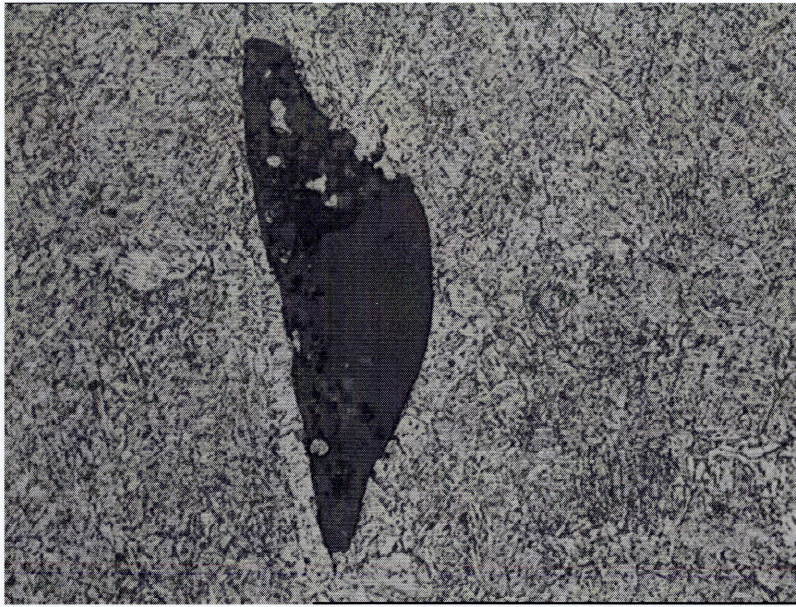


Figure 91: VS1M0325. Sample2F. Detail of weld metal defect at mid-thickness.



Figure 92: IIIS1MO325 – Die penetrant inspection after welding.

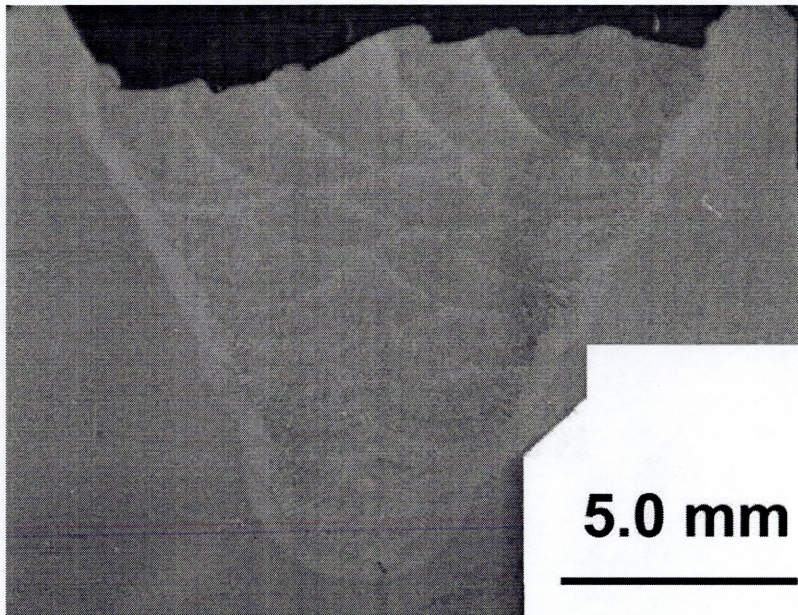


Figure 93: IIIS1MO325 – Sample1F – Macro picture of the transverse section.



Figure 94: IIIS1MO325 – Sample 1F – Cracking extension – a) Upper and b) lower portions.

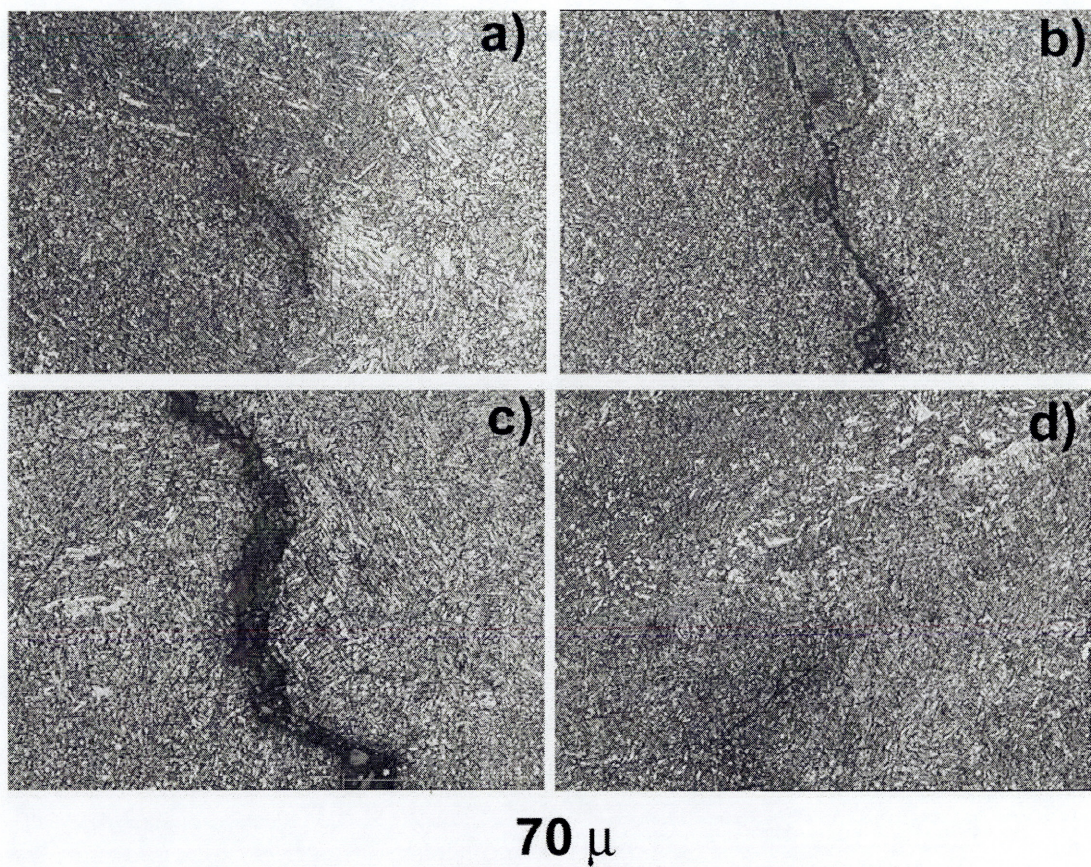


Figure 95: IIIS1M0325 – Crack detail, sample 1F; a) Lower extremity near to HAZ, b) and c) intermediate portions and d) Upper extremity in the last layer.



Figure 96: IIIS1M0325. Longitudinal cutting, sample 5L. HAZ defect.



Figure 97: IIIS1M0325. Longitudinal cutting, sample 4L. HAZ defect.



Figure 98: IIIS1M0325. Transverse cutting, sample 4R. WM defect.

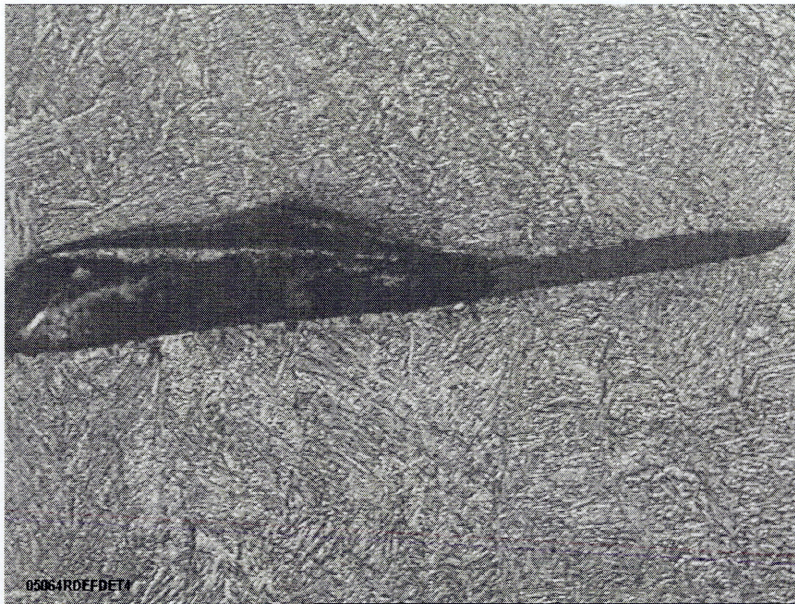


Figure 99: IIIS1M0325. Transverse cutting, sample 4R. WM defect detail.



Figure 100: IIIS1M0325. Longitudinal cutting, sample 3L. Root pass defect.

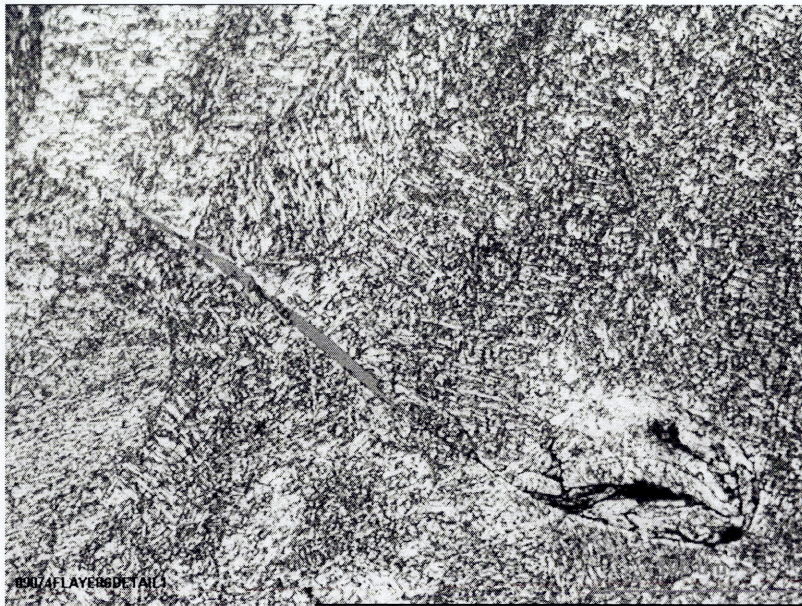


Figure 101: IIS2M0325. Sample 4F. Weld metal defect in a mid-thickness pass.

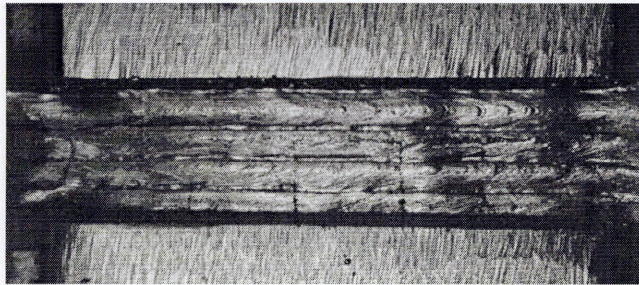


Figure 102: IXS1M0325. Surface macro-view.

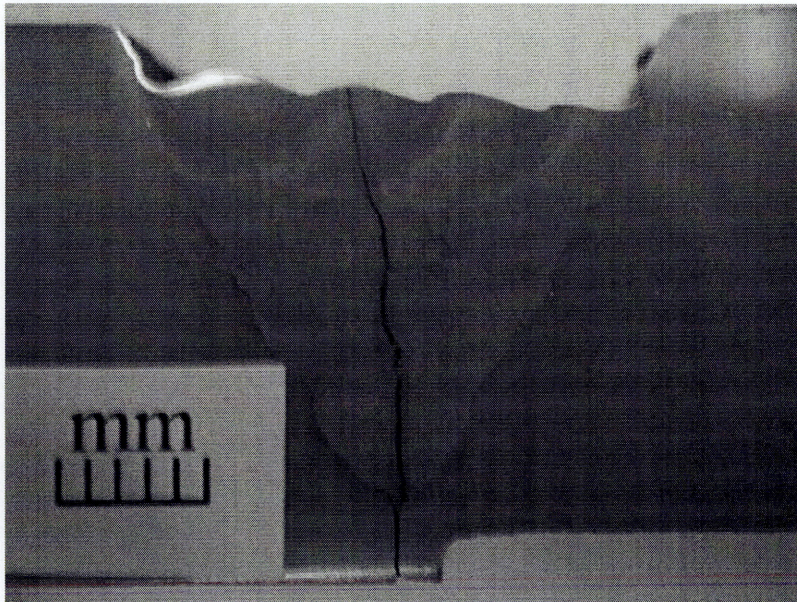


Figure 103: IXS1M0.325. Longitudinal cracking.



*Figure 104: IXS1M0325. Small cracking connected to main longitudinal cracking.
Unetched sample.*

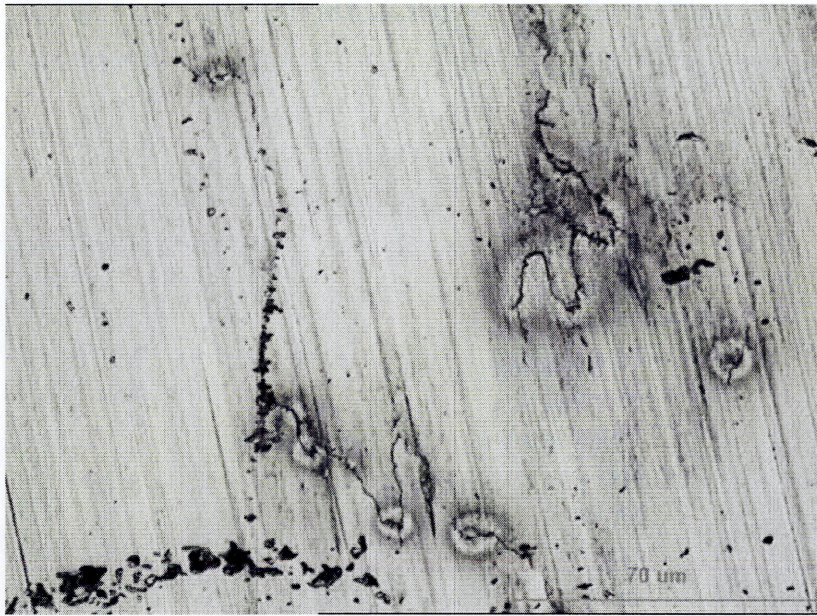


Figure 105: IXS1M0325. Small cracking near to main longitudinal cracking. Unetched sample.

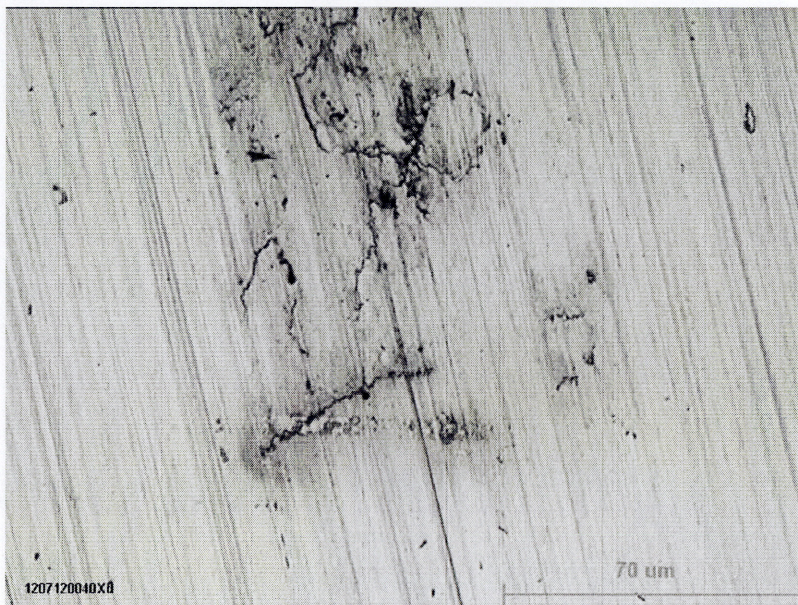


Figure 106: IXS1M0325. Small cracking near to main longitudinal cracking. Unetched sample.

