Weld hydrogen movement in the weld zone of commercial constructional steels - summary of investigative work

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Contents

1 The context of this investigation – why the movement of hydrogen in the weld zone

Hydrogen in solution in steels has the effect of causing embrittlement of the the steel structure which can take various guises, from fracture under a static load to the reduction of ductility on straining. These effects are significant and can become intrusive upon the commercial process of welding at only a few parts-per-million by mass. The details of hydrogen behaviour and its effects are therefore of great interest when welding or when formulating or selecting steels to be welded.

Hydrogen is invariably taken into solution to some extent in welds for all arc-welding processes. The intense conditions of temperature and ionisation in the electric arc dissociate all compounds entrained into it and the free hydrogen is taken into solution in the metal via dissolution at the weld pool surface upon which the arc impinges.

Of studies relating to the effect of hydrogen in the weld zone of structural steels, the issue of how hydrogen moves around seemed least investigated. Other topics are what quantity of hydrogen per unit length of weld goes into solution in the weld zone and what effect does hydrogen in a given concentration have on a given microstructure found in a given location, also given features like the state of stress.

The reason the distribution and movement of hydrogen in the weld zone is least investigated is the perceived considerable problems of investigating the issue. There are at least three reasons why hydrogen distribution is difficult to investigate in welds.

- None of the standard advanced investigative techniques used in metallography such as electron microscopy, X-ray interactions, *etc* are able to detect hydrogen in volume in a metal. A fundamental reason is that hydrogen, element number 1, does not interact strongly with illuminating radiations. Neutron radiation may be an exception; however the technique is only available at specialist centres, plus there is another reason why hydrogen does not interact strongly...

- The hydrogen is present in concentrations of only a few parts-per-million by mass, so even if an illuminating radiation in an investigative technique were to strongly interact with the hydrogen, the signal would still be very weak.

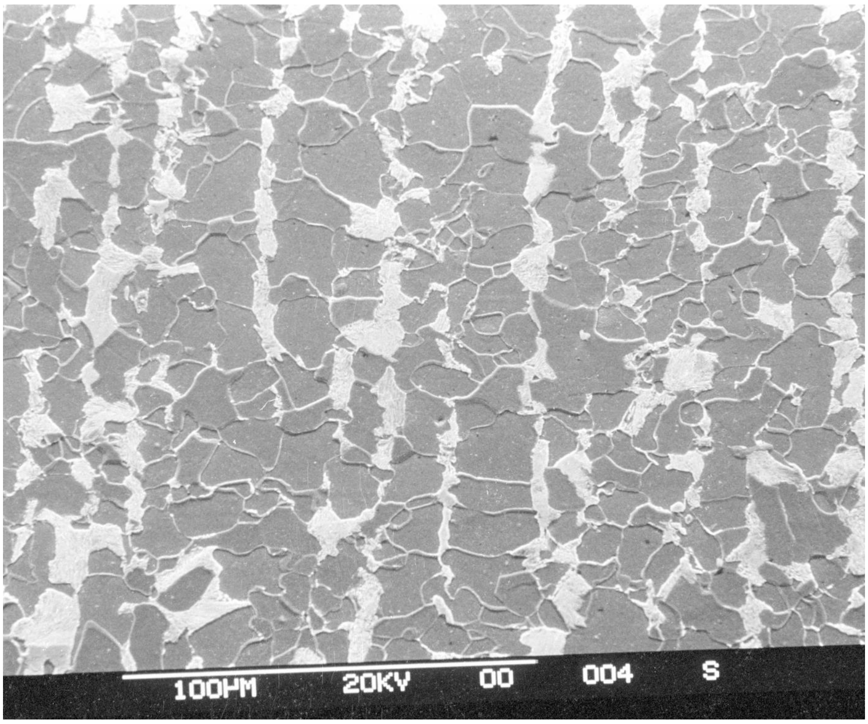
- Hydrogen has interesting effects because it does move around very quickly, which means that hydrogen cannot be studied by slicing a piece out of a component and examining it in great detail in subsequent time – approximately, the hydrogen is something like 80% gone in a minute from a sample of a millimetre size.

The last-mentioned difficulty, that hydrogen moves around very quickly, preventing the usual investigative technique of slicing a sample from the desired location and examining it in detail in subsequent time, presents one of the ultimate difficulties. This defeats most simpler investigative techniques which might otherwise be considered given that more sophisticated techniques do not work well.

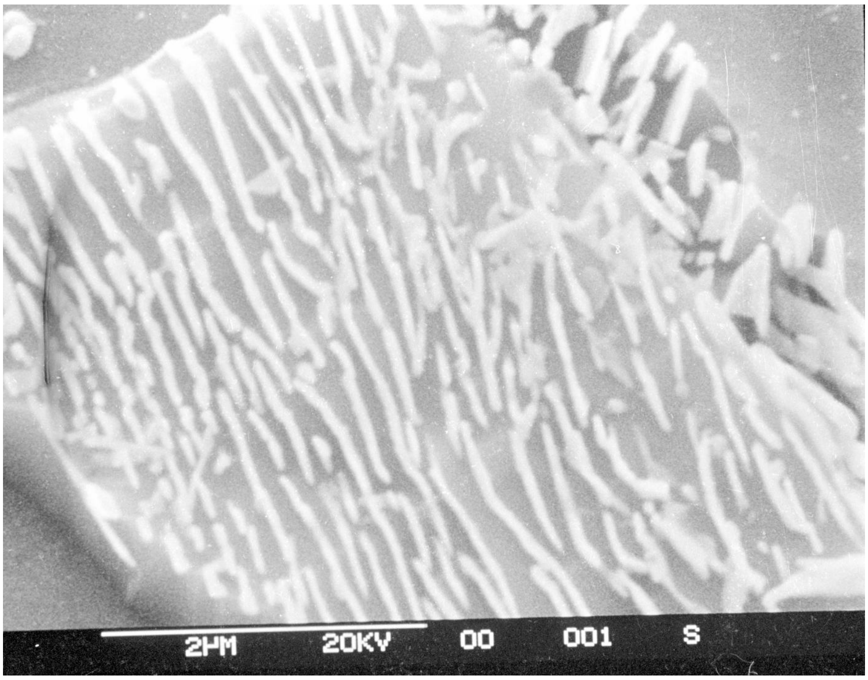
All of the investigative program had to use novel techniques. This article shows the investigative techniques used.

