Cold Cracking in the Welding of Steels

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1. Description of the phenomenon

1.1. *Morphology of cold cracks*

Cold cracks or hydrogen induced cracks can be classified on the macroscopic level in terms of the region in which they appear, their orientation in relation to the weld bead and their position.

In fact, two kinds of cracks may be distinguished (Figure 1), those in the heat affected zone (A) and those in the weld metal zone (F) ; some are longitudinal in relation to the weld bead (AL or FL), others follow a transverse path (AT or FT). The longitudinal cracks in the heat affected zone may propagate parallel to the weld junction (AL 1) without necessarily coming to the surface of the weldment, or else they become localised at a discontinuity in the cross-section, thus forming a notch at the toe of the weld (AL 2 "toe crack") or at the root of the weld (AL 3 "root crack"). The type of crack indicated at AL 1, which is very common when hardenable steels are welded with other than basic electrodes, has come to be known as "underbead crack" and this designation has been wrongly attributed to the whole of longitudinal cracks associated with the influence of hydrogen. In fact it will be seen, further on, that the conditions leading to the appearance of cracks of the "toe crack" or "root crack" type differ from those producing "underbead cracks", in that they are caused by the notch effect.

Even when, initially, they are of the "toe crack" or "root crack" variety, cold cracks do not necessarily propagate as far as the surface. This applies especially to "root cracks" in fillet welds (AL 3b) or to cracks which, appearing at the toe after one pass, are partly covered by a subsequent pass (AL 2b). The fact that cold cracks may or may not come to the surface of weldments is particularly important from the point of view of their detection and of their influence on the mechanical static and dynamic behaviour of the parts.

Some microscopic observations may be added to these morphological macroscopic features ; the cold crack is a true fracture without branching. Electron microfractography reveals an inter-or intra-granular type of crack (in relation to the austenitic matrix) ; cracking seems to be rather of the intergranular type in the case of sensitive martensite present in the most hardenable steels, of the intragranular type in the case of the less hardenable steels.

When cold cracks have not resulted directly or indirectly in complete fracture of the welded assemblies they may be detected by certain types of non-destructive inspection such as the dye penetrant test for surface

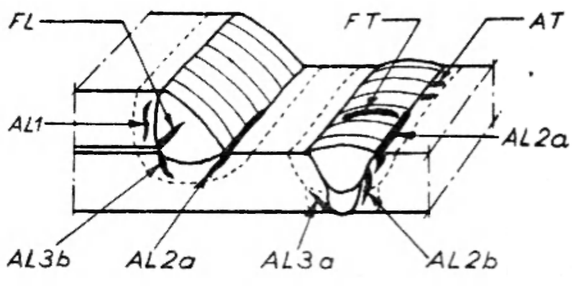

Fig. 1

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cracks, magnetic and ultrasonic testing. It must be stressed that radiographic examination does not provide a sure means of detecting cold cracks. Because of the delayed nature of some cracks it is recommneded that a certain lapse of time, for example 48 hours after the execution of the last weld in the welded assembly, be allowed before the non-destructive examination is undertaken. In view of the risk of extension of the crack during stress relieving by heat treatment, the non-destructive examination must be carried out after completion of this treatment.

1.2. *Conditions under which cold cracking occurs*

Cold cracking, as observed in practice and reproduced in laboratory tests, is the result of the conjunction of three necessary factors, no one of these being sufficient in itself to produce the phenomenon, at least in steels currently welded ; these factors are : *hardening* of the steel welded, *hydrogen*, and *stresses* associated with the welding operation under more or less restrained conditions. On the other hand, cracking may be studied from the point of view of the moment at which it occurs after welding.

In the first place, cold cracking is only observed to occur when, for the given welding conditions (thickness, energy, temperature of the workpieces), the steel is hardened, that is to say, undergoes a total or partial martensite transformation in the heat affected zone and/or in the weld metal. Thus non-alloyed steels are only affected by the phenomenon if their carbon content is relatively high ; low-alloy steels are more susceptible due to their hardenability. Susceptibility increases with a decrease in welding energy (tack welds, intermittent welds, first passes of multipass welds, etc....).

As for hydrogen, its effect has been understood for a long time and has been the cause of the development of electrodes with a basic covering. Joints welded with rutile or cellulosic electrodes are very sensitive to the phenomenon. Basic electrodes diminish the risk, and the MIG type welding processes have even further expanded the limits within which steels may be welded without being subject to cold-cracking. It will be seen further on that cracking in the heat affected zone is the result of the diffusion towards this region of the hydrogen dissolved in the weld metal zone.

It has also been known for a long time that cold cracking implies the existence of stress : unrestrained are less susceptible to cold cracking than restrained welds. Nevertheless, the stress developed simply by depositing a weld bead on steels with a high hydrogen content or on decidedly martensite structures is sufficient to induce cracking of the so-called "underbead" kind, whereas, in the case of deposited metal with a lower hydrogen content, only "toe cracks" or "root cracks" are observed and these only if relatively high stresses are present. Transverse cracks in the heat affected zone seem to be specific to highly hardenable steels. Transverse cracks in the weld metal imply the presence of high stresses.