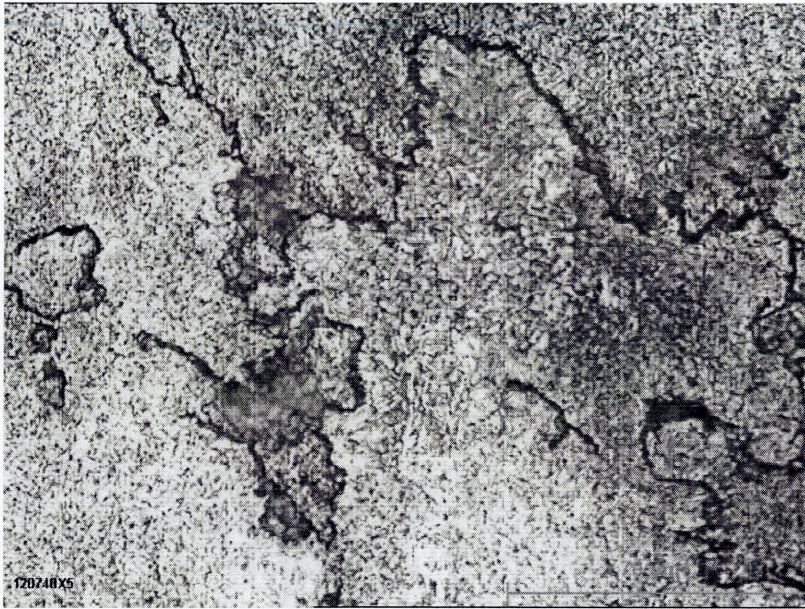


Figure 107: IXS1M0325.Cracking in a Nital 2 % etched sample.

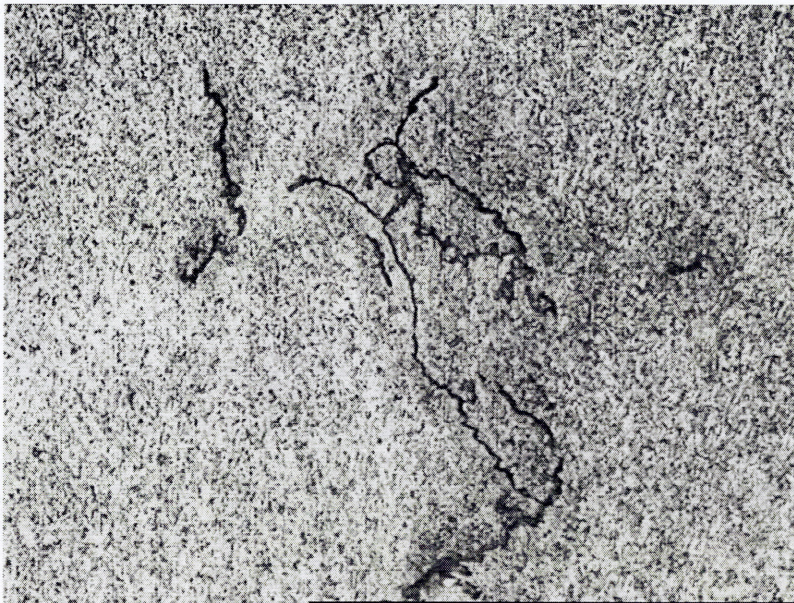


Figure 108: IXS1M0325.Cracking in a Nital 2% etched sample.

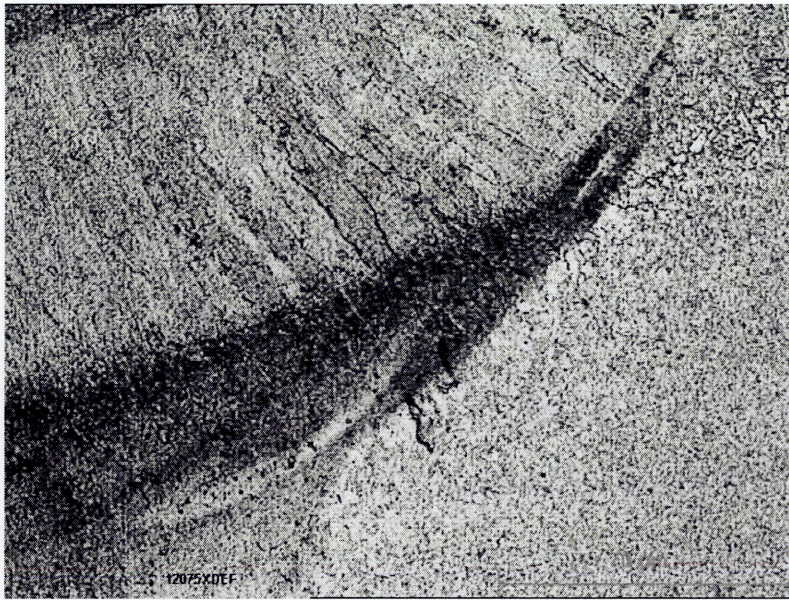


Figure 109: IXS1M0325. Macro-view of transverse section.

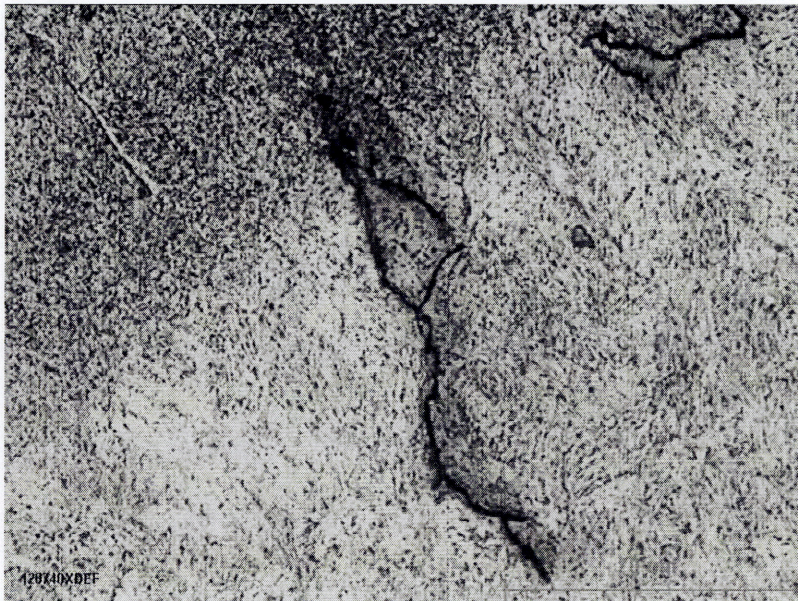


Figure 110: IXS1M0325. Detail of HAZ defect.

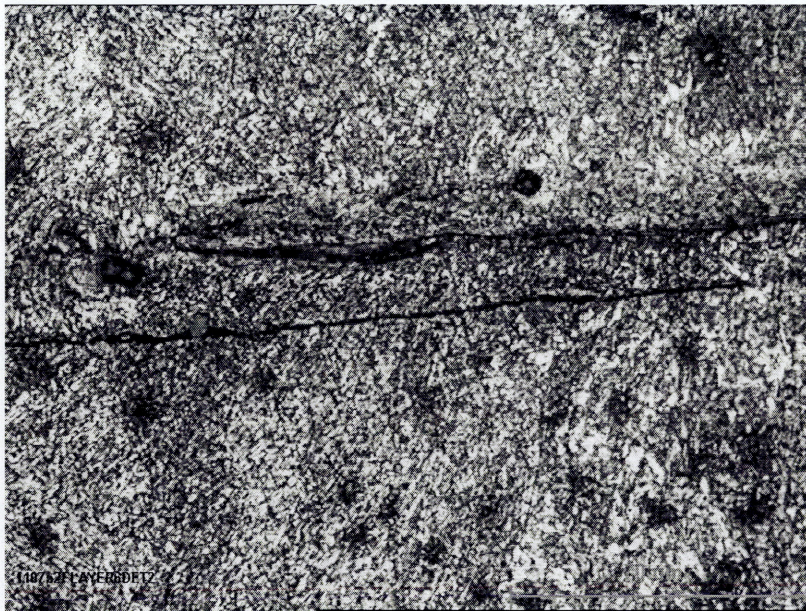


Figure 111: VIS2M0325. Sample 2F. Weld metal defect in the mid-thickness layer.

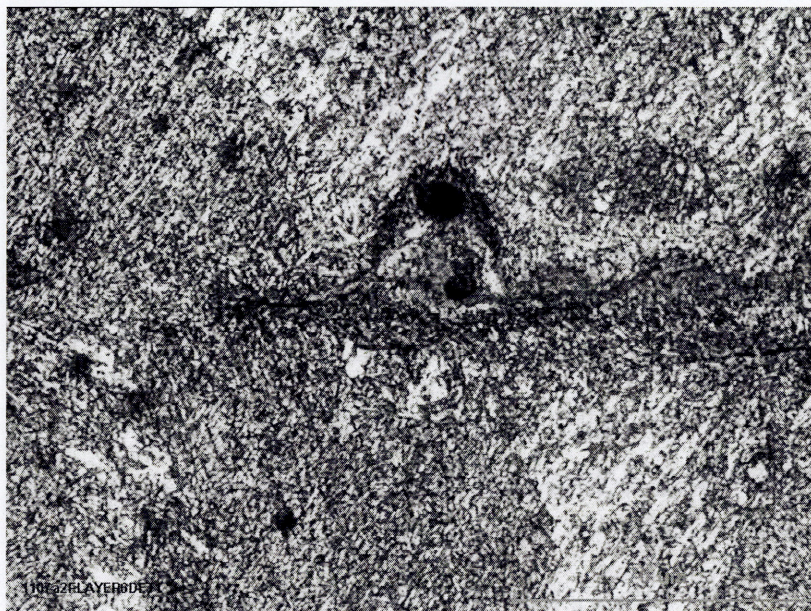


Figure 112: VIS2M0325. Sample 2F. Weld metal defect in the mid-thickness layer.



Figure 113: VIS2M0325. Sample 2F. Weld metal defect in the mid-thickness layer.



Figure 114: IIIS3R0325. Macro-view of cracking.

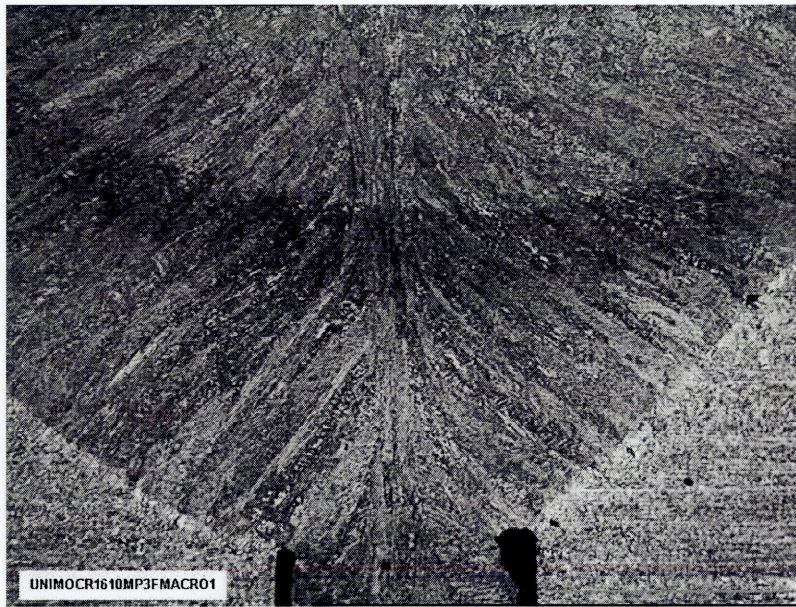


Figure 115: IIIS3M0325. Macro-view of the area near to the root.



Figure 116: IIIS3M0325. Macro-view of a side area and defect.

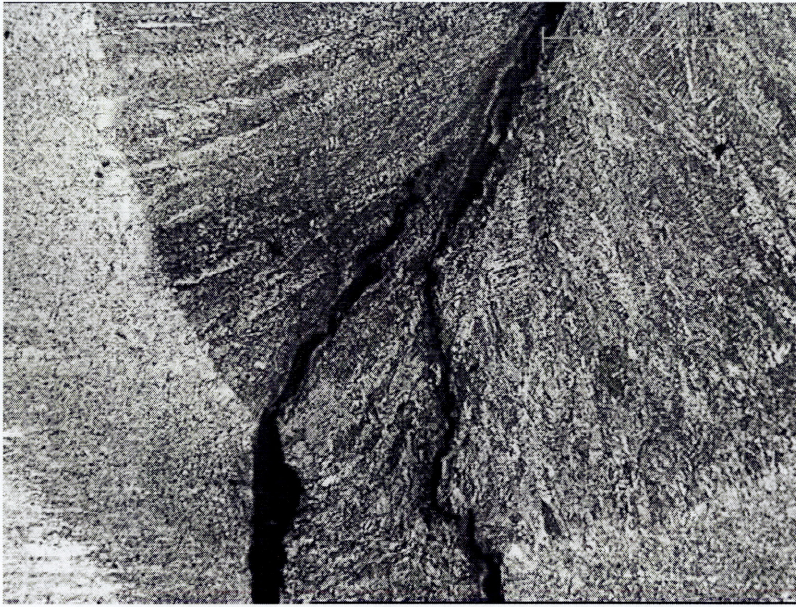


Figure 117: IIIIS4R0325. Macro-view of a cracked transverse section.



Figure 118: IIIIS4M0325. Macro-view of a cracked transverse section.



Figure 119: IIIS4M0325. Upper portion of a crack.



Figure 120: IIIS4M0325. Detail of a two cracking portions linked by a smaller crack.

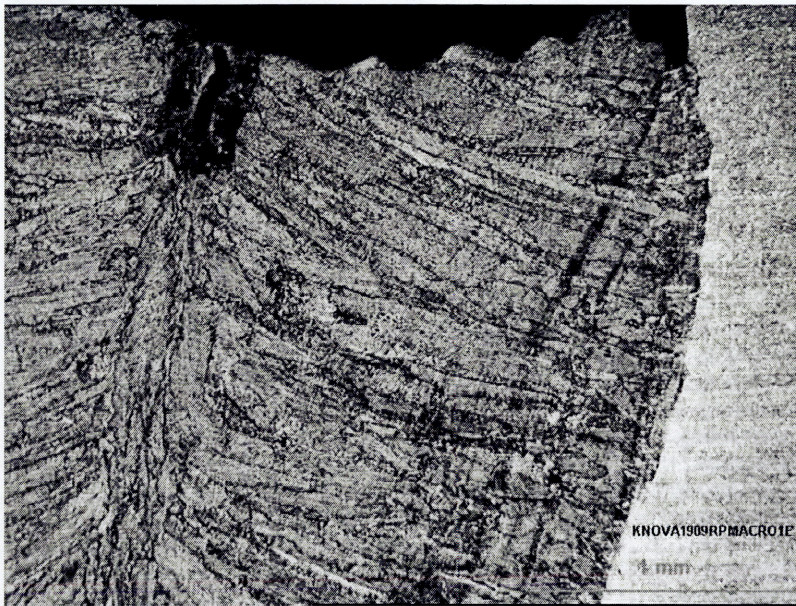


Figure 121: IVS4R0325. Surface\centre-line solidification crack.



Figure 122: IVS4M0325. Centre-line solidification crack.



Figure 123: IVS4M0325. Crack detail.