2 The steels featuring in the experimental program

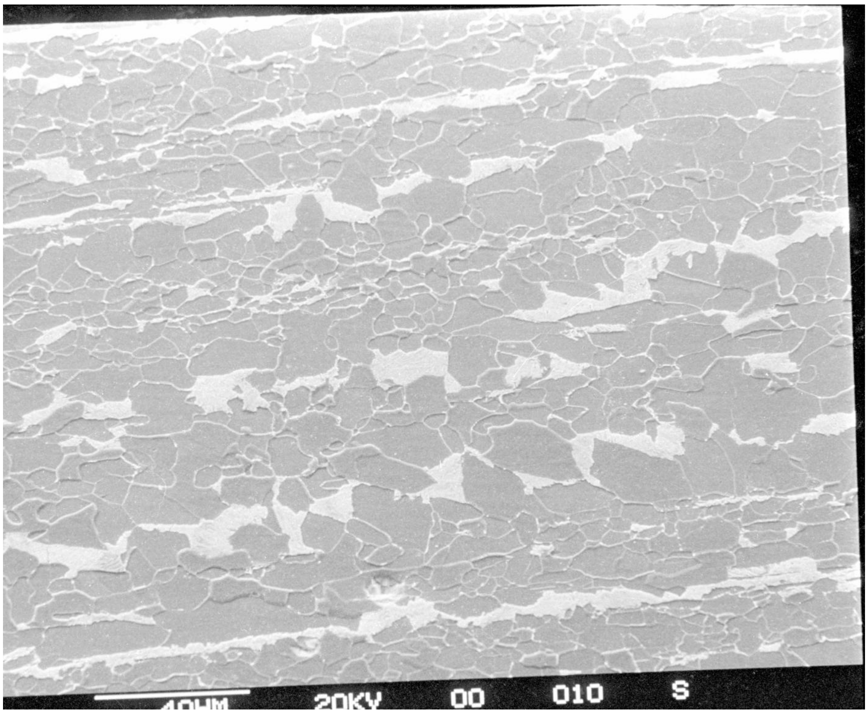
Four plate steels featured in / where the centre of the investigative program. They spanned a range from "classic" pearlitic plate steels of the early 1970's to the contemporary TMCP-HSLA's (Thermo-Mechanically Controlled-Processed, High-Strength Low-Alloy). Intermediate is a "TMCR" (Thermo-Mechanically Controlled-Rolled) steel which is of a formulation before the arrival of the application of Accelerated Cooling after the rolling process. Microstructures of these steels as observed by scanning-electron-microscopy (SEM) of samples sectioned and polished then metallographically etched. To extend the range of Carbon concentrations presented by the samples, a plain-carbon steel with a nominal 0.4%C, grade 040M80, was included in the sample set for the experiments performed.



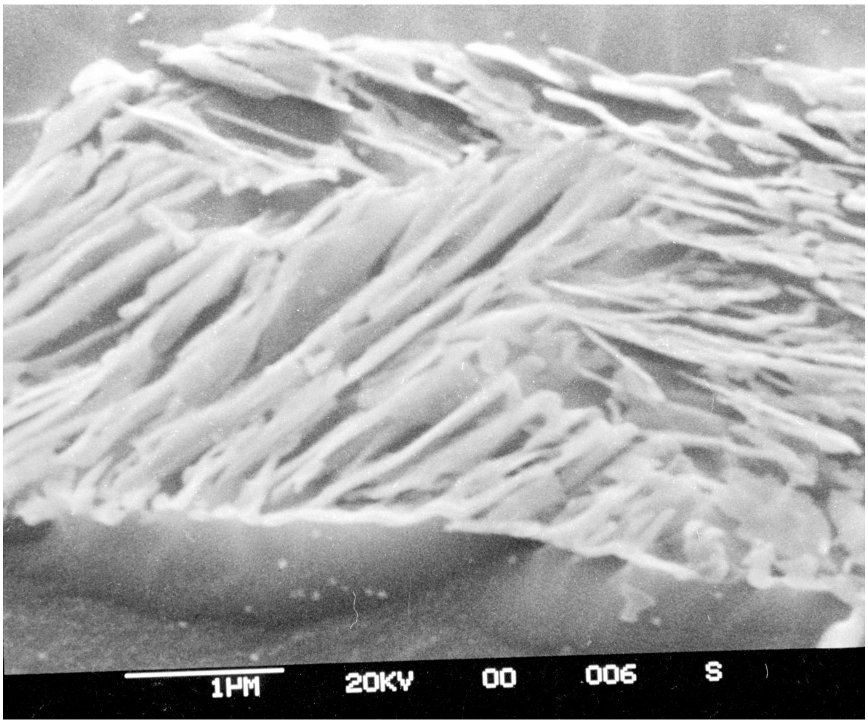
grade BS50D steel (0.22%C) at ≈ 500X magnification