Cold cracking is also called "delayed cracking" because sometimes it does not immediately become evident after welding, at least not visibly so. The conditions for true delayed cracking will be discussed further on in this paper but the important role of the time factor in this phenomenon should already be noted. It may also be observed that, as its name implies, this phenomenon always takes place at, or approaching, room temperature.

1.3. *Methods of studying cold cracking*

The phonemenon of cold cracking is of such practical importance that numerous tests, amongst the so-called weldability tests, have been developed to study the factors leading to its occurrence and to determine the optimum welding conditons by which it may be prevented.

The first group of tests which should be mentioned are those which, despite their empirical nature, have prevailed for a long time, viz. tests on restrained assemblies. The restraint is obtained either by arranging the test pieces so that they act together to produce a system of self-restraint, or by means of a rigid fixture into which these test pieces are set. The "H" plate weld test, the LEHIGH test, the CTS test or the TEKKEN Y-groove weld test may be cited as examples of tests on self-restrained welds. The RD test is typical of the second category, where a fixture is used to restrain the test pieces.

Even when it has been possible to vary the "severity", the main drawback of restrained weld tests of this category is in that they give no indication as to the magnitude of the stresses by the test weld after its execution. Thus, they provide comparison but do not allow for quantitative evaluation of the effect of the factors involved in cold cracking. Attempts have therefore been made to develop cracking tests in which the force exerted on the test weld causing it to crack is adjustable and measurable. The tests on weld samples subjected, during welding, to a tensile load in a transverse direction to the joint, belong to this category, as do the so-called "implant" tests.

Finally, the factors affecting cold cracking i.e. hardening, hydrogen and stresses, may be studied by methods known as "simulation methods", in which a specimen is heat treated, charged with hydrogen, and subjected to a mechanical force under conditions simulating welding.

These various testing techniques, especially the quantitative techniques for evaluating cold cracking factors, have greatly helped our understanding of this phenomenon, and made possible the preparation of the present monograph, which is intended, on the one hand, to be a compilation of all the data now accepted and to serve as a guide to users and, on the other hand, to point out aspects on which additional research is still required.

2. Influence of the transformation structure

2.1 *Transformation and cracking in the heat affected zone*

2.1.1. Under the influence of the welding thermal cycle, a certain volume of the steel base metal, called the "heat affected zone", is austenitised on being heated, then, during cooling, undergoes a transformation depending on the austenitising conditions and the law of cooling, both in turn being dependent on the welding conditions, that is on the combined effect of the heat input, plate thickness and the initial temperature of the parts. It is important to stress from the start, that this transformation takes place *step by step* along he weld bead. That is to say (fig. 2) that, for a given position of the welding arc, the heat affected zone comprises a portion 1, consisting of austenite not yet transformed, and, behind the isotherm T_b corresponding to the transformation temperature, a portion 2, where the transformation is complete or is in progress. In the same way, the weld metal comprises the weld metal zone proper 3, the solidified metal in an austenitic state 4, and behind the transformation isotherm T_f, the weld metal already transformed or in the process of transformation 5. It should be noted now that T_f and T_b do not necessarily coincide ; we will come back to this detail to explain the passage of hydrogen from the weld metal towards the parent metal.

Given the specific features of the welding thermal cycle (rapid heating to very high temperature, brief austenitisation), continuous cooling transformation curves had to be specially established to explain the modes of transformation of steel in terms of the welding conditions. To simplify the determination and the use of such curves, advantage is taken of the fact that the cooling rate in the transformation temperature range of steel is constant over the whole heat affected zone. It is thus possible, knowing the cooling rate associated with each welding condition, to forecast the modes of transformation in the heat affected zone. In particular, the welding conditions likely to provoke, partially or wholly, a martensite transformation in this zone can be determined. Thus, if (fig. 3) we take the representation transformation temperature/cooling time between two reference temperatures, two critical cooling times are observed : TR_1, below which the martensite appears, and TR_2, below which there is no longer anything but martensite. It can also be seen that the martensitic transformation region is the lowest, from which it follows that, in fig. 2, the isotherm T_B lags furthest behind when a martensitic transformation occurs.

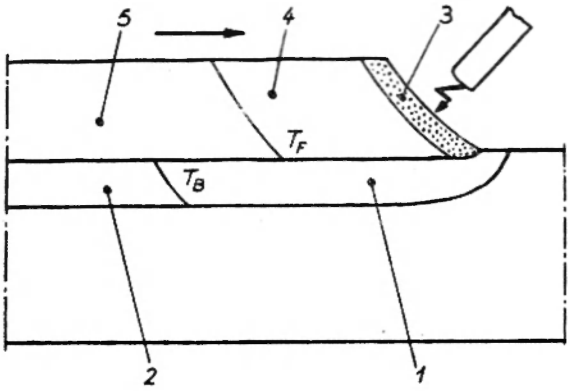

Fig. 2

Representing transformation curves as a function of cooling time has the advantage of making a comparison with the maximum hardness/cooling time curve possible. This comparison (fig. 3) shows that the associated values of maximum hardness can be *used as references* for critical cooling times.