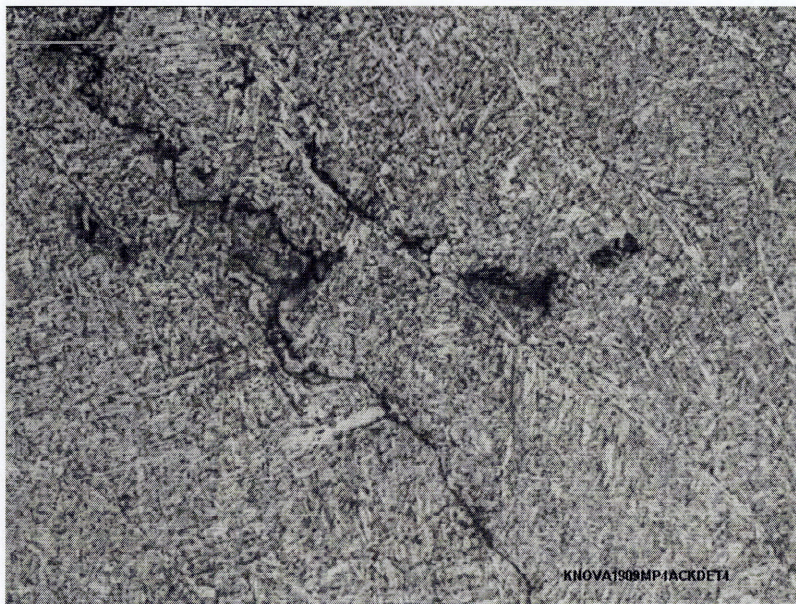


Figure 124: IVS4M0325. Crack detail.

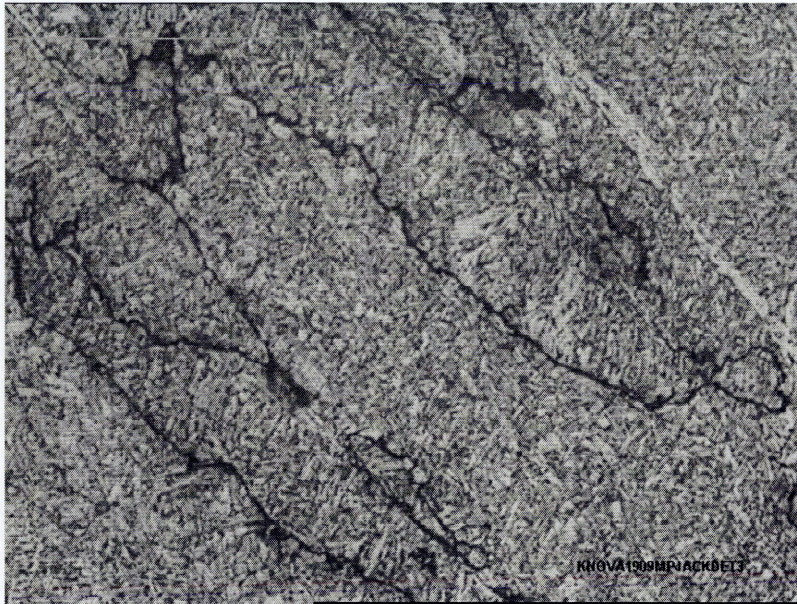


Figure 125: IVS4M0325. Crack detail.

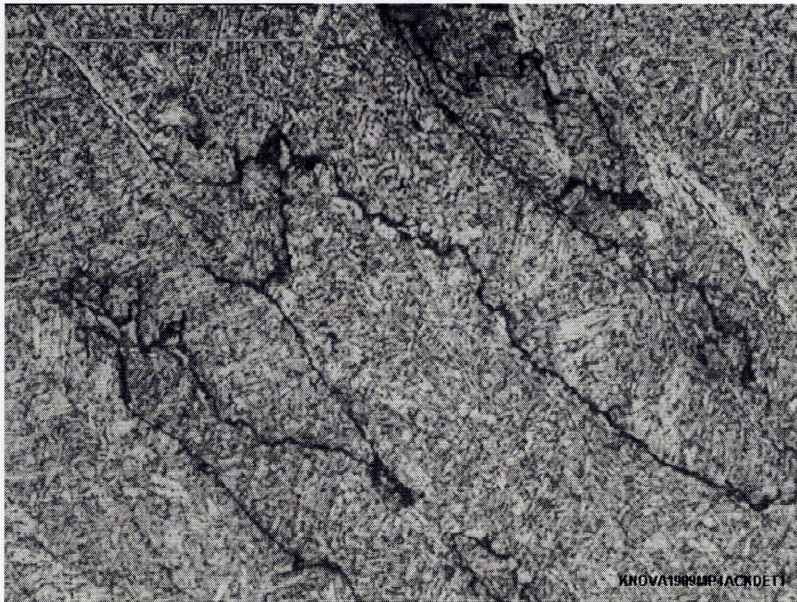


Figure 126: IVS4M0325. Crack detail.

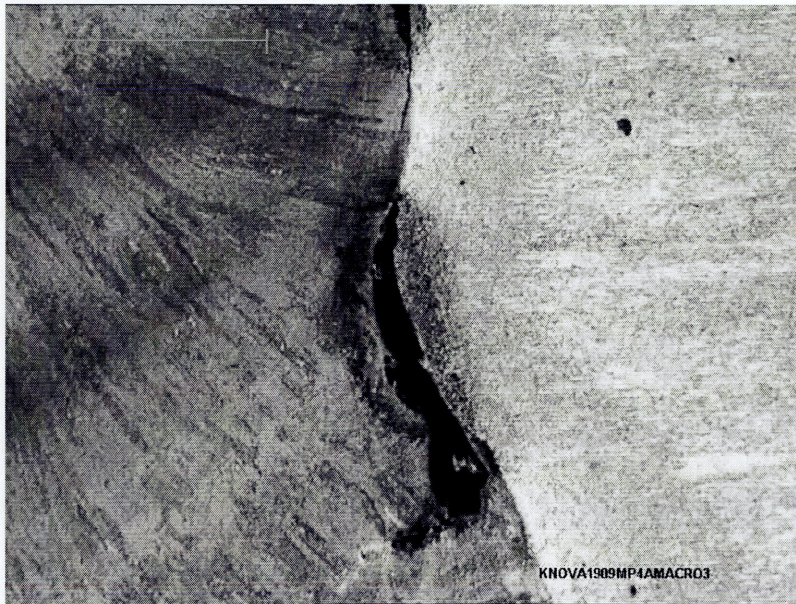


Figure 127: IVS4M0325. Side defect.

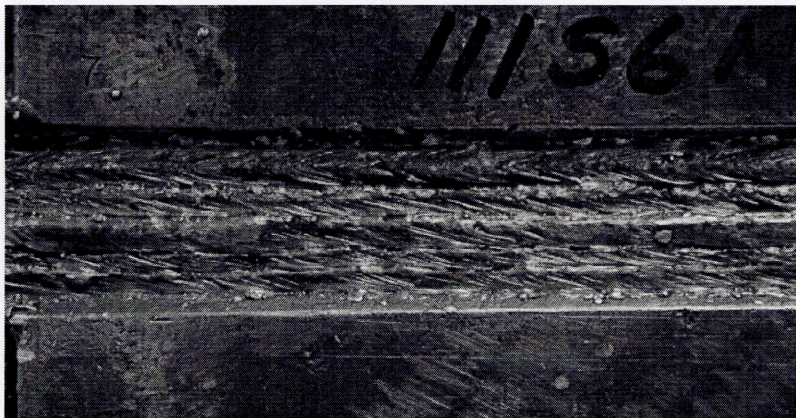


Figure 128: IIIS6M0325. Macro-view of weld surface.

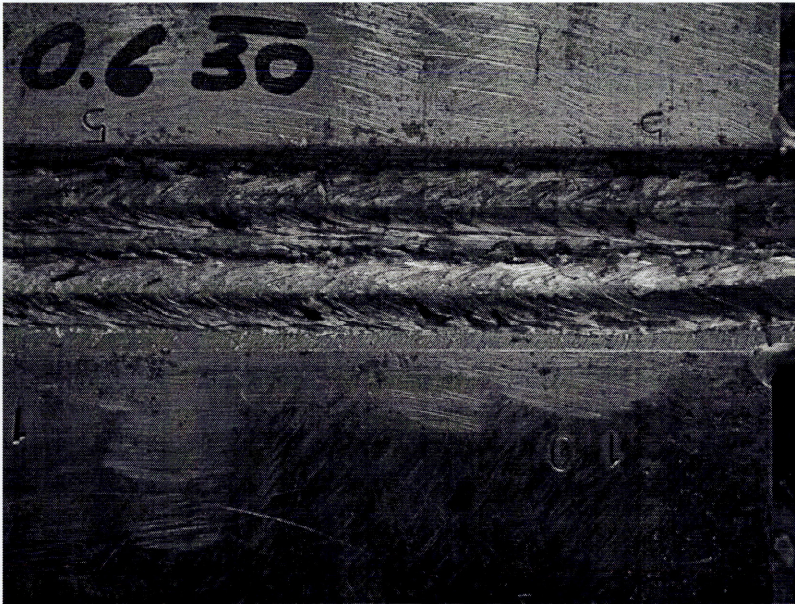


Figure 129: IIIS6M0630. Macro-view of weld surface.

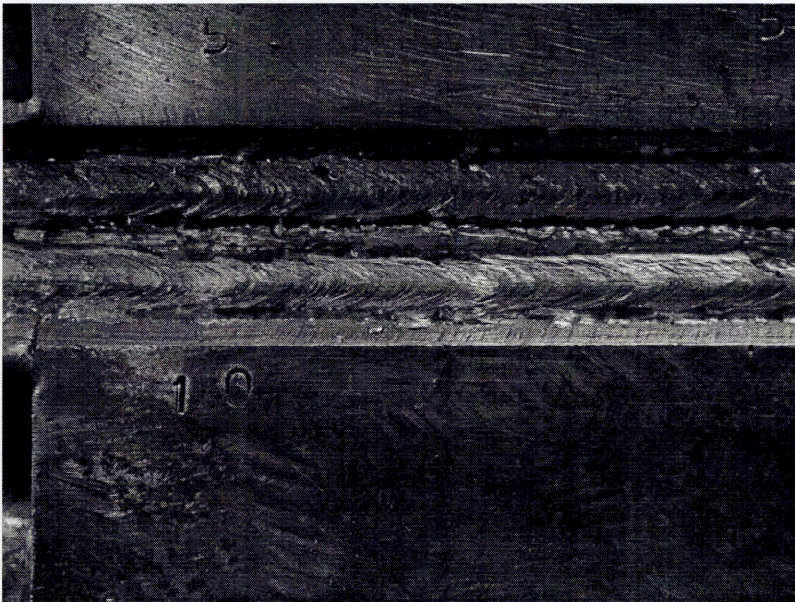


Figure 130: IVS6M0630. Macro-view of weld surface.

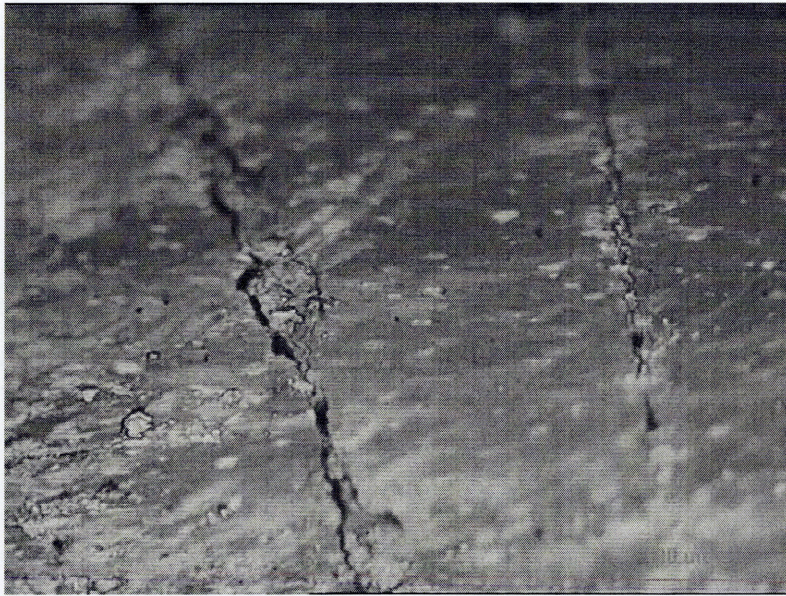


Figure 131: IVS6M0630. Detail of a surface crack.



Figure 132: IVS6M0630. Detail of a surface crack.



Figure 133: IVS6M0630. Detail of a surface crack.



Figure 134: IVS6M0630. Detail of a surface crack.



Figure 135: IXS6M0325. Macro-view of weld surface.



Figure 136: IXS6M0630. Macro-view of the weld surface.

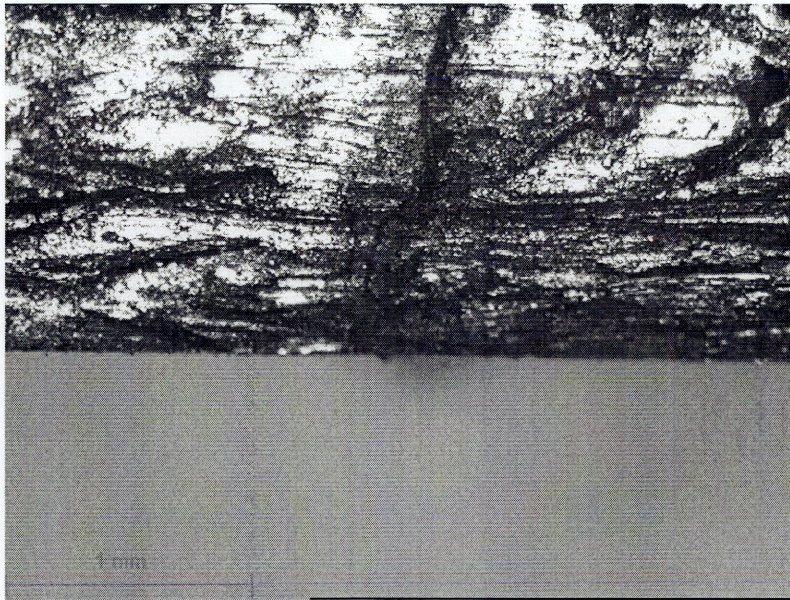


Figure 137: IXS6M0325: Detail of transverse surface crack near to the edge of longitudinal cut.