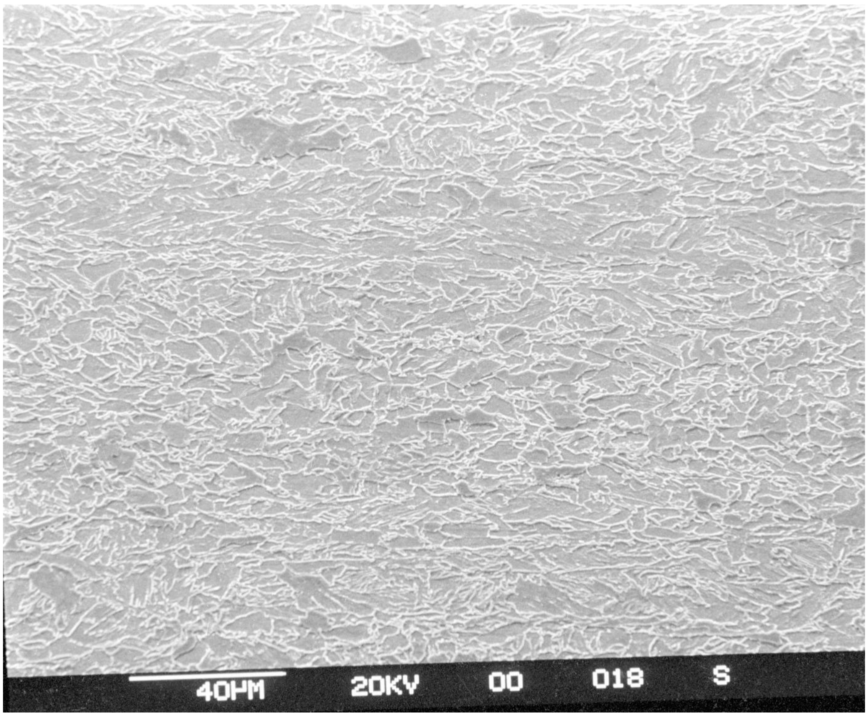
grade BS50D steel – area of pearlite at ≈ 20000X magnification



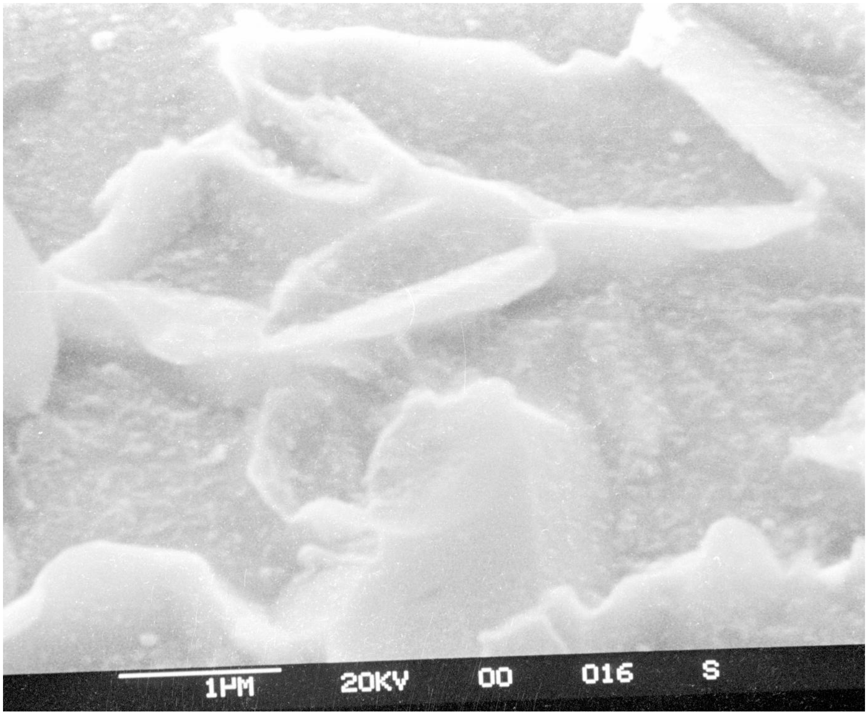
“9590C” – a TMCR steel of 0.08%C at ≈ 500X magnification



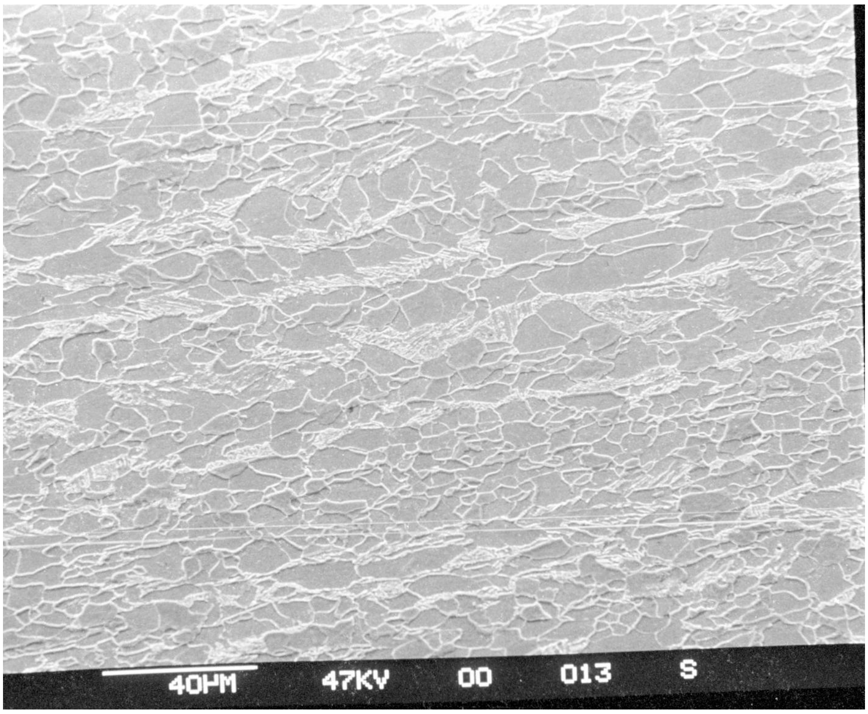
“9590C” TMCR steel – an area of pearlite at ≈ 20000X magnification