In fact, this representation is only a conventional approximation because it neglects the effect of the austenitisation temperature : for the same cooling time, the periphery of the heat affected zone, austenitised at a low temperature is less hardenable than the region adjoining the weld junction, where austenitisation takes place at a near-to-fusion temperature. It must, thus, be admitted that for the case of a weld executed on steel, transformation during cooling begins in the periphery of the heat affected zone, and moves towards the weld

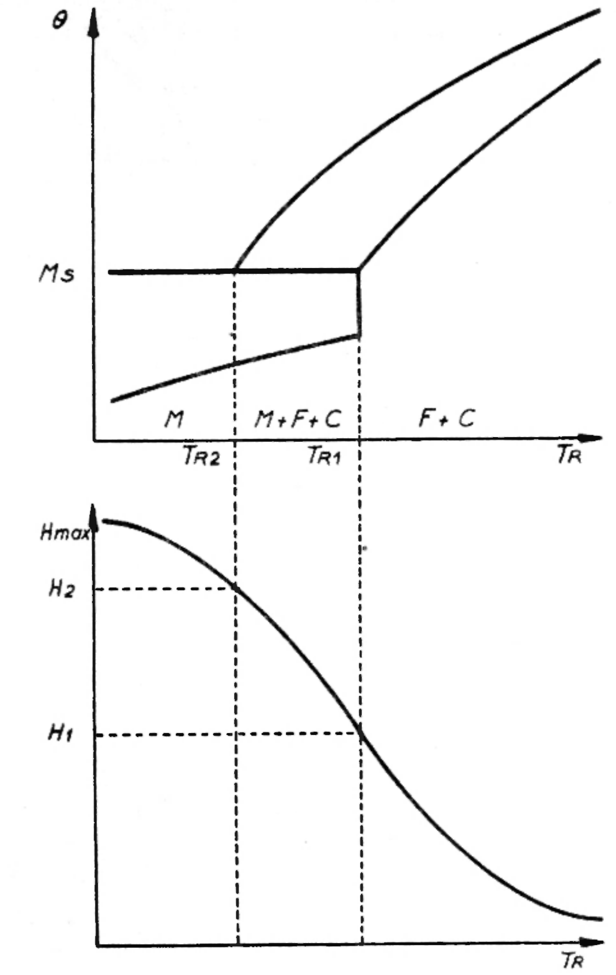

Fig. 3

metal zone. It will be seen further on, that this transformation front moves in an opposite direction to the hydrogen diffusion front. From the mechanical point of view it may be deduced that the part of the heat affected zone adjacent to the weld junction, which is the last to undergo transformation, does so on an already rigid support.

2.1.2. The preceding general considerations concerning transformation in steel having been recalled, the influence of the type of steel on the cold cracking phenomenon can now be examined. This influence derives either through the intermediary of the transformation diagram (position of the critical times TR_1 and TR_2) and from the susceptibility of martensite to hydrogen embrittlement.

The carbon content of the steel does not seem to have an important effect as regards hardenability, that is as regards the critical times TR_1 and TR_2. However, it does have a marked influence on the Ms temperature which drops with an increase in carbon content. Thus the temperature range (fig. 2) between T_F and T_B is enlarged and the possibility of hydrogen diffusing after transformation of the weld metal increased. But the most noticeable effect is the hydrogen embrittlement of the martensite, which is considerably heightened with an increase in carbon content, so that steels with high carbon contents, for example 0.30% and over, are susceptible to cold cracking even when the hydrogen content of the deposited metal is very low, to the point where the influence of such small quantities of hydrogen is questionable.

Most of the usual alloy elements have a direct effect on hardenability. Hence, for example, for an equal carbon content they affect susceptibility to cold cracking. But they also have an influence, which needs to be better understood, on the hydrogen embrittlement of martensite. It is for this reason that nickel martensites seem relatively resistant to embrittlement.

Other elements which have little effect on hardenability may however affect embrittlement. The question can be posed, for example, in the case of silicon.

The influence of chemical composition on the hardenability and the hardness of steel in the hardened condition has been formulated in terms of "carbon equivalent". Commission IX has already issued a statement on the significance and possible utilisation of this concept. Without going over the discussion which led to this statement, it should be noted that the multiplicity and interrelation of the factors affecting cold cracking make any explanation of the phenomenon solely in terms of the carbon equivalent illusory. It is essential also to take into consideration the hydrogen content and the stresses in relation to the welding thermal cycle.

2.1.3 Since the behaviour of a steel during the welding thermal cycle is illustrated by the continuous cooling transformation diagram, the influence of welding conditions on the cold cracking risk may be studied, either by trying to find the conditions under which the martensite transformation itself can be *avoided* or those which would make it possible to *control* the martensite transformation in such a way that the inherent risk is eliminated.

In order to avoid the martensite transformation, that is, to obtain a cooling time longer than TR_1, the energy will be controlled, since cooling rate is inversely proportional to the square of the ratio of energy/

thickness for light gauges and to the energy only for heavy gauges. The initial temperature θo of the parts will also be controlled, since the cooling rate at a given temperature θo is proportional to $(\theta - \theta o)^{3}$— for light gauges and to $(\theta - \theta o)^{3}$ for heavy gauges. In other words, preheating will be applied where suitable, keeping in mind that, if the preheating is local, the extent of the preheated zone on either side of the joint must be sufficient to guarantee the expected effect and to avoid any stressing of the joints during cooling because of the excessive localisation of the preheating.