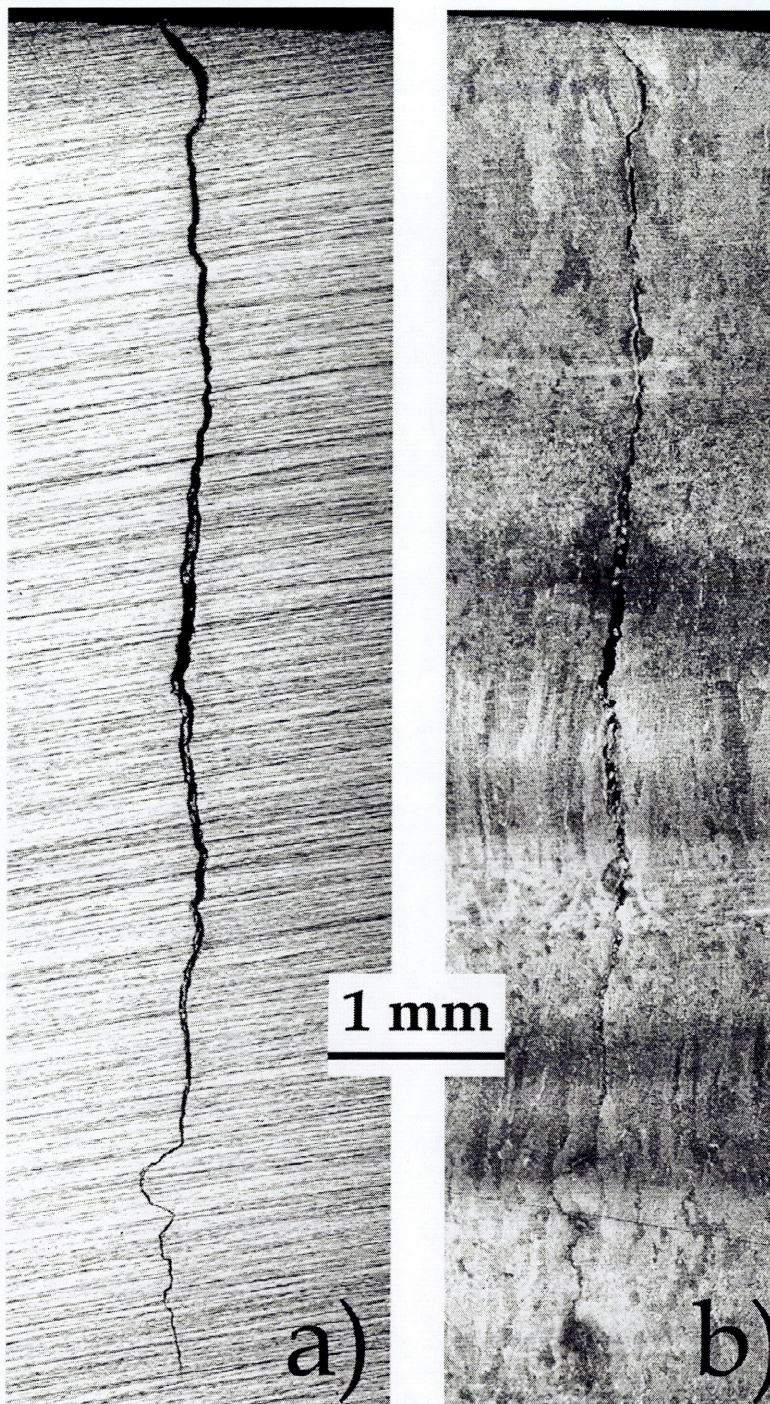


Figure 138: IXS6M0325 – Transverse surface crack, longitudinal cut.
 a) unetched and b) etched sample.

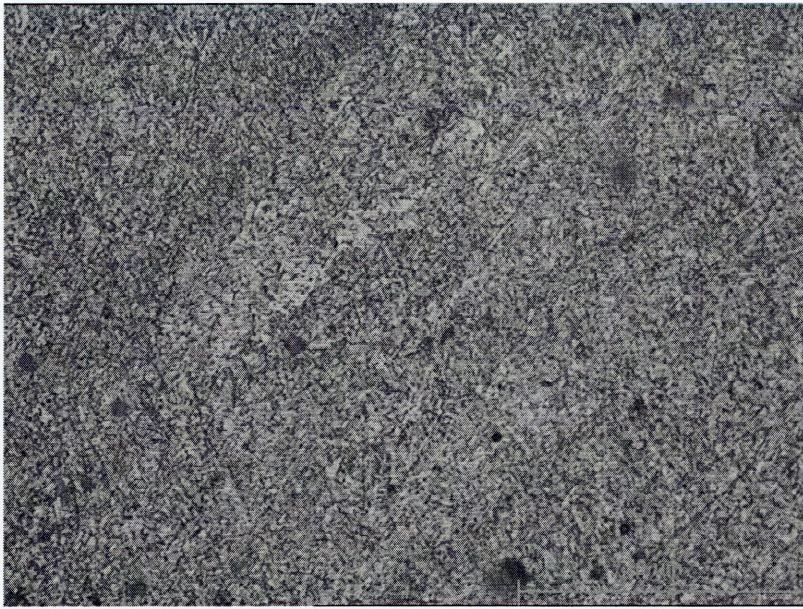


Figure 139: IS1M0325 – ADWM, cap pass.



Figure 140: IIS1M0325 – ADWM, cap pass.

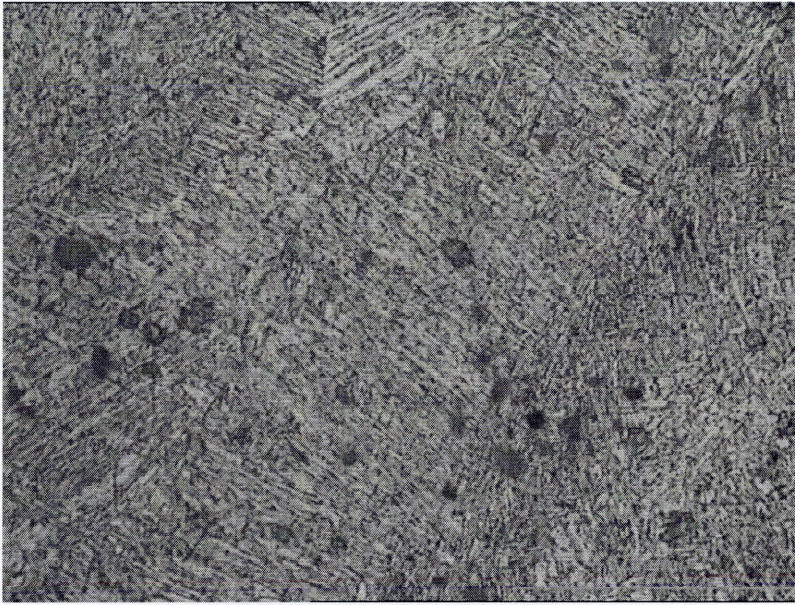


Figure 141: IIIS1M0325 – ADWM, cap pass.

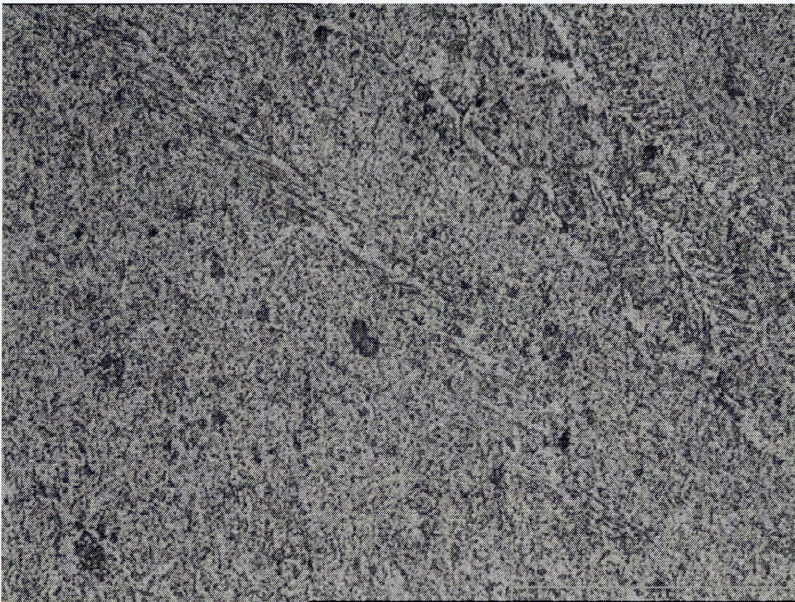


Figure 142: IVS1M0325 – ADWM, cap pass.

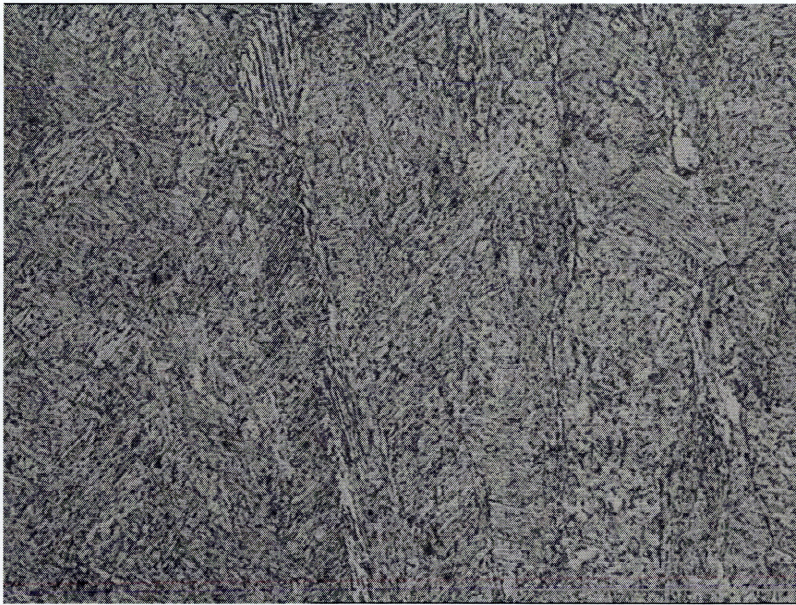


Figure 143: VS1M0325 – ADWM, cap pass.



Figure 144: VIS1M0325 – ADWM, cap pass.

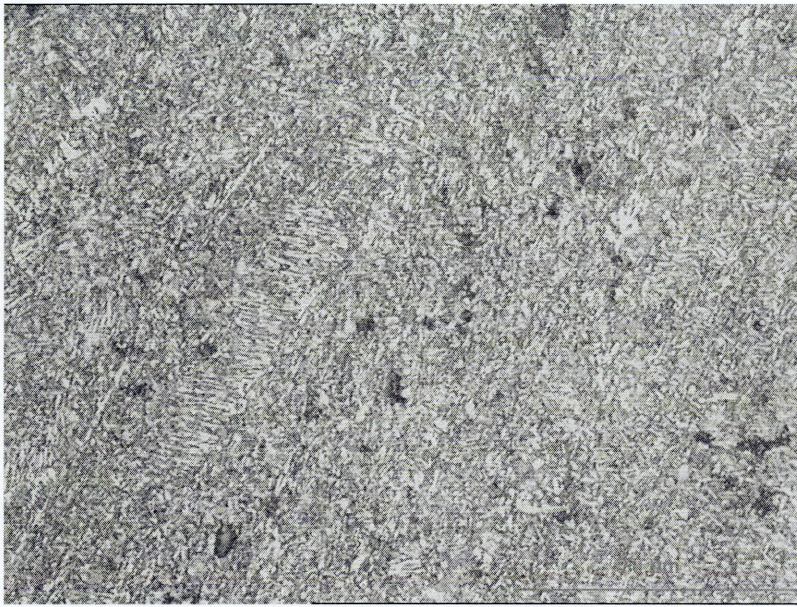


Figure 145: VIIS1M0.325 – ADWM, cap pass.

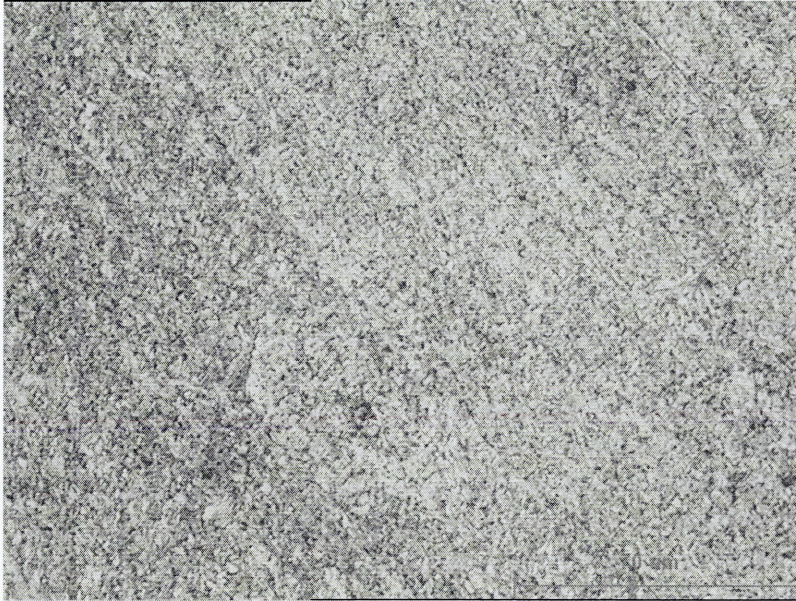


Figure 146: VIHS1M0.325 – ADWM, cap pass.



Figure 147: IXS1M0.325 – ADWM, cap pass.

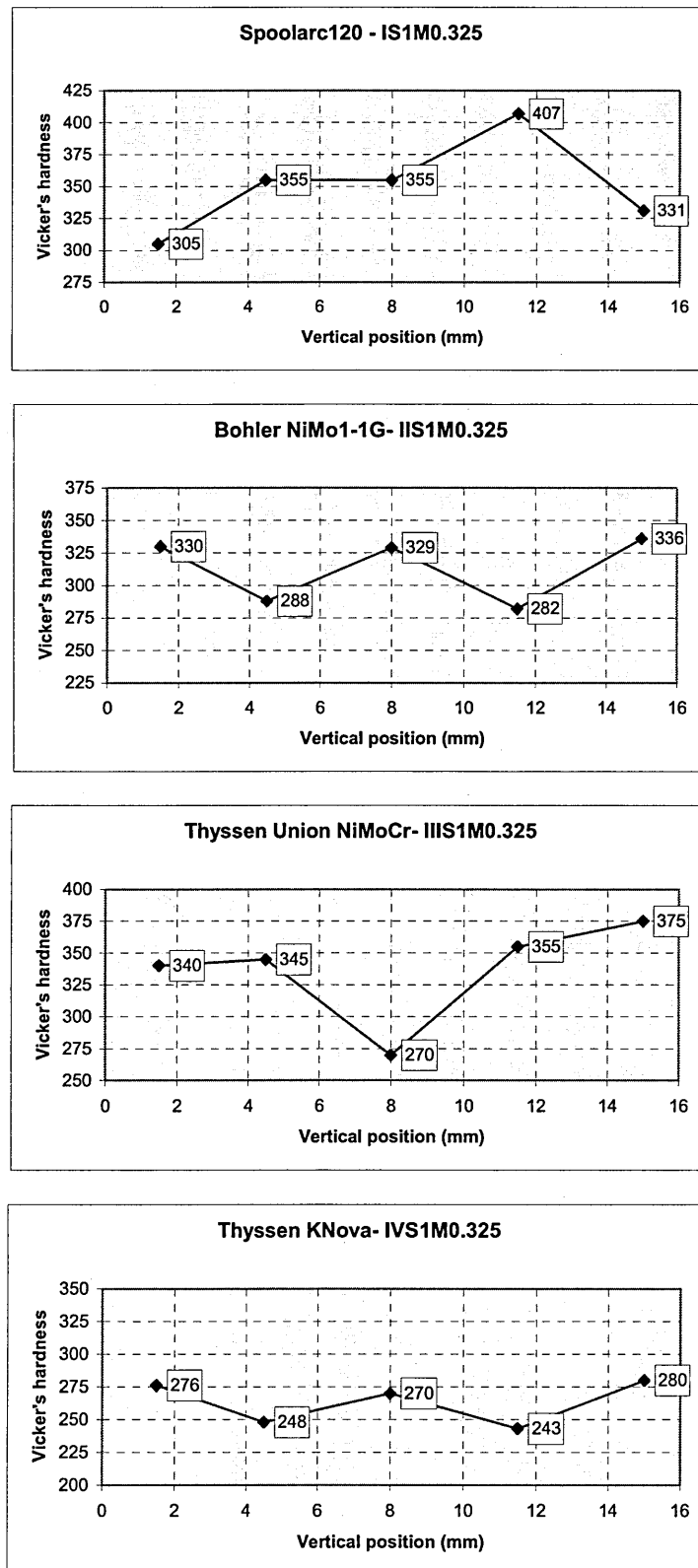


Figure 148: WM centreline hardness survey – Solid wires, 0.9 mm diameter.