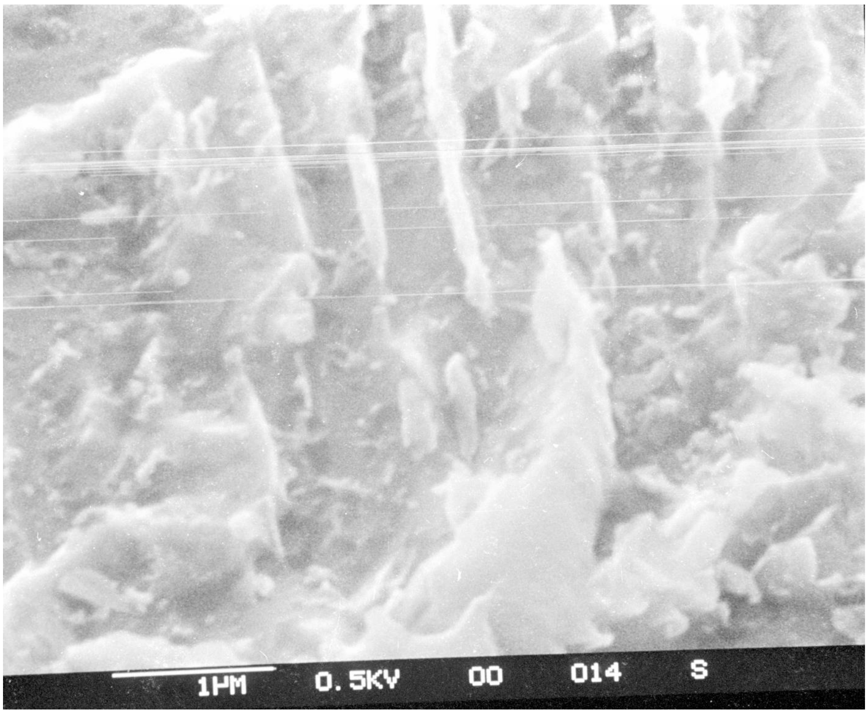
“0854C” – a TMCP steel with 0.06%C at ≈ 500X magnification



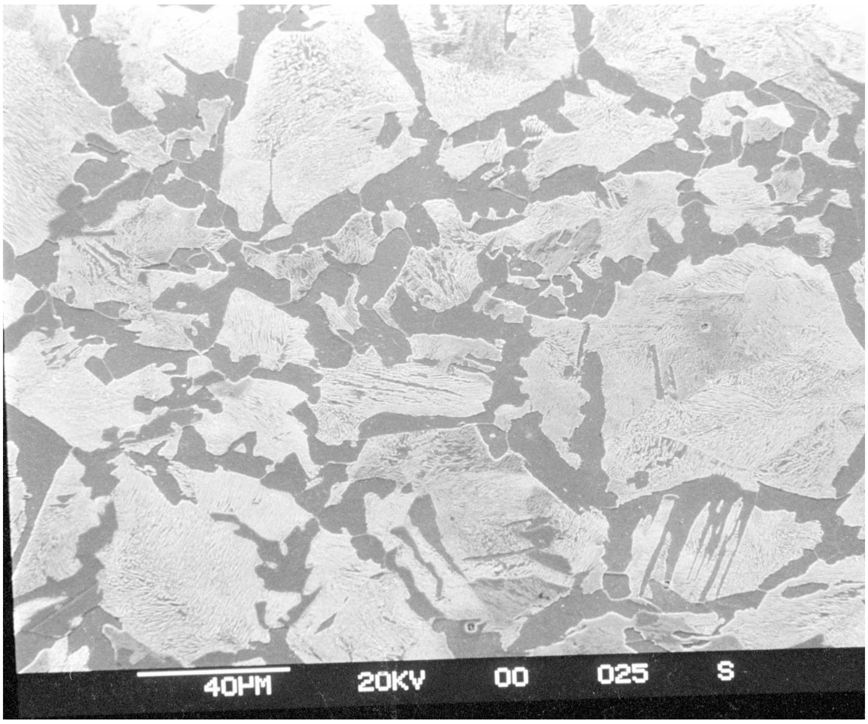
“0854C” TMCP steel with no pearlite in microstructure, at ≈ 20000X magnification