Thus, it is possible, for certain steels relatively resistant to hardening, to produce, by means of suitable welding conditions, a cooling time longer than TR_1, that is to say, to avoid any martensite transformation and consequently any risk of cold cracking. In the light of the relationship illustrated in fig. 3, between cooling time and maximum underbead hardness, it is possible to understand the origin of the criteria based on the limitation of this hardness ; in particular, the often quoted value of 350 HV corresponds, on an average, to the critical time TR_1 for structural steels whose carbon content is around 0.16 to 0.18%. The limitation of the maximum underbead hardness to this value amounts for these steels to the suppression of one of the conditions necessary for cold cracking, i.e. hardening. But since, as will be shown later, the hydrogen content of the deposited metal plays an important part, it is understandable that more advanced specifications set a higher maximum hardness, 400 HV and more, which amounts to accept ing a higher proportion of martensite, account being taken of a low hydrogen content in the deposited metal, that is, in terms of the welding process used.

It is in fact possible to use, without producing cracking, welding conditions giving a cooling time inferior to TR_1 or even to TR_2. Under these conditions, hardenable steels may be welded provided their hydrogen content is low enough and precautions (such as pre or post-heating) are taken to control the martensitic transformation without suppressing it. Pre-heating, even when it does not suppress the martensitic transformation, has the effect of prolonging cooling, thus allowing the hydrogen to diffuse more rapidly, and thereby reducing embrittlement. Post-heating, when carried out below M_F, produces the same, even more pronounced effect, possibly combined with a tempering effect, to which are added the benefits of temperature equalisation before the completion of cooling. When carried out between M_F and M_S, post-heating also arrests the martensitic transformation, which will only subsequently recommence where the temperature is uniform, and perhaps also leads to a certain stabilisation of the austenite.

In conclusion, if the transformation diagram of the steel in question is suitable, cold cracking can be eliminated by avoiding martensite transformation. But this is not obligatory and it is possible, if the hydrogen content is sufficiently low, to weld in conditions leading to the formation of martensite. In such cases, preheating and especially postheating can be very useful.

2.2 *Behaviour of the weld metal : transformation and cracking*

From the moment of its solidification, the weld metal, under the influence of cooling, is itself the site of solid state changes : in particular, it can undergo perlitic transformation while the base metal undergoes martensite transformation, or else, it too may undergo martensite transformation.

The first case, viz. that of a weld metal less hardenable than the base metal, is common, because the carbon content of the filler metal is rarely as high as that of the base metal. The weld metal transformation isotherm T_F (fig. 2) precedes the base metal transformation isotherm T_B. We will see further on that this favours hydrogen transfer towards the heat affected zone. It also creates an unusual situation from the mechanical point of view. In fact, the last section of the heat affected zone to undergo martensitic transformation is caught between two already transformed, hence rigid, zones, the heat affected zone below and the weld metal zone above ; from which arises an obvious stressing action, enough to initiate cracking if the hydrogen content is sufficient. This stressing action can be diminished if the weld metal can deform more easily.

In the second case, that is, in the case of a weld metal as hardenable as (or, in rare cases, more hardenable than) the base metal, cracking will be localised in the weld metal itself. Longitudinal cracking will occur under the influence of the notch effect of the root of the weld, or else transverse cracking will occur, without the presence of a notch, but possibly because of defects and under stresses which are necessarily high.

Thus, even now a difference in behaviour appears, which will ultimately be better explained, depending on the relative hardenability of the weld and base metal, cracking in the heat affected zone generally being promoted by a greater hardenability of the base metal.

3. The role of hydrogen

3.1 *Sources of hydrogen in steel welding*

The hydrogen involved in the mechanics of cold cracking comes from the weld metal where it settles during the welding operation. In almost all cases, the hypothesis that residual hydrogen in the steel base metal exerts an influence can be rejected.

The hydrogen results from the dissociation of water vapour in the welding arc, this water vapour itself varying in origin depending on the welding processes used :

— Arc welding with covered electrodes : water from crystallisation, water vapour resulting from the combusion of organic products, moisture adsorbed by hygroscopicity.

— Submerged arc welding : water from crystallisation from the fluxes, moisture adsorbed by hygroscopicity.

— Gas-shielded arc welding (MIG) : In the case of welding with flux-cored wire, same sources as for arc welding with covered electrodes ; in bare wire arc welding, moisture adsorbed from the wire surface. In both cases, moisture from the shielding gases or defective water-tightness in the cooling system.

— Gas shielded arc welding (TIG) : moisture adsorbed at the skin of the filler wire, moisture from the shielding gases or defective water-tightness of the cooling system.

These various hydrogen sources are certainly not equally important. But, even if they only account for less than 1 cc/100g of hydrogen in the weld metal, as in the case of bare wire MIG or TIG welding, their role becomes significant when welding the more hardenable steels.

In addition to these sources of hydrogen concerned with filler materials, external sources such as relative humidity of the atmosphere, moisture on the steel in the vicinity of the joint (adsorption or condensation), hydrocarbons possibly present, etc. ... should be mentioned.