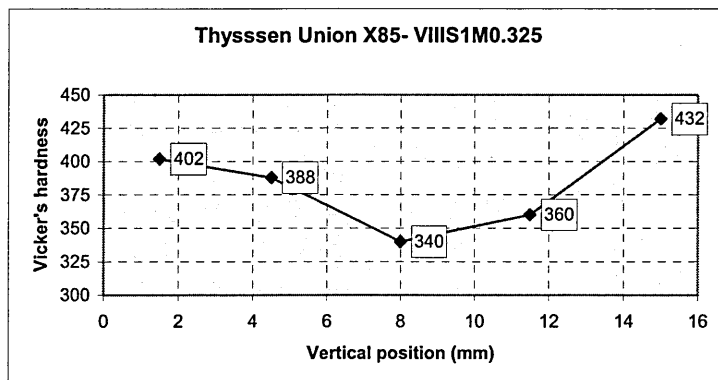
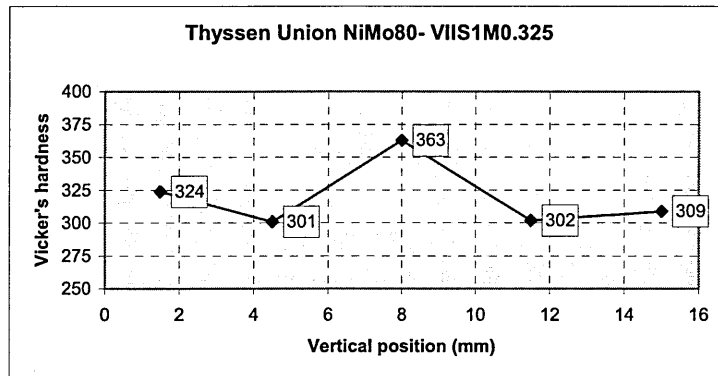
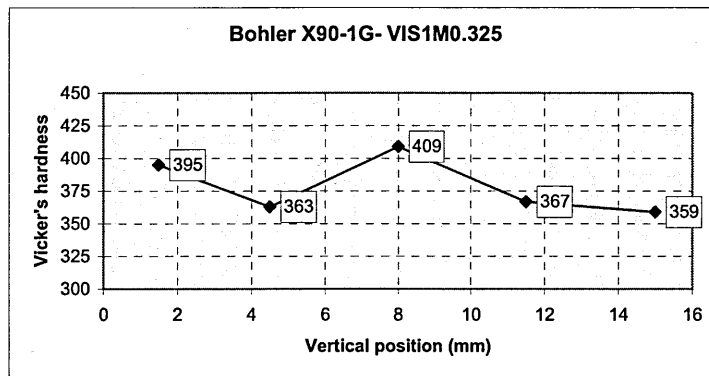
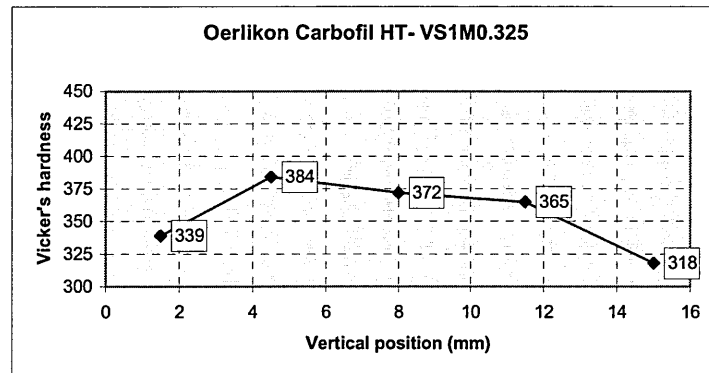


Figure 149: WM centreline hardness survey – Solid wires 1.0 mm diameter.

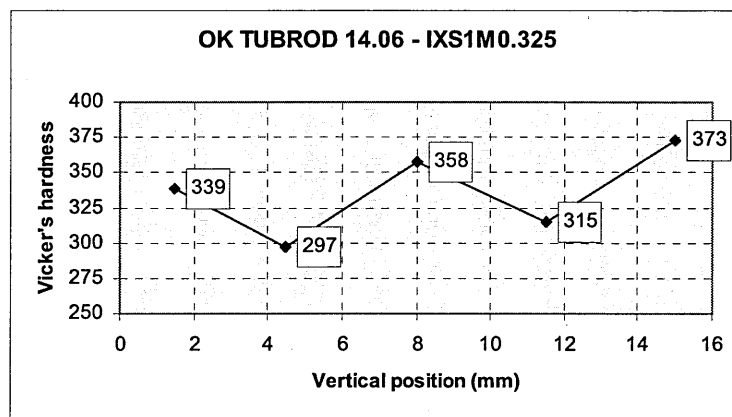


Figure 150: Wm centre-line hardness survey. Metal cored wire.

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APPENDIX A

**ANALYTICAL ASSESSEMENT OF WELD METAL TRANSVERSE STRESS IN
WIC TEST ACCORDING TO GRAVILLE**

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A.1 INTRODUCTION

An analytical procedure for assessing the severity of the WIC test was provided by Graville [1]. The net contraction of the test pieces (y direction) is calculated using a contraction model adapted from Satoh[2]. The contraction is then combined with the intensity of restraint concept [3] to obtain the transverse stress (y direction) in the joint.

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A.3 DEVELOPMENT

A.3.1 CONTRACTION ASSESSEMENT

According to the one-dimensional model of contraction adopted, the contraction would occur in two stages.

During the first one, just after welding, contraction results from three-dimensional heat transfer from the weld into the surrounding plate.

The second stage results when the heat leaves the plate or is conducted beyond the restraint points, which are assumed fixed. For high restraint conditions, the restraint points are closer together and the heat reaches them sooner causing the second stage to occur early on.

The critical plate thickness below which first stage contraction would not occur since the heat flow is two-dimensional in this situation is given in Eq. 1.

$$g_c = \left[\frac{H}{\rho c (800 - T_0)} \right]^{1/2}$$

Eq. 1: Critical plate thickness for "second stage" contraction.

Where:

g_c – critical thickness

H – heat input

ρ – density

c – specific heat

T_0 – initial plate temperature or preheat in °C

Considering this model, Eq. 2 to Eq. 4 give the net contractions due to contraction of weld and plate within the restraint length.

$$S = E_T - E$$

Eq. 2 : Net contraction.

$$E_T = \frac{\alpha H}{g \rho c}$$

Eq. 3 : Total free contraction (or expansion) of the plate.

$$E = 2\alpha \int_0^{x_0} \phi(x, t) dx$$

Eq. 4: The expansion of unrestrained length at time t .

Where α is the coefficient of expansion assumed to be independent of temperature and $\phi(x, t)$ is the temperature above initial plate temperature (Figure A. 1) and x_0 is the half distance between the restraints.

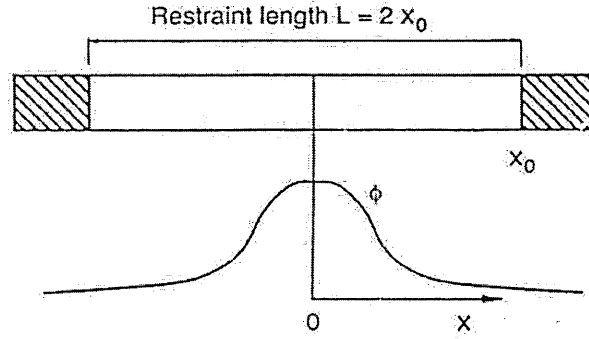


Figure A. 1: Temperature above initial temperature plate. After Graville[1].

Considering all second stage contraction occurs when heat flow is linear, the temperature distribution can be established from the delta function solution given by Eq. 5 (line heat source).

$$\phi(x, t) = \frac{H}{g \rho c \sqrt{4 \pi k t}} \exp \left(\frac{-x^2}{4 k t} \right)$$

Eq. 5: Temperature distribution.

Making the substitution given by Eq. 6 into Eq. 5 and after some algebraic manipulation the net contractions is obtained.

$$\beta^2 = \frac{x^2}{4 k t}$$

Eq. 6:

$$S = \frac{\alpha H}{g \rho c} \left[1 - \operatorname{erf} \left(\frac{x_0}{\sqrt{4 k t}} \right) \right]$$

Eq. 7: Net contraction.

Where:

x_0 – Half restrained length

ρ – density

k – thermal conductivity

c – specific heat

g – plate thickness

t – time

H – heat input

A.3.2 INTENSITY OF RESTRAINT

The concept of intensity of restraint was developed for the situation where a butt weld is rigidly held between two supports [2]. Graville [1] adopted the following formula to assess the intensity of restraint applied to the WIC test. It takes into consideration the geometry of the backing plate and stiffeners:

$$K = \frac{\frac{AEg}{LB}}{\left(\frac{A}{B} + g\right)} = \frac{Eg}{L\left(1 + \frac{gB}{A}\right)}$$

Eq. 8: Intensity of restraint applied to the WIC test.

Where:

A – cross-sectional area of the restraint plates g – plate thickness

L – restraint length

E – Modulus of Elasticity

B – weld length

K – restraint intensity

Departing from the above equation, some corrections were made due to eccentricity of weld bead in relation to the neutral axis of the test pieces and bending [1], as follows:

$$\gamma = \frac{e}{g/2}$$

Eq. 9: Eccentricity factor.

$$K_e = \frac{K}{1 + 3\gamma^2}$$

Eq. 10: Intensity of restraint corrected by eccentricity.

Where:

e – vertical distance between plate mid-thickness and weld metal centre (see Figure A. 2 for the geometry considered by Graville [1])

g – plate thickness

γ – eccentricity factor

K_e – intensity of restraint corrected by the eccentricity

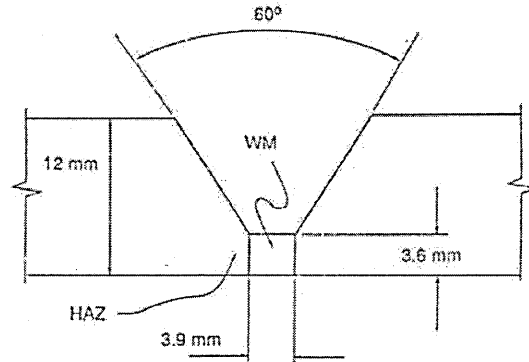


Figure A. 2: WIC test transverse section. After Graville[1].

A.3.3 STRESS ASSESSMENT

The stress acting transversely in the weld metal is given by:

$$\sigma = \frac{K_e S}{g_w} (1 + b\gamma)$$

Eq. 11: Weld metal residual stress.

Where:

b – constant obtained empirically

S – Net contraction of weld plate between the restraints points

g_w – thickness of the weld fillet

APPENDIX B

**PROCEDURE SPECIFICATION OF SMALL SCALE RESTRAINT CRACKING
TEST APPLIED TO MULTIPASS GMAW AND CONSUMABLES WITH VERY
LOW HYDROGEN CONTENT**

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B.1 SCOPE

This specification defines the procedures for the evaluation of high strength low hydrogen GMAW consumables to hydrogen cracking using the Welding Institute of Canada (WIC) test and its variations, which were applied in the research programme on hydrogen assisted cold cracking (HACC) at Cranfield University through 2000-2002.

The tests are used to ascertain GMAW consumables susceptibility to weld metal cracking in root-pass and multipass restrained groove welds.

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B.3 TESTING PROCEDURE

B.3.1 Test assemblies

The test assembly consists of a weld joint and a set of restraint plates. Two test pieces form the weld joint and are welded to the restraint set. A backing plate and stiffeners compose the restraint set. The length of the test pieces not welded to the backing plate is the "restraint length" (L). The restraint plates are welded to form the restraint set configuration. The shims are located beneath the test sections and the test sections are fillet welded to the backing bar as shown in Figure B. 1.

Several configurations of joint geometry, restraint length and sectional area of the restraint set can be used to create different levels of stress severity. The configurations applied are shown in Figure B. 2 to Figure B. 7. Table B. 1 lists the materials required to fabricate the test assemblies.

The restraint fillet welds are made using a GMAW process with very low hydrogen content wire (AWS 5.28ER100S) and welding proceeds outwards relative to the weld joint preparation. The specified restraint length, centred over the weld joint preparation, is not welded to the backing bar. Run-on and run-off tabs are used to ensure uniform weld deposition within the test weld. The run-on and run-off tabs are tack-welded to the backing plate only.

B.3.2 Number of Test Welds and Preheat

For each combination of steel, consumable and welding conditions, a minimum of three acceptable test welds are evaluated to determine the cracking percentage at a certain preheat temperature.

B.3.3 Welding Technique

All welding are performed in the horizontal (1G) position using a mechanised system ensuring a uniform heat input. If necessary, test assemblies are uniformly heated in an oven to a temperature slightly higher than the desired preheat temperature. The assembly is removed from the oven and the temperature at the bevels monitored using a contact thermocouple. Welding begins as the desired preheat is reached. Bead on plate welds prior to the tests shall establish the welding parameters to achieve the desired heat inputs.

B.3.4 Experimental Method

Root pass and multipass welds are conducted for each condition assessed. For multipass welds, each weld pass is deposited in a left to right direction using a mechanised system. After each pass is completed the joint is subsequently cleaned with a wire brush to ensure the joint is clean and free from scale and impurities. Deposition of the next pass takes place when preheat temperature returns to the desired level. This process continues until the requisite number of layers is laid down according to the standard pass sequence presented by Figure B. 8

B.3.5 Acceptable Test Weld Workmanship

The test welds must have a regular finish and merge smoothly with the base metal. The weld bead profile should adopt a profile that is typically associated with mechanised GMAW pipeline girth welding. The weld must be free of significant geometric flaws, which will include the following workmanship discontinuities:

- a) incomplete penetration of the root bead,
- b) incomplete fusion of the root bead,
- c) lack of side wall fusion,
- d) lack of inter-run fusion,
- e) porosity and hollow bead,
- f) coupon misalignment (high-low), and
- g) weld metal centre line solidification cracks.

B.3.6 Sampling technique

The test welds are allowed to cool to room temperature and are removed from the backing bar 24 hours after welding. The test weld is then sectioned in accordance with the Figure B. 9.

Transverse sectioning provides the samples for assessing longitudinal cracks (cracking occurring in a plan perpendicular to plane zy). Faces 1F, 2A, 2F, 3A, 3F, 4A and 4F shall be examined.

Samples 2, 3 and 4 are sectioned according to the plan xz. Faces 2R, 2L, 3R and 3L are examined (samples 1 and 4 are reserved for hardness survey). Before cracking assessment, each face is polished to a 1 μ finish and etched in 2% Nital solution.

B.3.7 Cracking assessment

Optical microscopy with magnifications of up to 500 times is used to identification, quantification and measurement of cracks for each face evaluated.

B.3.8 Acceptance criterion

No acceptance criterion is established.