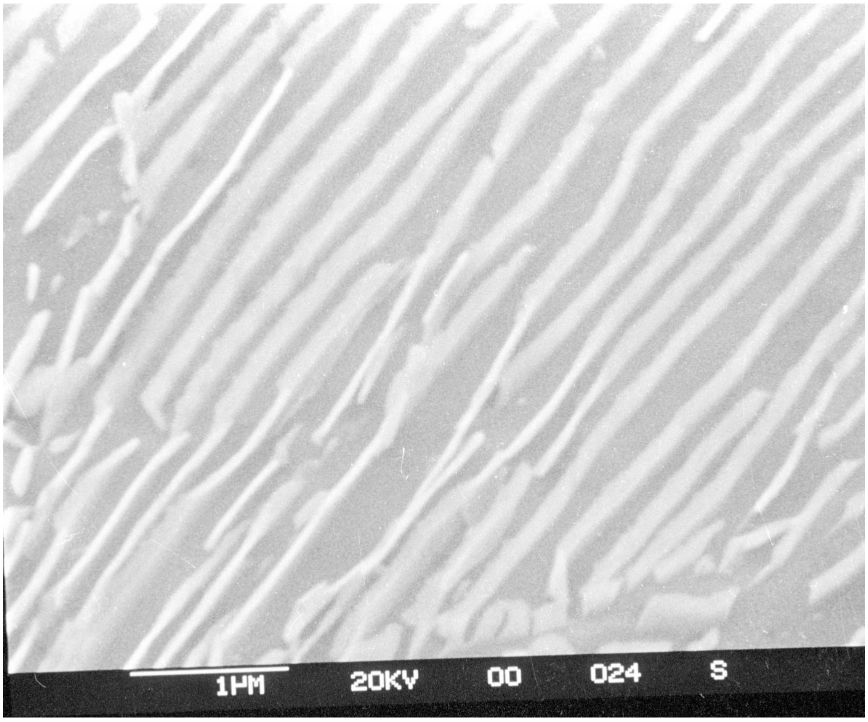
“0547C” TMCP steel with 0.05%C at ≈ 500X magnification



“0547C” TMCP steel showing no pearlite in microstructure, ≈ 20000X magnification



The 0.4%C plain-carbon steel, not a plate steel, at ≈ 500X magnification



The 0.4%C plain-carbon steel – a randomly chosen pearlite area at ≈ 20000X magnification

3 The “WWHP” test

The body of experimental results which most influenced the path of the investigation was the “WWHP” (Wedge Weld-Hydrogen Permeation) test. The hydrogen source providing the hydrogen flux by which the movement characteristics of hydrogen is investigated is a “real” weld. For a sample of this size, correct thermal conditions of the cooling of the weld due to the self-quenching by the heat capacity of surrounding plate metal was provided by clamping the sample between heat-sink blocks while the weld was being deposited. After welding, the cuboid-shaped sample had the face opposite the weld face machined away at an angle to the front face, presenting a continuous variation in thickness along the sample. Hydrogen moving from the weld into the plate metal therefore had different distances to travel before arriving at the back “wedge” face, where its emergence into the glycerol in which the sample was immersed, forming bubbles, announced its arrival. The effect of steel type and any other operative variables in a real weld which affect the rate of hydrogen redistribution in a weld was revealed by the rate at which the emerging hydrogen was able to travel the distances presented by the sample.

The following Figures show the hydrogen emergence observed as bubbles formed at the “wedge” face of the samples. Quantitative analysis is achieved by noting the position to which the hydrogen “carpet” had advanced along the wedge face in elapsing time after weld completion. The weld face can be seen in Figure 2 on page 13.

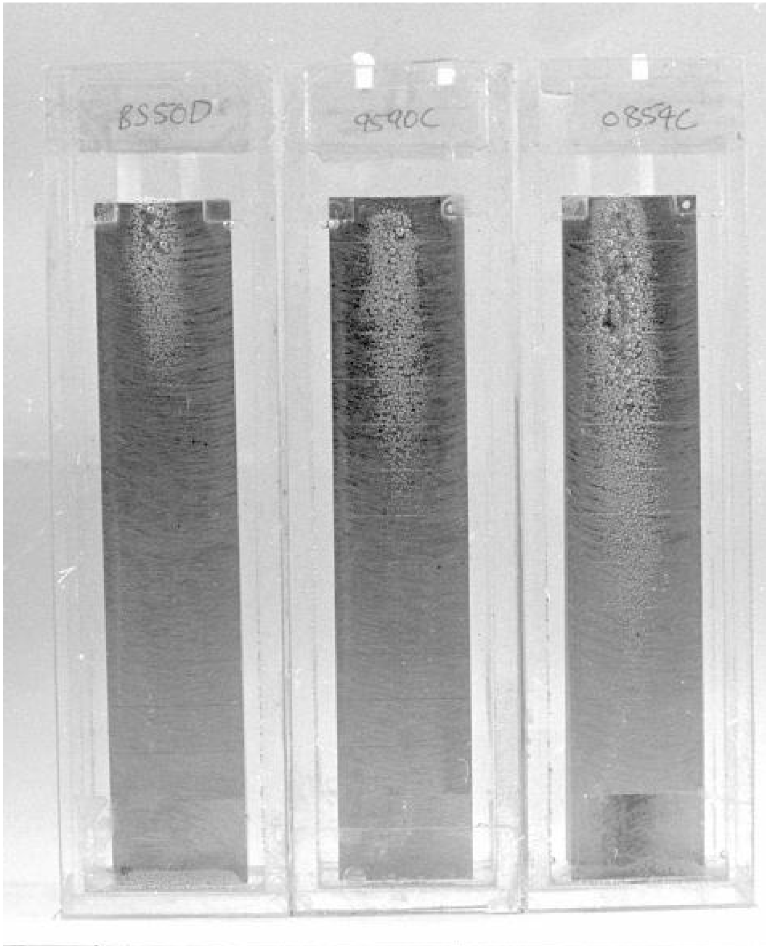


Figure 1: Typical "WWHP" test in progress. The different advancements of the hydrogen up the "wedge face", does reasonably represent the different rates at which hydrogen has diffused through the thickness of the sample, though the samples were not all initiated at exactly the same time. The bubbles are formed by hydrogen emerging out of the surface after traveling through the volume of the sample from the opposite side upon which the weld is deposited