3.2 *Hydrogen evolution and participation in cracking*

3.2.1. At the high temperature to which the molten metal is heated in the electric arc, the hydrogen, dissociated into H atoms or even into H+ protons, dissolves, in this metal, where it is held in supersaturation, first because of cooling during the liquid phase, then by a discontinuity in solubility during solidification. The solubility curve of hydrogen in iron (fig. 4) gives (qualitatively, since equilibrium is not present) an idea of the evolution which takes place in the case of iron : in the course of the cooling of the solid phase, already supersaturated by the cooling conditions, a discontinuity in solubility occurs during the austenite to ferrite transformation, while an inverse discontinuity intervenes in respect of the diffusion coefficient which is higher in the ferrite than in the austenite at the level of the transformation temperature. These two characteristics play an important part in the migration of hydrogen towards the heat affected zone.

But, for the reasons previously given (see 2.2. above), when a high proportion of hydrogen remains in the weld metal, it may cause embrittlement and hence, cold cracking, longitudinal or transverse.

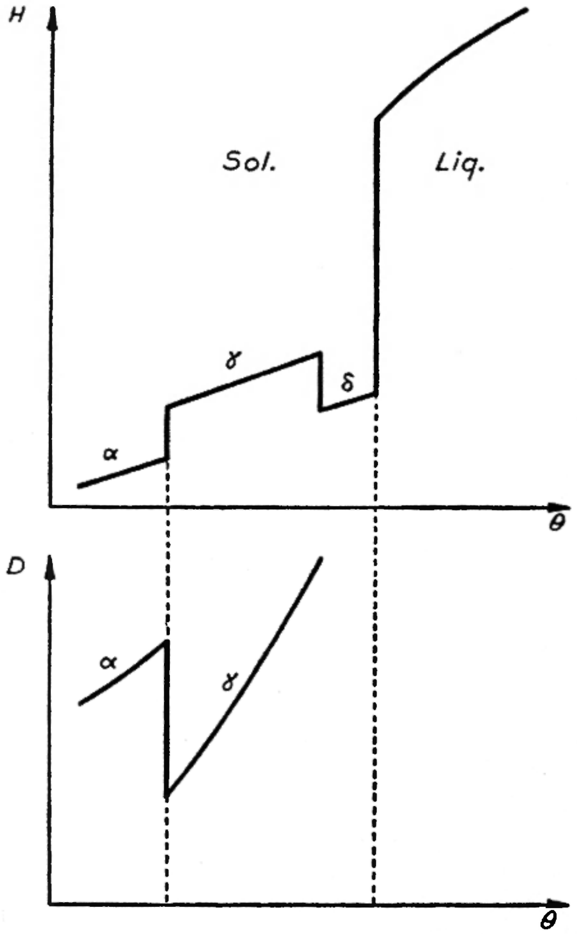

Fig. 4

Having reviewed the mechanism of hydrogen pickup in the weld metal, we must also explain what precautions can be taken to reduce its level : *for arc welding with covered electrodes*, basic electrodes must be chosen each time the steel base metal is susceptible to hardening either because of the nature of the steel or because of the welding conditions, unless other conditions lead to the choice of another type of covering (the case of pipelines) with the corresponding risks and precautions. The basic electrode has to be dry or dried by the user, which involves, a real heat treatment, at a temperature of at least 350°C, and storage in an enclosure at about 150°C. Short-circuit electrode drying is of little value and cannot be recommended. Certain basic electrodes are known to be non-hygroscopic and consequently require fewer precautions.

The term "basic" was expressly chosen to the exclusion of the expression "low hydrogen". Indeed, even if the low hydrogen content is associated with the basic nature of the covering (Type B of Recommendation ISO R 635) it also depends on the condition of this covering itself.

In *submerged arc welding* cold cracking problems are comparatively rare because, on the one hand, of the low hydrogen content of the weld metal, and, on the other hand, of the relatively high welding energy levels generally used. However, weld metal cracking in low alloy steel, associated with the hygroscopic nature of certain fluxes requiring the same treatment as basic electrodes, has been known to occur.

In *gas shielded arc welding* of the MIG type, precautions regarding filler products must be taken by the manufacturer responsible for their preparation and packaging. Flux-cored wires give a weld metal which is richer in hydrogen than bare wires but less rich than covered electrodes.

3.2.2. If figure 4 of this chapter relating to the hydrogen solubility in iron-diagram and the diagram showing the variation in the diffusion coefficient of hydrogen in iron, is compared with fig. 2 showing the sequence of transformations in the weld metal and in the heat affected zone, the mechanism governing the diffusion of hydrogen from the weld metal to the base metal (fig. 5) when only the latter undergoes martensite transformation can be explained :

— In front of the isotherm T_F, the weld metal is in the austenitic state, laden with hydrogen which has little time to diffuse into the underlying base metal which is also austenitic.