B.3.9 Reporting

A final report is to be completed for each weldability evaluation. The report, to include all the test welds completed for the evaluation, contains the following information:

- a) material description, diameter, wall thickness, and grade;
- b) steelmaking practice, steel manufacturer, and location of steel mill;
- c) mill test chemistry;
- d) consumable brand name, consumable manufacturer's traceability number (heat number or batch number or both), and the electrode diameter;
- e) weld parameters (amps, volts, travel speed, and heat input) and preheat;
- f) number of cracks and crack length distribution for each cracking type (transverse and longitudinal);
- g) bead dimensions; and
- h) summary of test results;

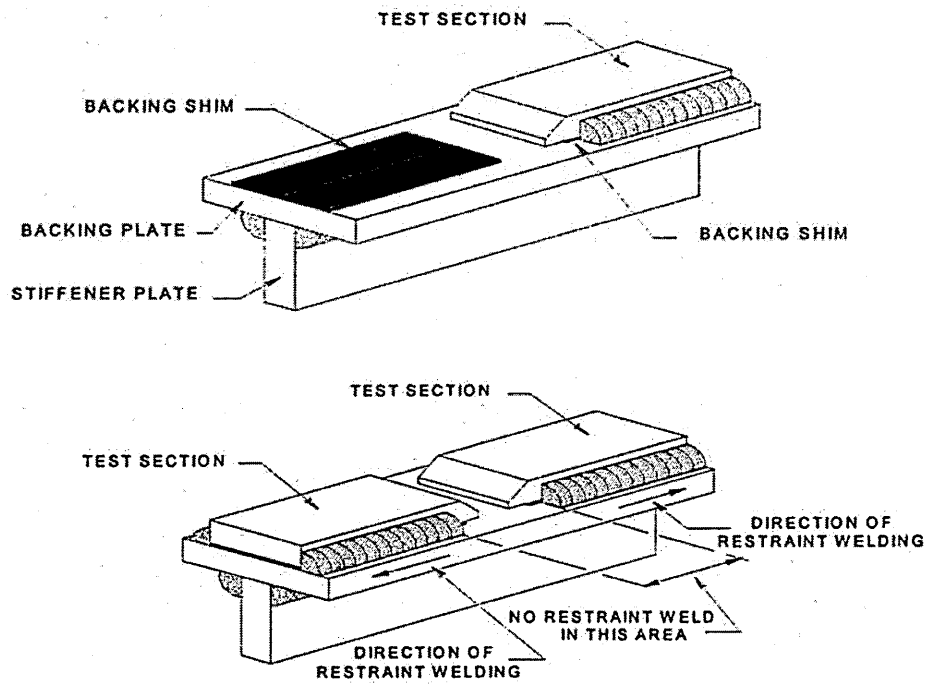
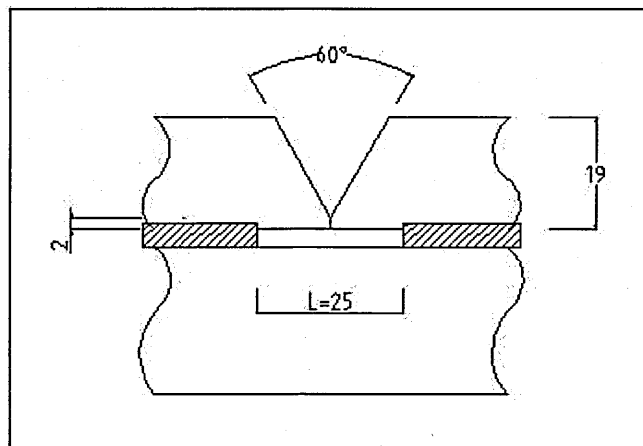
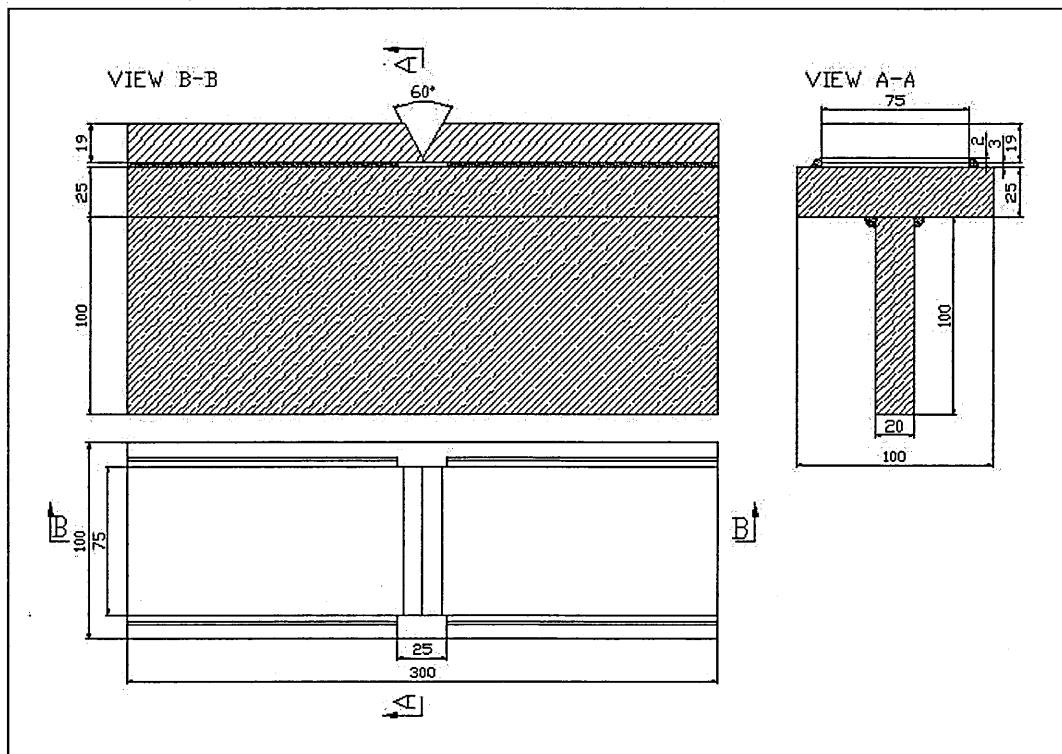


Figure B. 1: Test assembly fit-up. After Caizley [2].

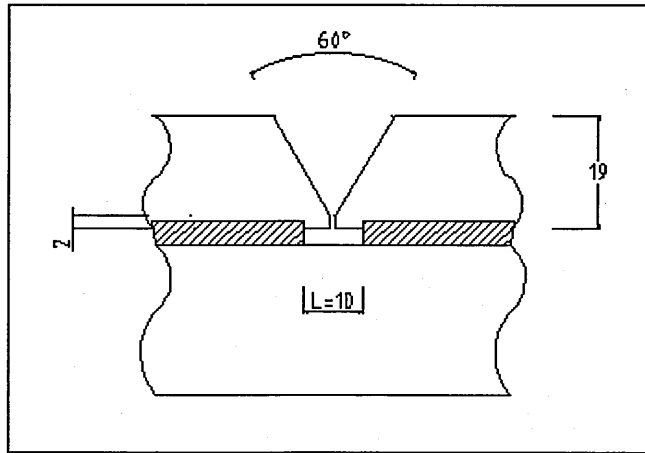
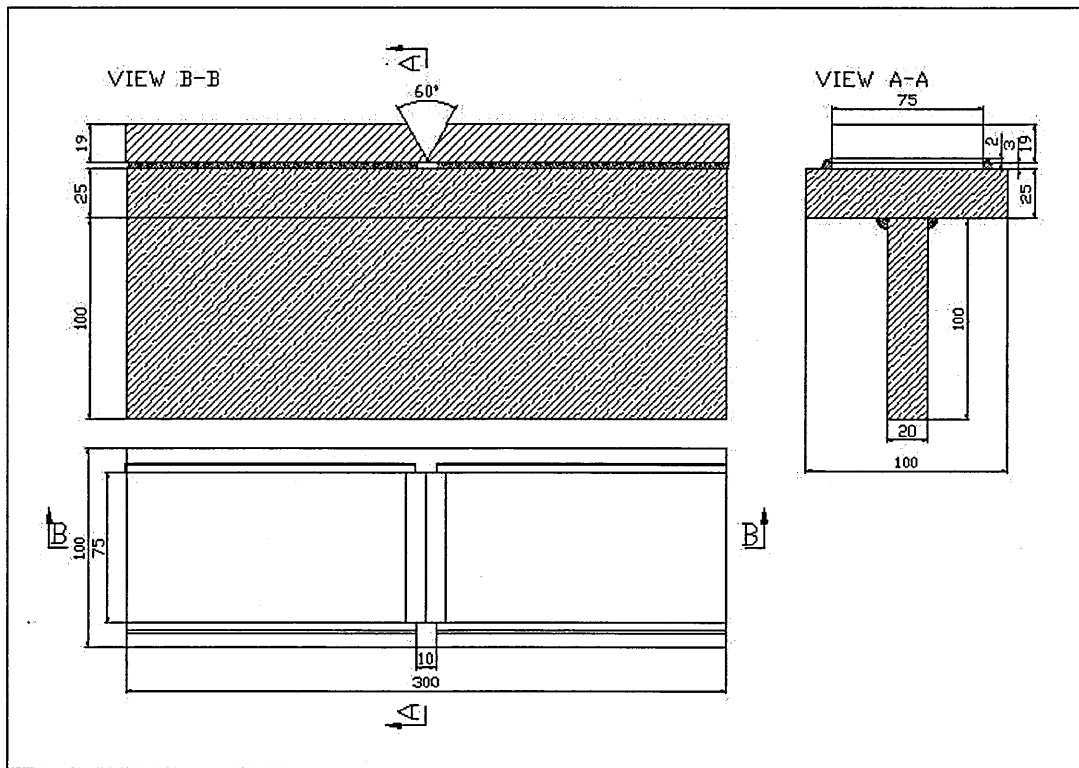


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 4500 \text{ mm}^2$

Root gap, $RG = 0 \text{ mm}$

Figure B. 2: S1 configuration - dimensional drawing.

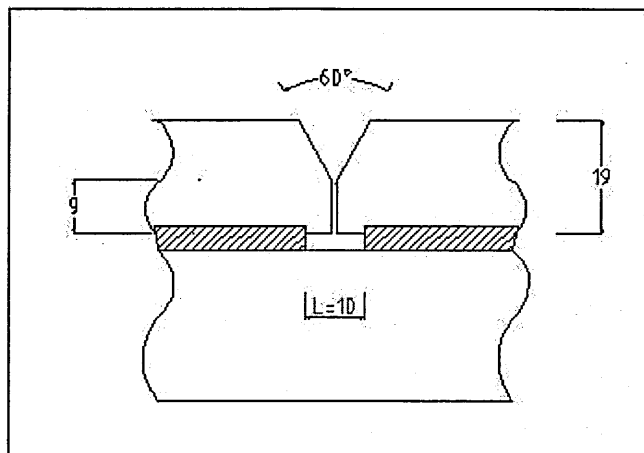
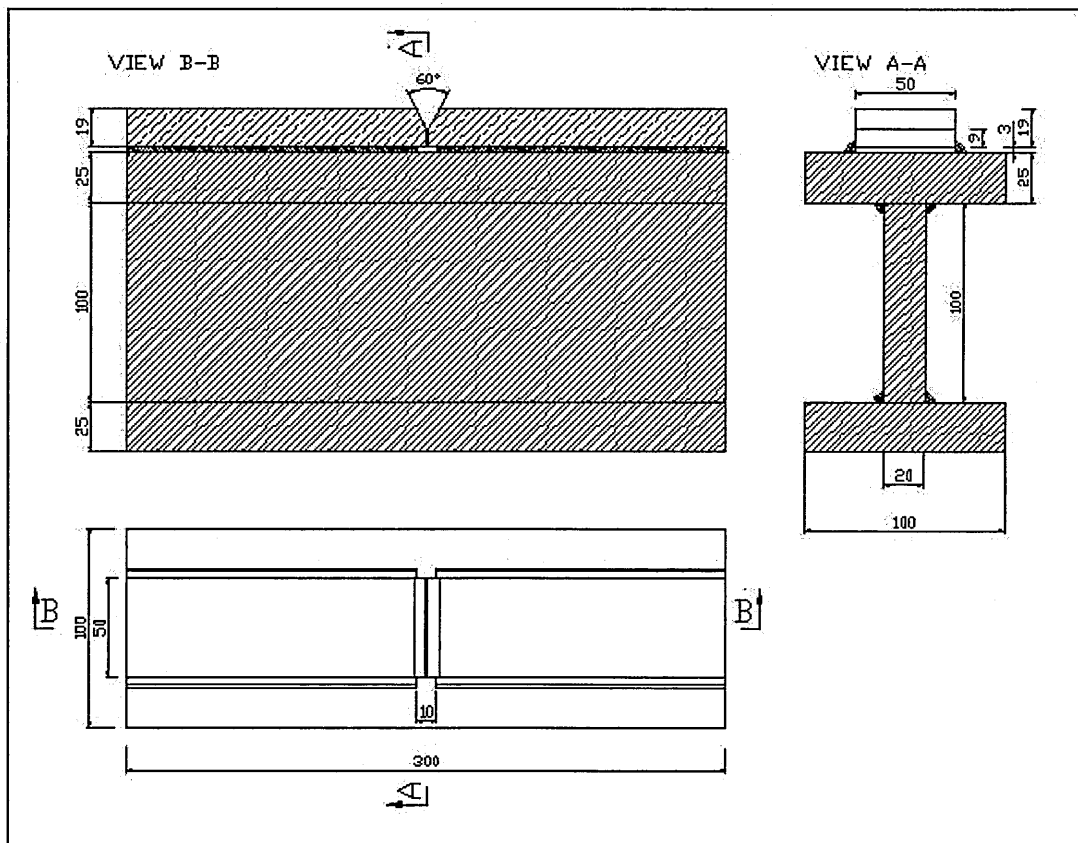


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 4500 \text{ mm}^2$

Root gap, $RG = 1 \text{ mm}$

Figure B. 3: S2 configuration - dimensional drawing.

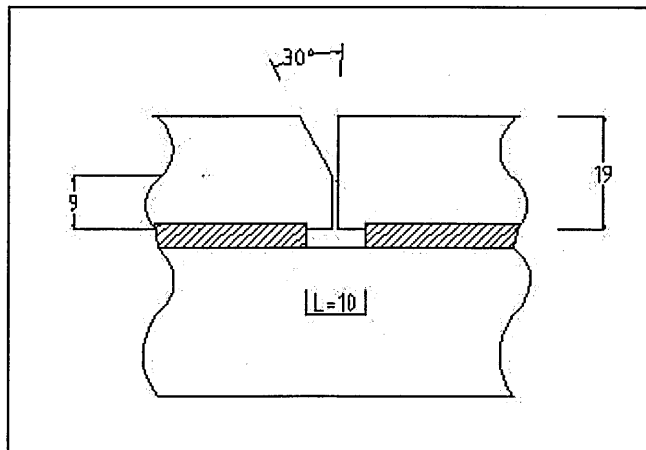
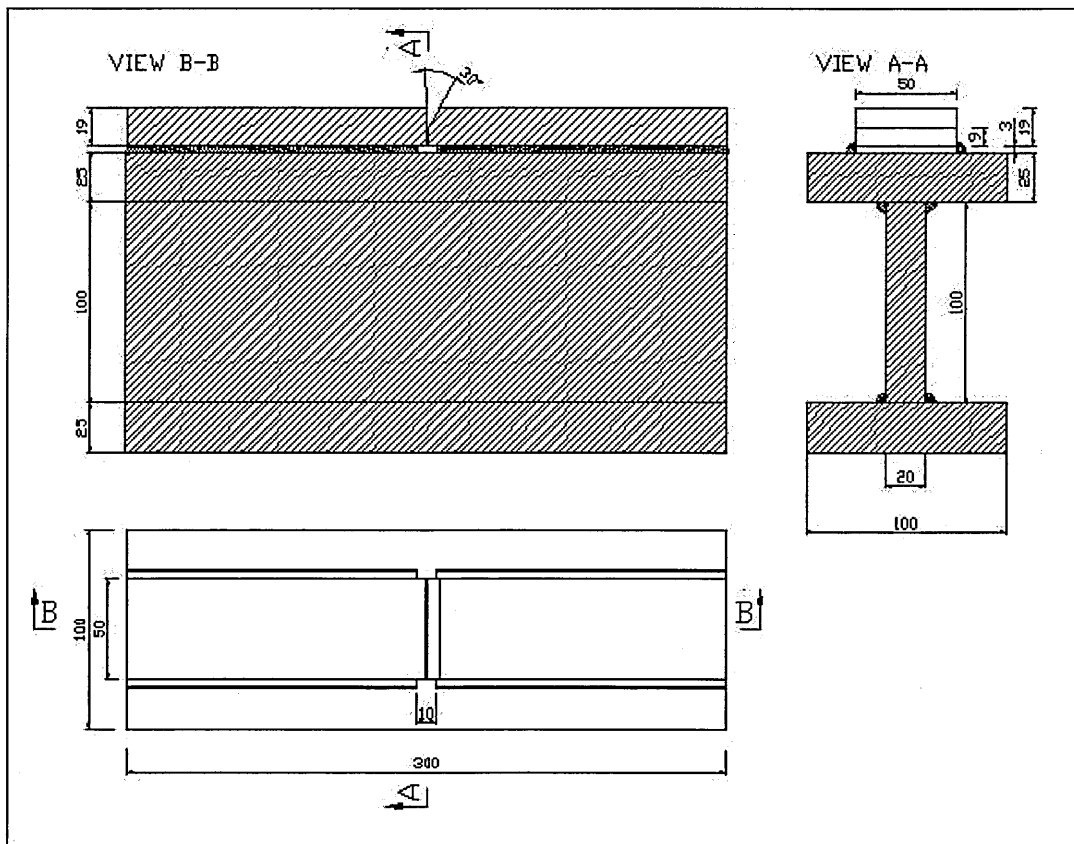


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 6900 \text{ mm}^2$

Root gap, $RG = 1 \text{ mm}$

Figure B. 4: S3 configuration - dimensional drawing.