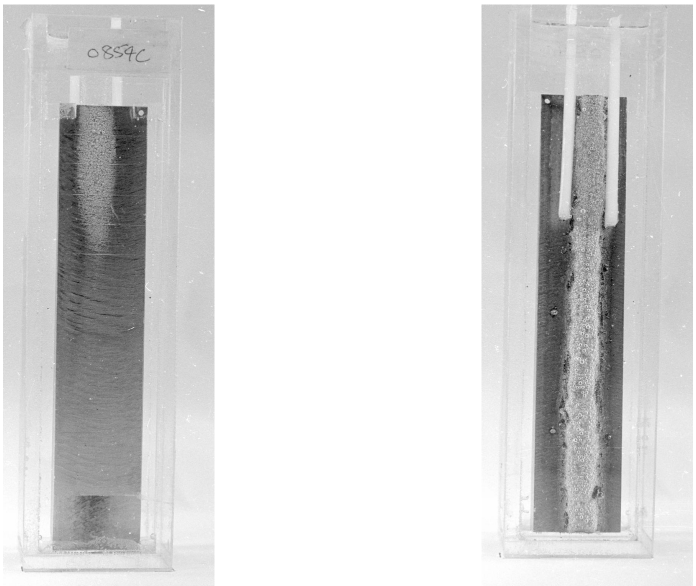


Figure 2: "WWHP" test ongoing for TMCP steel 0854C (rutile MMA weld was deposited). Observation back "wedge face" view on left-hand-side, front "weld face" view on right-hand-side

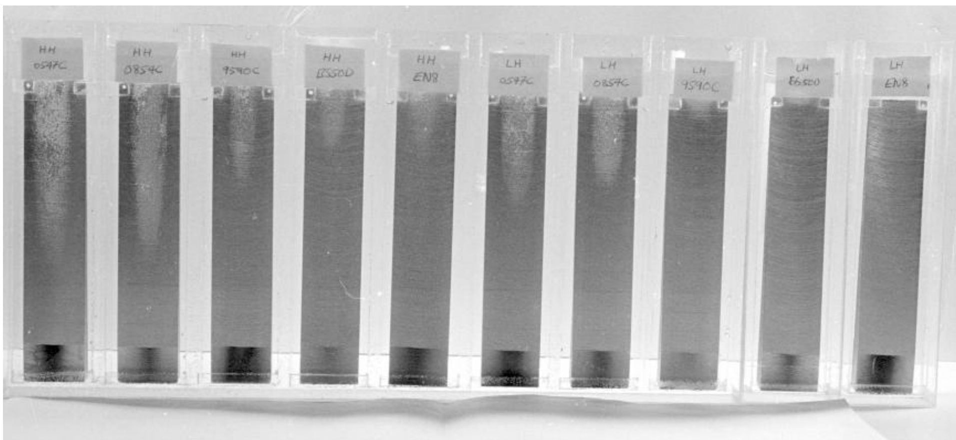


Figure 3: Ongoing "WWHP" test with all five steels at two different hydrogen levels of weld deposited by rutile flux-cored-wire MIG

Figure 4: The equipment ready for performing an LN2T sectioning procedure

4 The Liquid-nitrogen-temperature sectioning of weld samples

The ability to directly observe the location of hydrogen in welds seemed very valuable. Deduction of an initial state by projecting back in time using the pattern of results observed is a very powerful technique which is commonly used in science. This is only applicable though when the operative phenomena are well-understood, which is not the case for hydrogen movement in welds. For this reason, direct observation was desired in order to inspect the validity of deductions obtained by other experimental procedures, such as from the "WWHP" test. The liquid-nitrogen-temperature (LN2T) sectioning procedure used a standard machine tool, a shaper, fitted with cutting tool and sub-vice which are insulated from the body of the machine by polymer inserts.

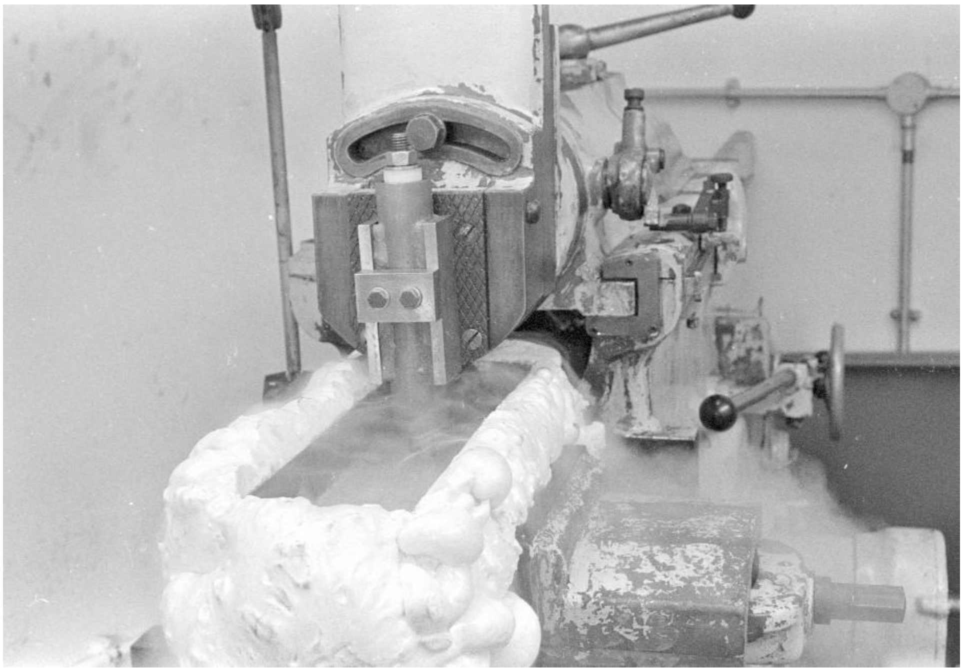


Figure 5: The LN2T sectioning equipment operating, reducing half of a "standard weld sample" to swarf, so presenting the longitudinal-vertical central plane as an external surface. The liquid in the tank is liquid nitrogen. The sample is fully immersed in the liquid nitrogen