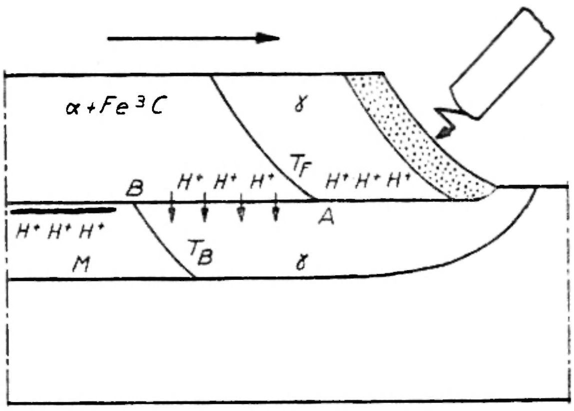

Fig. 5

— With the intervention of the perlitic or bainitic transformation of the weld metal, the hydrogen becomes abruptly less soluble and at the same time more easily diffusible ; it shows a tendency, at this point, to cross the weld junction along A B to enter the not yet transformed austenite of the heat affected zone. But since this austenite has a relatively poor diffusion coefficient, it does not diffuse very far beyond the weld junction, near which a hydrogen-laden front is created.

— It is from point B onwards that the martensite transformation of the heat affected zone of the base metal occurs. As was seen in the previous chapter, a transformation front, moving from the exterior towards the interior, advances to meet the hydrogen diffusion front, so that the austenite transforming into martensite in the vicinity of the weld junction is already loaded with hydrogen. Embrittlement occurs immediately if the hydrogen content is high enough, since the stresses brought about by welding and by the transformations are sufficient even with one restraint. At this stage, what is called an "underbead crack" (Type AL 1 of chapter 1) is observed. Alternatively the hydrogen level is lower and then cracking occurs only if there are stresses from notches, by means of a mechanism which will be described further on ; the cracks will be situated at the toe or root of the weld (AL 2 and AL 3 types of chapter 1).

The advantage, with respect to cold cracking, of using a Cr-Ni austenitic metal for the filler product, becomes clear in the light of this mechanism of diffusion from the weld metal zone towards the heat affected zone. The weld metal, having no transformation point, retains its hydrogen without any diffusion across the weld junction taking place. This is not, however, the only explanation ; in fact the great elongation of the weld metal also plays a part.

3.2.3. With respect to the *mechanism* of hydrogen embrittlement leading to cold cracking, there is no reason to suppose this is a process peculiar to welding. The peculiarity, in this case, lies in the fact that the austenite which transforms into martensite is already hydrogen-laden, but *momentarily* so, a circumstance which may be put to advantage as will be seen later. Again, since ultimately the most hardenable steels are susceptible to cold cracking in an almost total absence of hydrogen, the explanation of embrittlement must be consistent with those explanations in which hydrogen is not involved. It is tempting for this reason, to try to explain the cracking which is intergranular in the case of the latter steels, on the basis of the theory according to which cracking is initiated as a result of the contact between the austenitic grain boundaries and the developing martensite plates, hydrogen being expelled at these places by this development.

The intragranular cracking occuring in less hardenable steels may then be associated with a partially bainitic transformation, thus with the appearance, prior to the martensite, of intragranular components localising within the grains the effect of this appearance.

As has already been indicated in chapter 2, cold cracking may be prevented, even in the presence of martensite, by prolonging the cooling time (preheating), or by maintaining a constant temperature before cooling (post-heating). It is easier, in the light of the preceding explanations, to understand the effect of these precautions ; they lead, by means of diffusion, to a gradual disappearance of the hydrogen content gradient, at a temperature at which embrittlement does not yet occur. Once the temperature drops, the hydrogen, the cause of embrittlement, has disappeared, so that cracking does not take place.

4. Influence of stresses

4.1 *Origin of stresses*

The stresses to be considered when studying cold cracking fall into three categories, direct, indirect and external.

The *direct stresses* appear locally in the vicinity of the joint. They are due to a non uniform distribution of temperatures to which are added the effects of transformations. They are unavoidable.

The *indirect or restrained stresses* result from the welding process due to external restraint liasons. They can be controlled to some extent at the design stage.

External stresses are those, arising from various circumstances of fabrication, which may act upon a welded joint during and after its execution, independently of this execution e.g. the parts' own weight, elastic reactions in the parts, shrinkage of other weld beads in the process of cooling, clamping of the parts etc. Thus, a joint exposed to little restraint during its execution, hence, subject to little residual stress, may become loaded later, at a moment when it is still susceptible to the particular mechanism of hydrogen migration which will be described further on (see 4.2 below).

Whatever the origin of the stress acting upon a weld bead, one is led to assume that it is about equal to the yield strength of the base metal, or of the weld metal, if the latter is less resistant than the base metal.

4.2. *Role of the notch effect*

When the hydrogen content of a deposited metal is sufficiently high and hardening sufficiently pronounced, underbead cracking occurs quickly and spontaneously under the sole effect of direct stresses and apparently without the presence of a notch effect, on a macroscopic scale at least. For unalloyed steels the phenomenon is initiated at a temperature lower than 100°C ; it has often ended around 50 or 30°C. This may be the case, for example, for unalloyed steel pipe line welding with cellulosic electrodes : if the first pass is left to cool completely, a crack could occur in the heat affected zone ; if the second pass is made before the temperature has fallen below 100°C, the accompanying reaustenitisation prevents cracking.