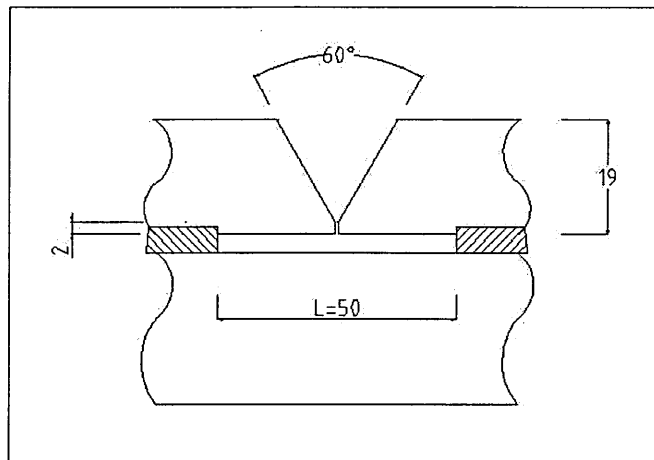
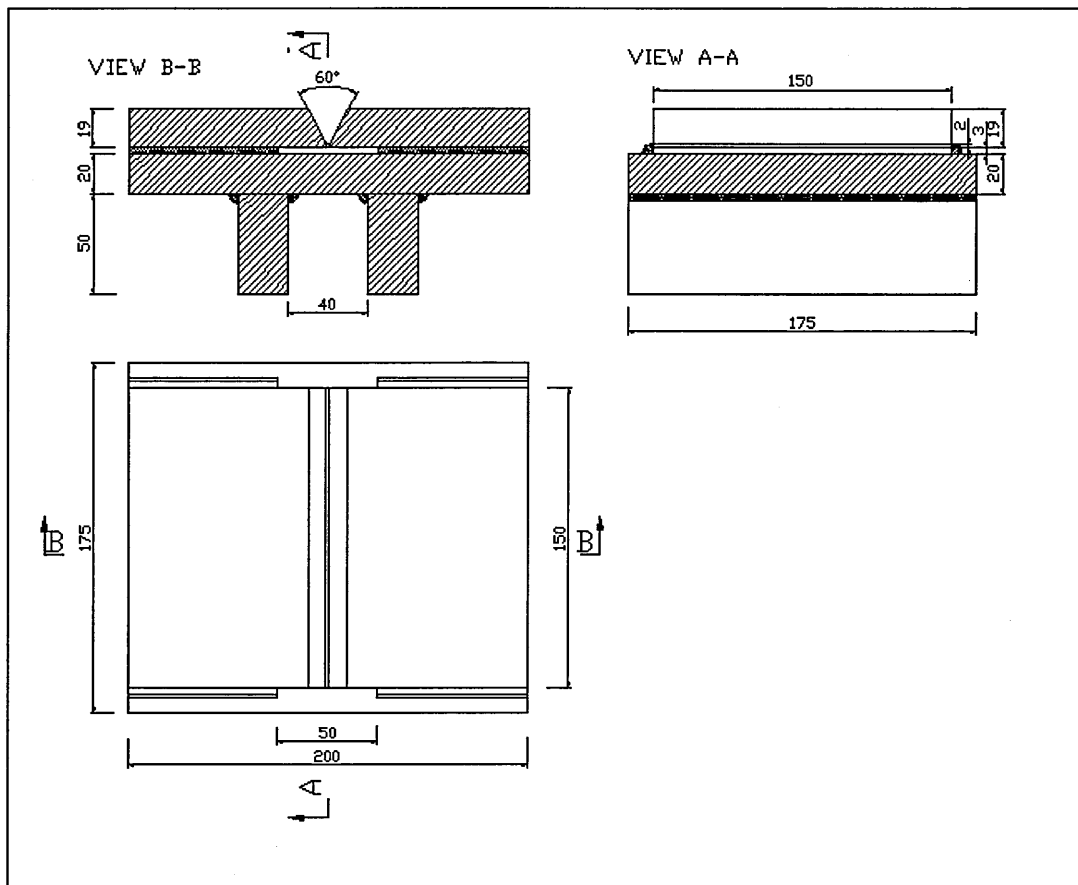


Dimensions in mm, not to scale.

Sectional area of restraint plates, $A = 6900 \text{ mm}^2$

Root gap, $RG = 1 \text{ mm}$

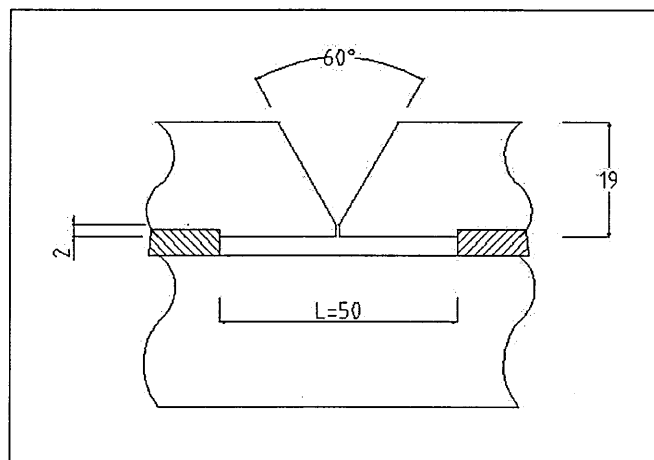
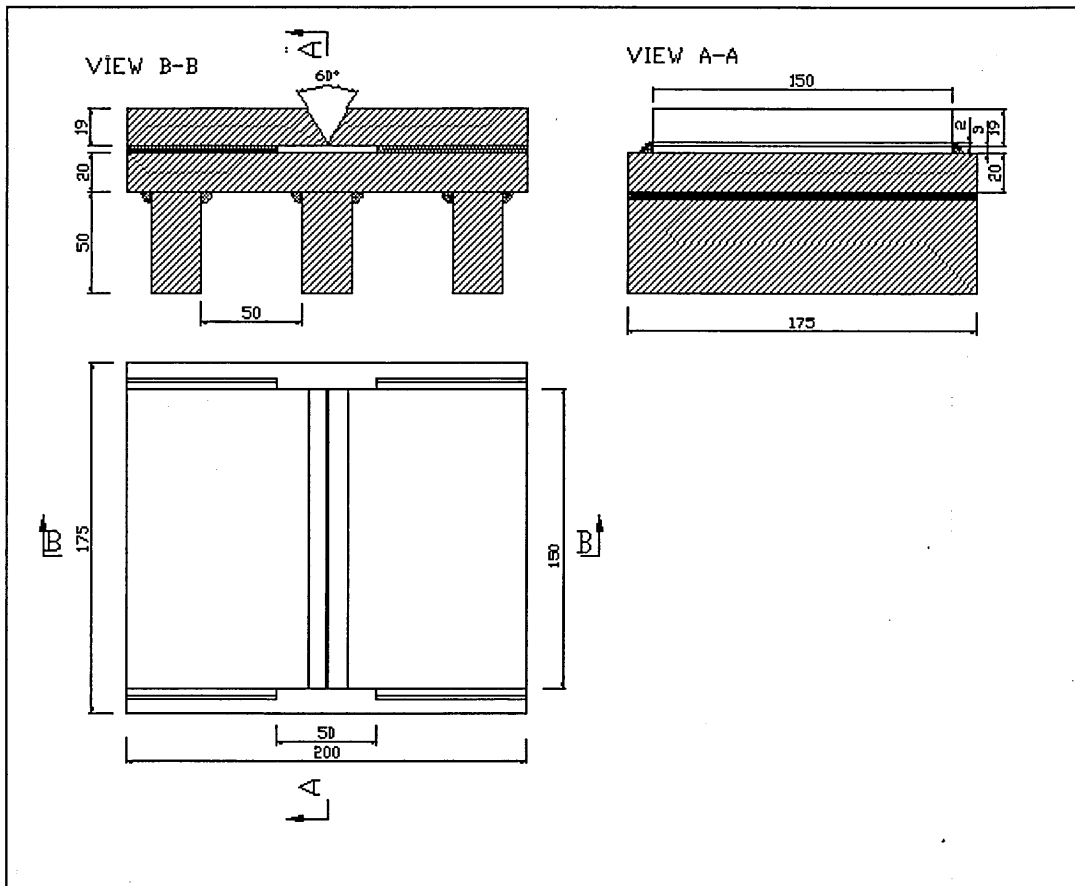
Figure B. 5: S4 configuration - dimensional drawing.



Dimensions in mm, not to scale.

Root gap, $RG = 1$ mm

Figure B. 6: S5 configuration - dimensional drawing.



Dimensions in mm, not to scale.

Root gap, RG = 0.5 mm

Figure B. 7: S6 configuration - dimensional drawing.

Table B. 1: Test assembly material dimensions.

Description	Material	Dimensions and allowances	Comments
Test sections	material under evaluation	Dimensions according to the dimensional drawings Allowances: t – from tested material w $\pm$ 1 mm l $\pm$ 5 mm	One end prepared with the designed bevel specification and oriented such that the actual test weld is deposited perpendicular to the plate rolling direction
Restraint plates	Mild steel	t $\pm$ 1 mm w $\pm$ 1 mm l $\pm$ 1 mm	Number and configuration according dimensional drawings
Backing shims	Mild steel	t = 3 mm (min.) w : same as test piece l = 140 $\pm$ 1 mm	
Run on/off tabs	Mild steel	t = 3 mm w = 19 $\pm$ 5 mm	

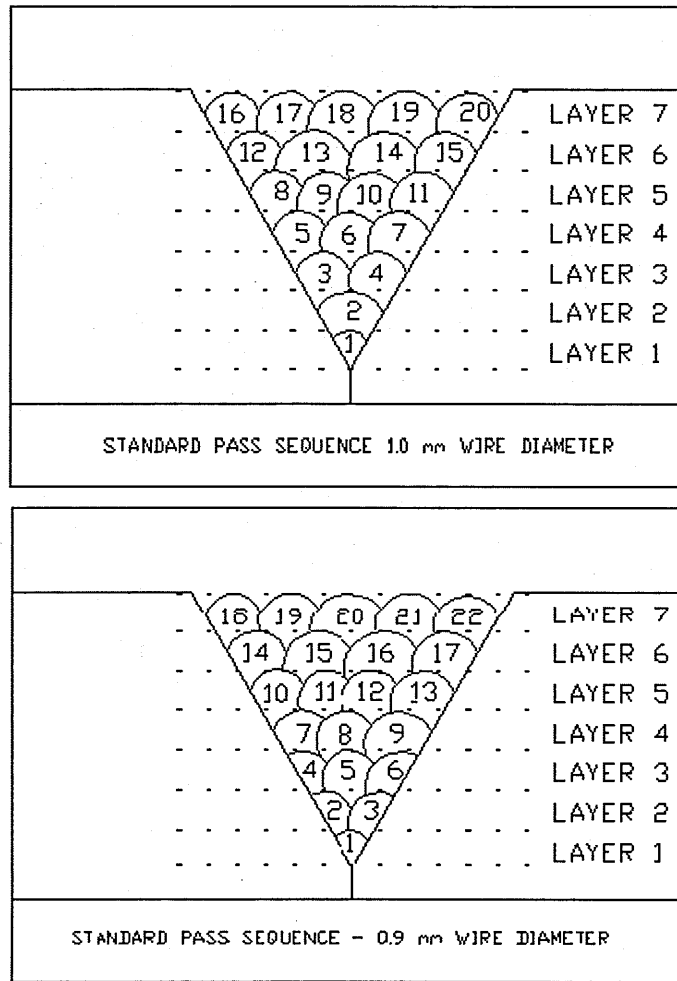


Figure B. 8: Standard pass sequence for multipass tests.

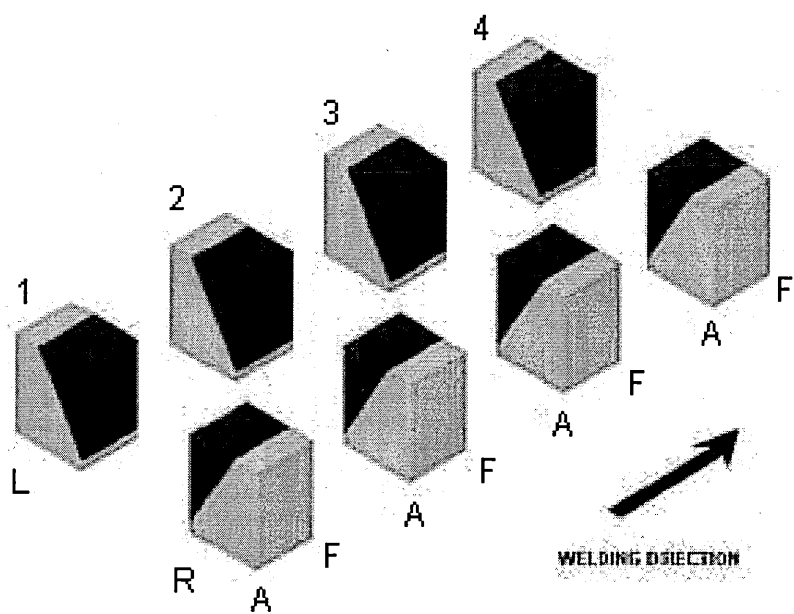


Figure B. 9: Sampling technique.

APPENDIX C

PROCEDURE FOR DETERMINATION OF HYDROGEN CONTENT IN FERRITIC STEEL GMAW

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C.1 SCOPE

This specification defines the procedures for the sampling and determination of diffusible and residual hydrogen content in ferritic steel weld metal arising from the welding of ferritic steel using the GMAW and FCAW processes.

Hot extraction of the hydrogen in a gas carrier apparatus followed by hydrogen detection in a thermal conductivity sensor is the method employed to measure the hydrogen contents in weld samples.

The standard BS EN ISO 3690:2000 (ref. 1) provided the main base for this procedure and the same redaction of paragraphs were adopted whenever they fully applied.

C.2 REFERENCES

1. BS, *Welding and allied processes - Determination of hydrogen content in ferritic steel arc welding*.
2. BS ISO, *Welding consumables and shielding gases for arc welding and cutting*.
3. STROHLEIN, *HMAT2500 - Operating instructions*.
4. Grong, O. *Metallurgical Modelling of Welding*, 2nd ed. London, UK: IOM, 1997.