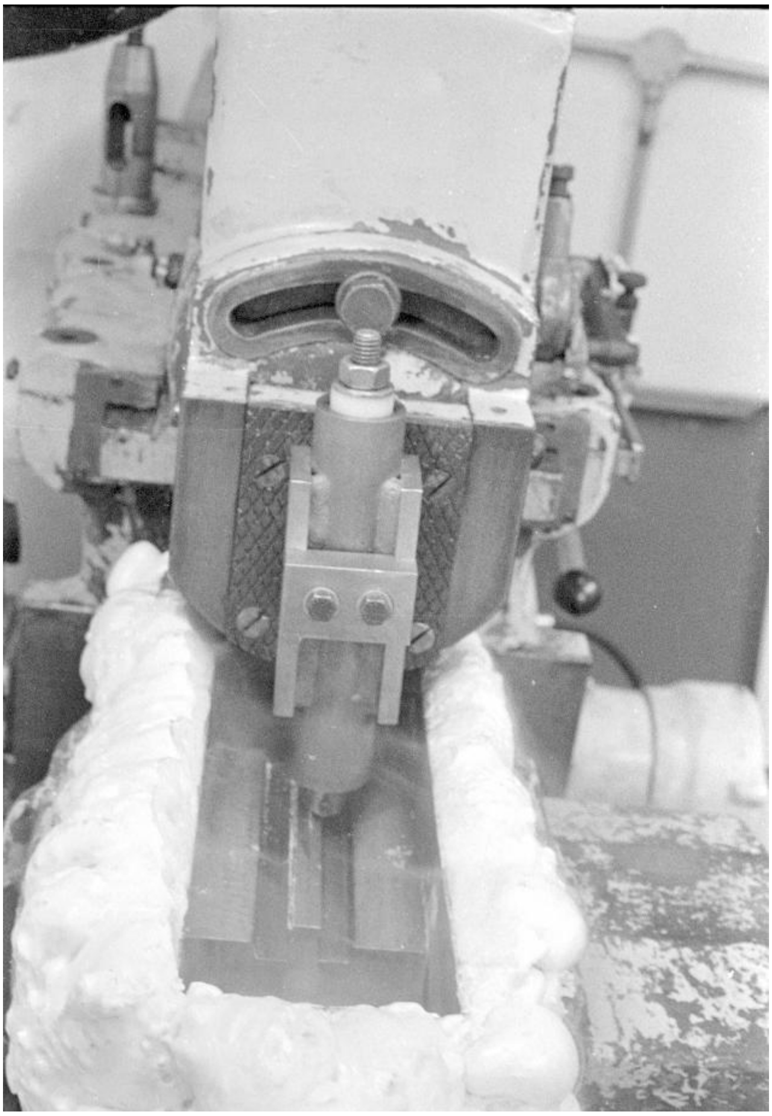


Figure 6: The sample in the LN2T sectioning procedure made visible by draining the holding tank of most liquid nitrogen – **not** part of the normal procedure

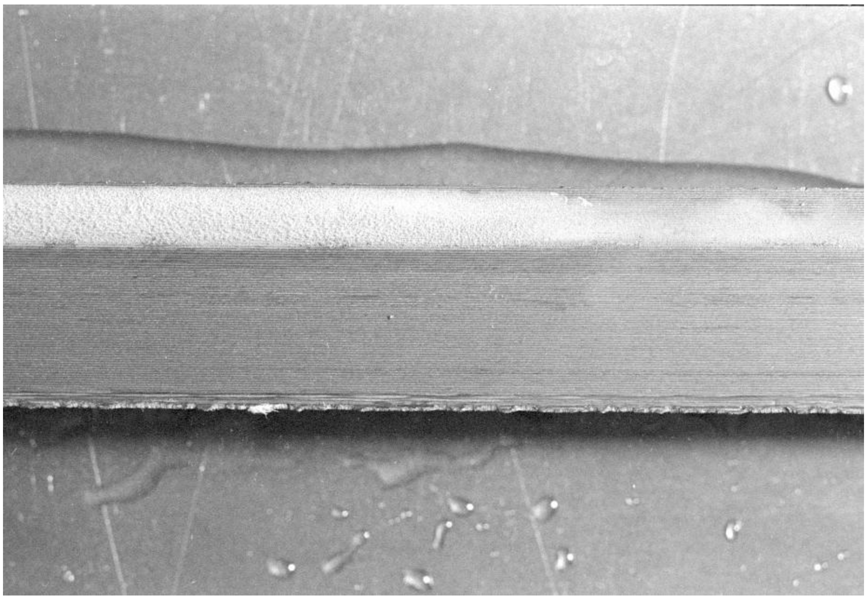


Figure 7: Hydrogen emerging from weld on longitudinal-vertical central plane exposed by LN2T sectioning. The steel is the “0547C”, which is a 0.05%C TMCP steel. The weld is the higher hydrogen rutile flux-cored-wire weld, giving around 9ppm by mass of weld by the standard determination procedure (which is not necessarily the concentration of hydrogen in a deposited weld due to the many factors this depends upon)