However, given equal welding thermal conditions, and with a deposited metal less rich in hydrogen, underbead cracking does not occur spontaneously, under the sole effect of direct stresses, at least not in the case of steels of medium resistance. For example, the same pipe line welded with a dry basic electrode or by the CO_2 process does not crack. It could crack, however, at the toe or at the root, in the presence of, for one of the reasons cited above, a rigid restraint and/or an external stress. This behaviour is due to the fact that the hydrogen, which has diffused in the heat affected zone, is not present in sufficiently great quantities at the moment of martensite transformation to cause the embrittlement which leads to underbead cracking. But the movement of dislocation produced by the stress effect and the concentration of the resulting deformation at the notch tip causes a migration of hydrogen towards the notches where it collects. With continued cooling the critical hydrogen level is reached and the cracking mechanism is set in motion, giving rise to toe or root cracks. In any case, these are cracks which, because of a relatively low initial hydrogen level, only form at notches and then only under relatively great stress.

4.3 *Evolution as a function of time. Delayed cracking*

The explanations given so far of the cold cracking mechanism have not taken account of the sometimes delayed nature of the phenomenon. In fact, it must be pointed out that this delayed nature is not specific. Most of the so-called "cold" cracks are in fact cracks appearing at the end of cooling and delayed cracking must not be confused with the sometimes catastrophic late appearance of cracking.

With regard to its development as a function of time, cold cracking manifests itself as a progressive, but limited, phenomenon. In fact, once the weld bead is deposited, the amount of hydrogen available to supply the mechanism of migration caused by dislocations in the manner described above is itself limited. The phenomenon may thus be initiated, continue for a certain time, then cease. This is why when inspecting certain construction, cracks of limited size are found, which were initiated immediately after the end of cooling, continued to develop for some hours, then ceased developing. In other cases, this development may attain, when considered in terms of the cross-section subjected to loading, a critical dimension at which fracture occurs. This is why it is possible to speak, sometimes, of delayed *fracture* (and not cracking).

Another aspect of the influence of the time factor appears when the effect of the time interval, between the completion of a weld and its loading, is examined. Normally the weld is loaded just before complete cooling has taken place, and as seen earlier, cracking is not delayed. If the state of stress is only subsequently increased (for example in the case where shrinkage in another subsequently welded joint acts on the first joint, or when a clamp is lately removed,) the hydrogen present in the heat affected zone (or in the weld metal zone, if it is a question of cracking in the weld metal) tends to diffuse, and the hydrogen content gradient disappears gradually. On the application of an external load, the time needed for the accumulation of the hydrogen neceasary for the cracking mechanism is all the greater, the longer has been the delay in loading, and cracking, when it takes place, is truly delayed : for certain hardenable steels, cracking has been observed to be delayed by ten to twenty hours or more. Finally, if the stress intervenes late enough, cracking is no longer possible. This explains the beneficial effect of post-heating, apart from the effect of tempering, by accelerating the diffusion of hydrogen, precluding cracking. Even here, insufficiently long post-heating can lead to delayed cracking.

5.1 *Modern trends in cracking tests*

The present development of cracking tests has already been discussed in relation to the exposition of the phenomenon (in para, 1.3.) but it is essential to return to it in the conclusion of this short review of cold cracking.

Given the influence of the three factors or groups of factors involved in cracking, namely transformation, hydrogen and stresses, which moreover are not independent of one another, cracking tests must be so designed as to make these three factors occur *simultaneously*, while at the same time enabling each factor to be varied *separately*. For example, it must be possible to vary the welding thermal cycle without altering the stress ; to change and compare the welding process, which is distinguished on the one hand by the hydrogen content, and on the other hand, by the deformability of weld metal with another process having the same thermal cycle, etc... The evaluation of the influence of these factors must, of course, be *quantitative*.

These considerations, gathered together in document IX-710-70 "Note on cracking tests", question the empirical type of tests in which a welded joint is subjected to stresses (not evaluated), caused by the welding operation in a more or less constrained jig, or undergoes more or less severe notch effects. This is not necessarily a sufficient reason for abandoning these tests which have been known and used for a long time, since until now, experimental literature has often been based on their results ; but they need to be "calibrated", that is, they must provide a quantitative determination of the level of stress, or, in other words, of the "intensity of restraint", which they bring about. This work is being carried out within Commission IX of the IIW and should lead to the establishment of a list of practical cracking tests, classified according to their intensity of restraint.

In fact, whether genuinely quantitative tests or empirical tests graded in this manner are considered, the problem of knowing the actual amount of restraint occurring in practice in various types of welded construction remains to be solved. Normally, the choice of a welding procedure likely to avoid cold cracking should take this restraint into account ; this choice implies a knowledge of the stress or of the intensity of restraint to be applied in the cracking tests.

A welding procedure, chosen in this way, on the basis of a representative cracking test, can be determined by the maximum underbead hardness value, at least insofar as the heat affected zone is concerned. Thus, the determination of maximum underbead hardness value, which is used as a reference in this context, has no value in itself and cannot be taken into consideration independently of the welding process and procedure envisaged.

Despite this reservation, the use of maximum underbead hardness is of interest in that, for an identical chemical composition, it is possible to transpose to other thicknesses, for the same cooling time, the results of cracking tests obtained on a given thickness.