C.3 TEST PROCEDURES

C.3.1 Production of weld specimens

C.3.1.1 Principle

The welding process to be tested is used to deposit a single weld bead, which is rapidly quenched and subsequently stored at -78 °C or lower until required for preparation and analysis.

C.3.1.2 Welding fixture

A copper welding jig for heat inputs up to 2 kJ/mm, which may be water cooled, is shown in Figure C. 1. It is designed to promote the proper alignment and clamping of the test piece assembly by means of the single clamping unit which is used with a ring spanner or other suitable means.

A welding jig without water-cooling may be used as long as the same dimensions are retained and as long as the temperature is controlled in the manner described in C.3.1.4 below.

The welding jig shown in Figure C. 2 will allow the production of test welds with a heat input greater than 2 kJ/mm and up to about 3 kJ/mm.

C.3.1.3 Test piece assemblies

The test piece assembly is prepared from a plain carbon, non-rimming steel with a carbon content of not more than 0,18 % and sulphur content of not more than 0,02 %. The test assembly is made according to the dimensions shown in Figure C. 3, with a tolerance of ± 0.25 mm on all dimensions except the length of the run-on and run-off pieces.

All surfaces are finished at right angles to ensure good contact between adjacent pieces during the welding operation. Each test piece assembly may be finished with one operation on a surface grinder so as to ensure a uniform width, or closer dimensional control may be exercised to obtain proper clamping. See C.3.1.4 for evidence of proper clamping.

Prepare three or more sets of test pieces and number them by engraving or stamping the opposite side to that to be used for welding. Number and degrease each centre test piece in each set. Determine the weight of each centre test piece (m_1) to the nearest 0,01 g. Degas the centre test pieces in a vacuum, or dry inert carrier gas at $650\text{ }^{\circ}\text{C} \pm 10\text{ }^{\circ}\text{C}$ for 1 h and keep the pieces cooling in a vacuum or inert carrier gas prior to welding.

If the welding conditions produce weld beads incompatible with the dimensions of test piece assembly as shown aligned in Figure C. 1, the test assembly shown in Figure C. 2 is used. The centre test piece is rotated 90° about a vertical axis but the run-on and run-off pieces must be compatible with the new cross-section and the length increased to accommodate the longer weld bead.

The test piece assembly is clamped in the welding fixture using annealed copper foil as shown in Figure C. 1 and Figure C. 2. The annealed copper foil may be used to prevent erosion of the fixture. The foil may be annealed repeatedly and quenched in water after each annealing. Oxide scale after annealing is removed by pickling with dilute nitric acid (10 %) followed by washing with distilled water and drying.

C.3.1.4 Welding and test piece storage

The temperature of the welding jig before each weld is made is temperature ambient or not more than 25 °C above ambient, which can be obtained by water cooling the jig.

Using the welding parameters appropriate to the type of investigation, make a single weld bead on the test piece assembly that is clamped in the welding jig as shown in Figure C. 1 or Figure C. 2.

- a) Welding is initiated on the run-on piece at a point sufficiently distant from the centre test piece such that a stable arc and a stable deposit shape are achieved before reaching the centre test piece.
- b) Welding is terminated with the trailing edge of the crater within 25 mm of the centre piece.
- c) After extinction of the arc, and without any delay, the clamp is released and the test piece assembly removed and quenched as rapidly as possible to below room temperature in stirred iced water and then transferred to a low-temperature bath saturated with solid carbon dioxide, or to liquid nitrogen.
- d) Once chilled, the underside of the central test piece is examined to assess the uniformity and extent of heat tinting. Properly aligned and clamped test assemblies shall show parallel and uniform heat tinting of the underside of the central test piece, and dark oxidation shall not extend to the edges of the underside of the central test piece.
- e) The run-on and run-off pieces are broken off and the centre piece returned to cold storage. The centre pieces may be stored at -78 °C in the solid carbon dioxide bath for a period of up to three days, or at -196 °C in liquid nitrogen for a number of weeks if necessary, before analysis.
- f) For purposes of classifying welding consumables, during welding of the test assembly, the ambient absolute humidity must be at least 3 g of water vapour per 1 000 g of dry air (this corresponds to 20 °C and 20 % relative humidity). If the absolute humidity, measured using a sling hygrometer or other calibrated device, equals or exceeds this condition, the test is acceptable as demonstrating compliance with the requirements of the standard of reference provided that the actual test results satisfy the diffusible hydrogen requirements of the applicable consumable classification standard.

C.3.1.5 Recording of data

All welding details such as current, voltage, travel speed, filler metal type and composition, etc. are recorded on the appropriate weld data sheet as given in Figure C. 4.

C.3.2 Welding procedures for the production of weld specimens

C.3.2.1 Filler material

The filler material to be tested is used in one of the following ways:

- a) For purposes of classification, the welding parameters are the same as those used in the preparation of the all-weld-metal test assembly for mechanical property determination, with travel speed adjusted to obtain a deposit weight on the centre test piece of $4 \text{ g} \pm 0.5 \text{ g}$.
- b) For investigation purposes, the filler material and welding parameters are those given in the specific welding procedure under evaluation.

C.3.2.2 Shielding gas

The shielding gas is of a welding grade as specified in ISO 14175 (ref. 2). The shielding gas used and gas flow are according to the manufacturer's recommendations. Details of the shielding gas composition and flow are recorded on the report form. For investigation purposes it may sometimes be necessary to dry the shielding gas in order to remove moisture. If this is done, then the moisture content of the gas are measured and reported.

C.3.2.3 Making the test welds

The run-on and run-off pieces of the test piece assemblies may be 45 mm long when using the assembly shown in Figure C. 1, and 85 mm long when using the assembly shown in Figure C. 2. The welding parameters are chosen to ensure that the heat input for the fixture in use is not exceeded.

Using the welding fixture appropriate to the heat input, the test piece assembly are clamped in the fixture using the annealed copper foils.

Three or more test welds are made on different test piece assemblies. The deposit is made along the centre line of the test piece assembly and the time spent in deposition is noted. The trailing end of the crater is placed on the run-off piece at a distance from the central test piece not greater than 25 mm. The length of the run-on portion of the weld

deposit must be sufficient to achieve arc and deposit stability before reaching the central test piece. The welding fixture is used as described in section C.3.1.4.

The welding current, polarity, voltage, time, weld length, electrode extension, wire feed speed and gas flow and ambient temperature and humidity at the welding station are noted for each of the triplicate welds and recorded on the report form. After extinction of the arc and without any delay, the test piece assembly is released from the fixture, quenched, cleaned and stored as described in section C.3.1.4.

For all purposes, the details listed in the report form (Figure C. 4) are recorded.

C.3.3 Measurement of hydrogen in the test weld

C.3.3.1 Strohlen H2500 equipment calibration

A Strohlen H-MAT2500 hydrogen analyser is employed to determine the hydrogen content of wires and fused weld metals. The hydrogen content of the welded samples is determined by hot extraction in a carrier gas method.

The equipment is calibrated in accordance to the manufacturer's recommendations (ref. 3).

C.3.3.2 Hydrogen determination

After living the liquid refrigerant the samples are quickly washed with acetone or alcohol and air-dried. They are weighed and introduced in the hot furnace, where the hot extraction starts immediately. The samples are kept at 400 °C for 20 minutes. The equipment set up is made according its operation instructions (ref. 3).

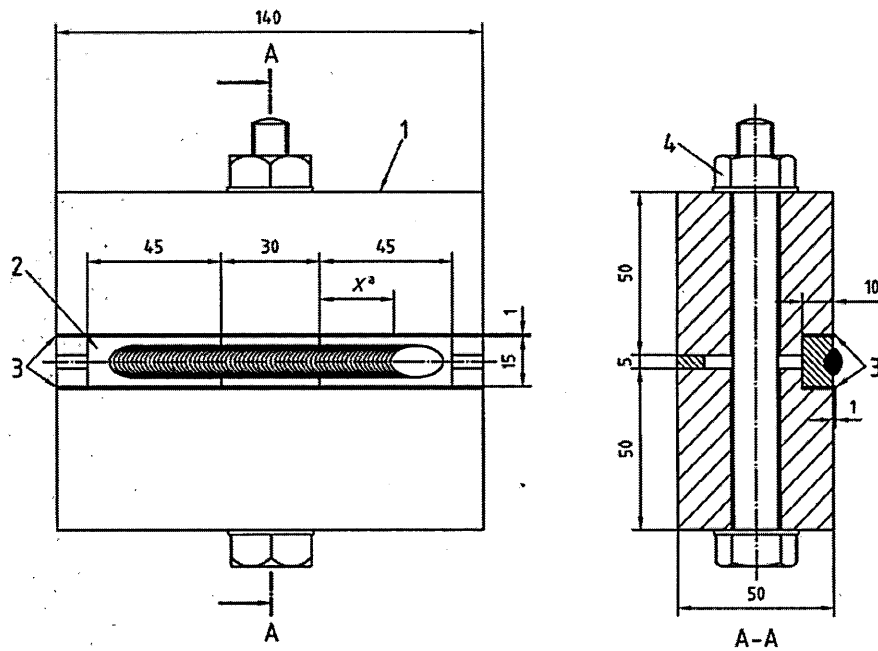
C.3.3.3 Results

The results provided (ml/100g) are recorded in the report form and additional information, like the plotted hydrogen evolution graph are attached. Those results refer to the hydrogen evolved in relation to the reference mass of 4 g and are corrected to relate to the real mass of deposited weld metal. The final results are given in terms of diffusible hydrogen in deposited weld metal (H_{DM}).

If results in terms of diffusible hydrogen in fused weld metal (H_{FM}) are required, the cross sectional area of the sample are examined for assessing the area of the weld zone in comparison with the area of the weld bead, as follows (4):

$$H_{FM} \text{ (ppm)} = H_{DM} \times 0.9 \times [D/(B+D)]$$

Where D is the mean area of the deposited weld metal and $(B+D)$ is the mean area of the fused metal (Figure C. 5).



Key

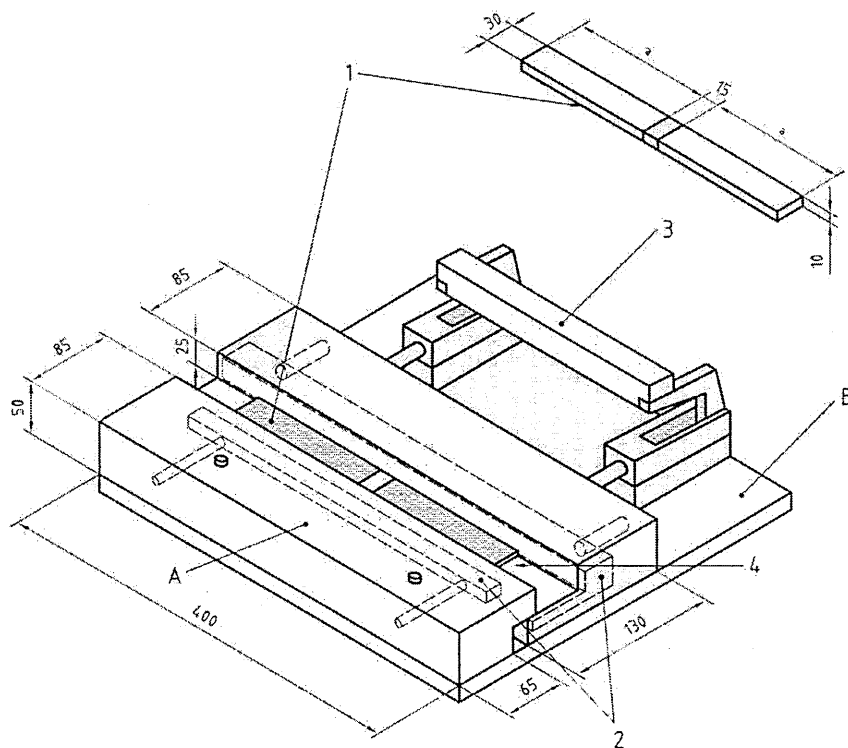
- 1 – Copper block
- 2 – Test piece assembly
- 3 – Copper foil
- 4 – M12 bolt

Note: Water cooling channels may be used

^a – Dimension $X \leq 25$ mm

Dimensions in mm

Figure C. 1: Jig for welds of up to 2.0 kJ/mm. After ref. 1.



Key

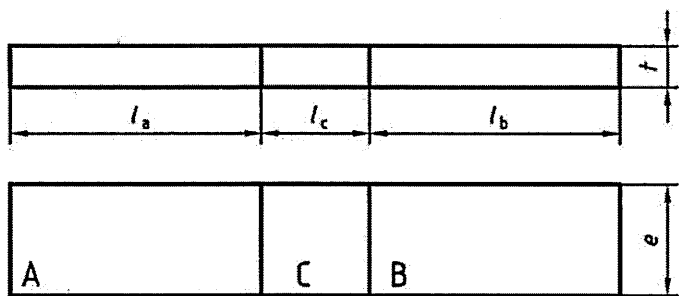
- 1 – Test piece assembly
2 – Water cooling jacket
3 – Lever clamp
4 – Copper foil is inserted here
A– Made of Copper
B – Made of Copper

Note: The run-off bead length is such that the trailing end of the crater is within 25 mm of the test piece (see distance X in Figure 1).

a – 85 mm

Dimensions in mm

Figure C. 2: Jig for welds of $2 \text{ kJ/mm} < \text{heat input} < 3 \text{ kJ/mm}$. After ref. 1.



Test assembly	$l_a=l_b$	l_c	e	t
Figure 1	45	30	15	10
Figure 2	135	15	30	10
	85	15	30	10
A/B	Run-on / run-off test piece			
C	Centre test piece			
NOTE: The centre test piece has the same dimensions in all three cases.				

Figure C. 3: Test piece assembly. After ref. 1.

Weld Metal Diffusible Hydrogen Content Test				
Report n.				
Investigating laboratory:	CRANFIELD UNIVERSITY		Test date:	
Investigator's name:	Pedro Barbosa			
Type of filler material:			Drying treatment:	
Filler material designation:			Shielding gas:	
Diameter of filler material, mm:			Gas cup i.d., mm:	
Electrode polarity (dc +ve, dc -ve or ac):			Details of tungsten electrode, if any	
H determination method			Make:	
Hot extraction temperature:			Diameter (mm):	
Hydrogen collection time (min : s):			Cone angle:	
			Designation:	
Number of test piece:	1	2	3	
Test piece code:				
RH (%) / temperature (°C) at welding station during welding:				
Shielding gas flow (l/min):				
Voltage (V); ac or dc:				
Current (A); type of meter:				
Welding time (s):				
Weld length, mm:				
Welding speed (min/s):				
Heat input (kJ/mm):				
Wire feed speed (min/s):				
Electrode extension, mm:				
Mass of test piece before weld (g):				
Mass of test piece after weld (g):				
Mass of deposited metal on test piece (g):				
Test piece to crater distance (mm):				
Diffusible hydrogen	1	2	3	Average
(a) HD, ml/100 g of deposited metal				
(b) HF, ppm of fused metal				
Other test details not included above:				
Cranfield, 17/07/2002 10:08 PM	Investigator Signature			

Figure C. 4: Report form.

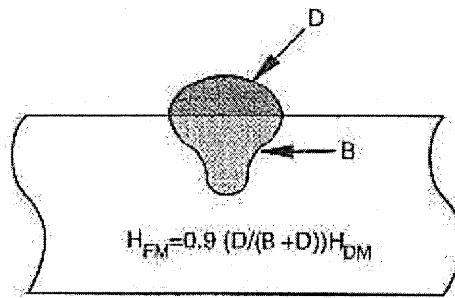


Figure C. 5: The relation between H_{DM} and H_{FM} . After ref. 4.