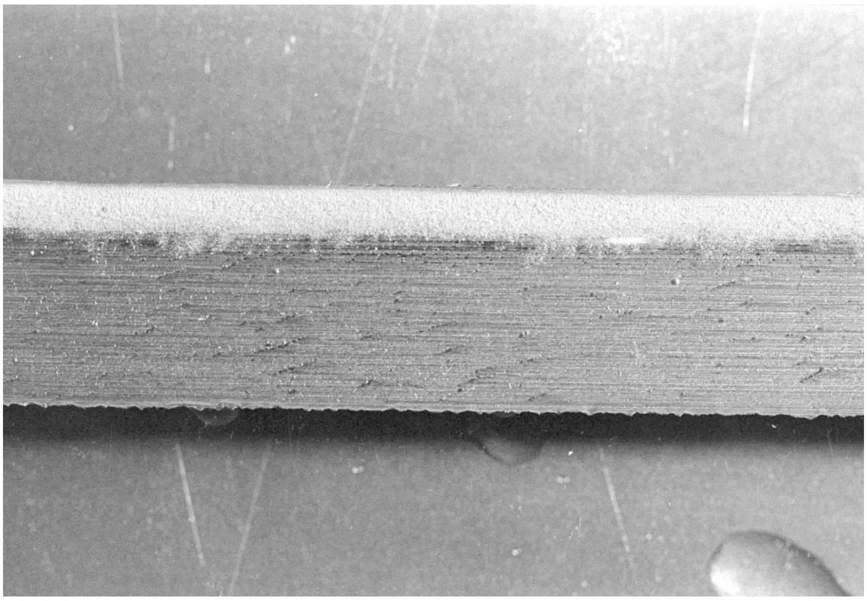


Figure 8: Hydrogen emergence from longitudinal-vertical central plane of a 0.4%C plain-carbon steel, prepared under the same conditions as for the sample in Figure 7

5 Notable observation for austenitic CrNi stainless steel

In the course of experiments the observation presented by the photograph, Figure 9 on page 19, was noted. The very thin remaining layer of stainless steel in the sample on the right-hand-side is not allowing any observable flux of hydrogen through. A weld upon a 0.4%C plain-carbon steel with the same preparation conditions is seen on the left-hand-side. It shows “normal” WWHP test behaviour, with hydrogen copiously emerging from the back “wedge” face. It seems that the stainless steel is providing a diffusivity to hydrogen which is orders of magnitude less than that offered by a ferritic unalloyed steel.

This behaviour was not analysed in this experimental program. Upon the realisation that the general case of the austenite allotropic phase of iron compared to the ferritic phase cannot be made without taking into account the unknown effect of around 18% by mass of Chromium and 8-to-10% by mass of nickel in the stainless steel, this investigative direction was not included in the “hydrogen movement in structural steel welds” project.

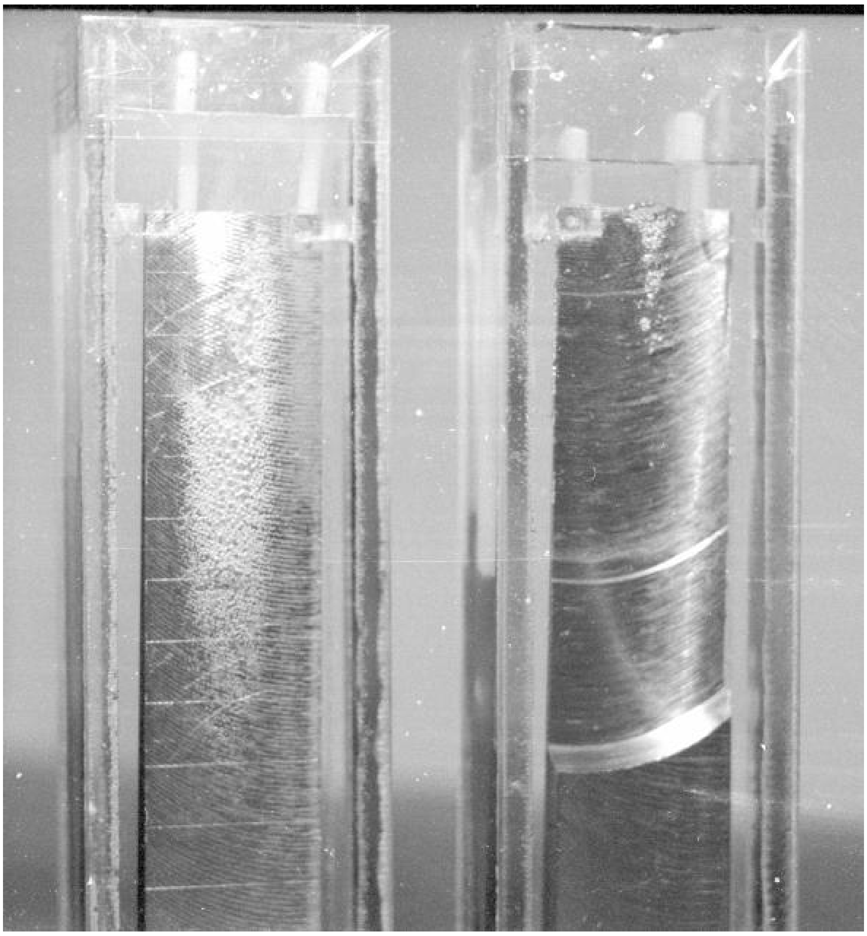


Figure 9: Stainless-steel (right-hand-side) and plain-carbon steel (left-hand-side) samples showing hydrogen emerging from the back-face. For the stainless steel sample the hydrogen is only emerging where the cutting of the back face has cut into the deeper penetration swirls of the weld bead, which is a standard ferritic weld