5.2. *Precautions to be taken against cold cracking*

The precautions to be taken to avoid cold cracking when welding steel may be summed up under three headings, namely :

—Choice of welding process and state of filler products.

—Fabrication conditions.

—Welding procedure.

5.2.1. With respect to *the choice of welding processes*, it may be said that susceptibility to cold cracking is in direct relation to the hydrogen content of the weld metal. However, in the case of high resistance, highly hardenable steels, the risk remains, even when the hydrogen content is very low and only an appropriate welding process can alleviate it. Furthermore, care must be taken to eliminate moisture from the filler products, whether they be covering, powder fluxes, protective gases or even wires. Likewise, protection against external sources of hydrogen must be guaranteed.

5.2.2. *Fabrication conditions* determine the stresses to which the welded joints are subjected at the moment of their execution and in the following hours. The more susceptible is the steel to be welded, the more necessary it is to guard against restraint during assembling and to limit the reactions of the joints one against another, as well as the elastic reactions of the parts to be assembled, without forgetting the possible effect of the parts' own weight.

5.2.3. In summarising the precaution relating to *welding procedure*, the role of the relevant factors may be summarised as follows :

Welding energy : For equal thickness, an increase in energy increases cooling time ; it is a means therefore of avoiding or of reducing hardening.

Initial temperature : This works in the same way as energy and thus preheating contributes to the lessening of hardening. At the same time it prolongs cooling and favours the diffusion of hydrogen. It should be remembered that a too-localised preheating may be dangerous because it may provoke an aggravation of the state of stresses.

Interpass temperature : Since cold cracking only occurs below a certain quite low temperature, it can, in the case of multi-run welding, be avoided if the interpass temperature is kept above this value. This may be achieved by varying either the initial temperature (preheating) or the *time interval between successive runs.* In order to do this, it may be necessary to use the technique of block welding.

Postheating : Depending on the temperature at which it is carried out, postheating (keeping the assembly at a stable temperature for a certain period after welding) can prevent or interrupt martensite transformation. In all cases it promotes the diffusion of hydrogen and makes a subsequent cooling without cracking possible.

Heat treatment : Reheating immediately after welding (more precisely, starting from temperature higher than the cracking temperature) brings about an even more rapid diffusion of the hydrogen, followed by a temperature of the martensite. The risk of cracking is thus eliminated.

Choice of filler metal : Cracking is avoided by the use of a Cr-Ni or a Cr-Ni-Mo austenitic filler metal. More generally speaking, within the limits of the resistance required of the welded joint, the *softest possible* filler metal should be selected in order to take advantage of the capacity to deform of the weld metal.

5.3 *Problems to be solved*

While knowledge of cold cracking in steel welding has shown considerable progress in recent years, a certain number of questions have remained unanswered. The resolution of these questions by the development of research techniques would further improve the safety of welded constructions. The questions which seem to require further study are listed below in the same order as the cold cracking factors, that is to say, in connection with transformations, hydrogen and stresses.

5.3.1. With regard to steel *and the transformations* it undergoes during welding, the following questions remain unanswered :—Is it solely martensite which is involved in the cracking phenomenon or can bainite also be affected ?

—Does a knowledge of the continuous cooling transformation diagram (by welding) and the maximum hardness/cooling time curve, allow the cold cracking behaviour of steel to be predicted ?

—What, independently of their effect on hardenability, is the individual influence of each of the elements constituting the steel (Cr, Ni, Si, etc.) on the susceptibility of martensite to hydrogen embrittlement ?

—What is the influence of inclusions (oxides or sulphides, for example) on sensitivity to cold cracking ?

5.3.2. With regard to *the influence of hydrogen* the following questions need to be answered :

—Is it possible to define the conditions under which cold cracking can occur in the absence of hydrogen ?

—What is the influence of the welding conditions on the weld metal hydrogen content ?

—Is it possible to determine the quantity of hydrogen which diffuses from the weld metal to the heat affected zone ?

5.3.3. Finally, *the influence of stresses* raises the following questions :

—Among all the stress contributing to cracking, what part is played by those due to the transformation of the heat affected zone ?

—Can the influence of the plasticity of the weld metal on the cracking process be determined, given that a softer weld metal causes the diffusion of a greater quantity of hydrogen towards the base metal, while, however, the stresses which develop are less severe ?

—How does the notch effect at the toe or root of the weld vary with the yield strength of the weld metal ?

—What influence does the initial state of the base metal have ? This question is of primary importance for the study of the weldability of quenched and tempered steels.

5.4.4. One last question arises, not related to the cold cracking mechanism but to its consequences : What is the influence of cracks on the mechanical behaviour of welded assemblies and constructions ? It is a fact that at the present time we are in a much better position to detect or even explain cracks than to predict their effect on the life of the structure under consideration.

We cannot here enter into details of a reply to this question or the research that would have to be undertaken. Our intention is only to stress the importance of the question and also its variety, for depending on whether the crack reaches the surface or not, whether it affects the microstructure in which it was initiated or a subsequently acquired structure (multi-run welding or heat treatment), or whether a static or dynamic load is applied, a different problem is broached, each one likely to interest not only Commission IX, but also other Commissions of the IIW.