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2912-189-73.

I.I.W. Working Group 2912: "Brittle Fracture Tests for Weld Metal".

Progress Report 1973 by J.J.W. Nibbering.

1. During the excellent chairmanship of mr. van den Blink W.G. 2912 has with great enthusiasm and skill worked on the problem of realistic testing of welds. A great amount of experiments has been carried out in some ten different countries.
The final goal of W.G. 2912 has not yet been scored, but it may be said that the work has contributed greatly to a proper understanding and appreciation of all factors involved. The inherent philosophy has gradually become clear, and is reflected largely in mr. van den Blink's progress report 1970 /1/ and his 1972 /2/ review. In this connection special mention should also be made of /9/ by Vrbenský and Müncner to be discussed in 4.

The time has come to try to bring the W.G. activities to a conclusion and to this end the present start has been written. It is thought that, although intended primarily for the 2912 members, it may also fulfill the purpose of "state of the affairs" report for committees II, IX, X and XII.

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2. In the W.G. three themes have largely influenced the discussions:
   1. Should the welded joint be tested as such, or in parts (for instance by taking Charpy specimens)?
   2. Should weld metal be tested for its resistance to crack initiation or propagation?
   3. In case of initiation tests, should the loading be static or dynamic (by impact)?

The first question has soon be answered by giving preference to testing complete joints.

As to the second point it has for a long time been answered in favour of initiation tests.
The argument was that in practice cracks always leave the welded region. Consequently resistance to propagation was of little interest. In other words: a structure can be made sufficiently safe by avoiding crack initiation. This is mostly much cheaper than the alternative, viz. the use of crack-arresting steels (base metal). It should be added that in many sectors of structural engineering both aspects are taken into account. In that way a double safety barreer is created. For instance in shipbuilding the former riveted crack arresters have been replaced by E-steel plates in bilge and deck-shell corners.

New problems arose when high heat input welding methods became popular, especially in case of thick plates of fine grained steels. The notch-toughness of the welds and especially the H.A. Zones of these connections often do not meet existing specifications.
Another unfavourable fact is that the residual stresses have a smaller gradient and are lower than in case of multirun welds. Experiments have proved that in such cases eventual cracks (fatigue and brittle) starting

in transverse welds or H.A. Zones do not leave the weld region /3/, /4/. In other words there is no guarantee that they will be arrested in the base metal in case it is good enough to do so in principle.
There are two possible approaches for such cases:

a) Either crack initiation should be prevented by all means for the use of crack-arresting steels may not constitute an effective second barreer.
b) Or weld and H.A.Z. should be able to stop small running cracks, (principle of Pellini's drop weight test).

Ad a) As said before in many cases the welds and H.A. Zones considered cannot meet existing specifications. Then the first question to ask is, whether these specifications are perhaps too severe (or too mild) or whether the testing methods (for instance Charpy) are not too unreliable.

Apart from this a reliable estimation of the resistance to crack initiation is always difficult because:

1) In most crack-initiation tests only a very small quantity of the material is tested. In case of welds and H.A. Zones this counts double, because both are mostly very heterogeneous.
2) The loading of the specimen can in many cases not be made equivalent to that in service.
3) The condition of the material at the tip of defects in reality is difficult to simulate in testing.

Item 1) is selfevident and applies to static C.O.D.- and Niblink-tests, but also to wide plate tests and deep notch tests. Indeed a very small part of the whole specimen is really tested; the rest is required for providing certain edge and loading conditions for the notch tip material. Due to this the number of specimens cannot be too limited.
This handicap is less pronounced in the case of estimating the specific fracture energy of welds with defects, as proposed by Guillemot and Konkoly /5/, (more defects in one specimen). But the problem then is to get a representative sample of specimens (in fact the problem mentioned under 3)).
The solution proposed by Nibbering /4/ is to apply fatigue-bending to specimens at low temperature. Then in principle as many points of the weld or H.A.Z. are tested as there are numbers of cycles.

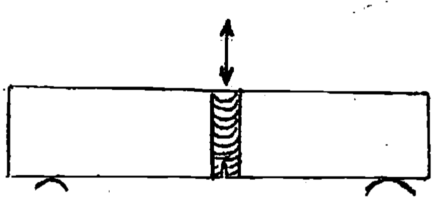

fig.1

The test immediately provides a critical crack length for the temperature concerned. Of course the need of using several specimens remains, in order to test the full width of the weld (or H.A.Z.). This method of testing often also will meet at least partly the difficulties 2) (realistic loading) and 3) (condition of notch-tip material, viz. fatigue damage).
Finally a fatigue-notch is the most realistic and best reproducible notch.

An additional advantage viz. the possible occurrence of "brittle steps" during fatigue-loading will be discussed in 3.

Point 3 of page 1 (loading, static or dynamic?) has not yet been discussed. It is included in the following part:

Pag. 2. Items 2 and 3 (loading rate and condition of material).

For many structures the rate of service loading is so small, that from the viewpoint of brittle fracture it can be considered as static. However fracture need not always be a result of normal service loading. Incidental or better accidental events can be the primar cause. Such events can have the character of impacts. For instance small pressure-vessels may be subjected to bumps during transport, bridges may be hit as a result of traffic accidents, cranes may hit other ones or buildings. These are all events with external causes. But in the structures concerned it is also possible that conditions gradually become favourable for the arising of a shock-like event during normal service loading. For instance corrosion, especially stress corrosion and fatigue may lead to fracturing of connecting bolts and thus create impact effects.

Another source of dynamic loading is the "Greene-Wells" type of cracking in statically loaded structures. It is unlikely that it can be guaranteed that in all structures weld defects locally surrounded by material of extra low quality can be avoided. For instance when a weld defect is present close to a weld crossing, subsequent welding of the crossing weld may create a situation similar to that in Wells' wide plate specimens. Then when during static loading a brittle fracture initiates it should be arrested immediately in the surrounding more sound material. In other words the latter should be resistent to an impact-type of loading. One might object that it is precisely the purpose of static C.O.D.-testing to prevent that cracks initiate at "Wells-type" notches or defects. Indeed, but then one must be able to define accurately the type of hot-straining to which a C.O.D.-bend specimen must be subjected in order to simulate the worst of possible conditions met in service. The least one can do is giving quite a number of specimens different hot-straining treatments in order to select the worst. But even this will in many cases not suffice. A great many structures are normally subjected to one or another form of cyclic loading. Incorporation of this into the testing is absolutely necessary when one will arrive at results which are directly correlating with service behaviour. Of course this means a severe complication of the testing. Yet it is often imperative because it has been proved /4/ that under high-stress low-cycle loading small brittle steps in the order of magnitude of the cyclically deformed plastic zone can occur. Again for the material outside the plastic zone, this event means a severe local impact, which it should be able to sustain.

Connected to the foregoing is the problem that static C.O.D.-testing when it would be effectuated in the sense stated above, would very often lead to solutions quite unacceptable from an economical point of view. Imagine the combination of a severe hot-straining treatment of a notched specimen and subsequent cyclic loading. This treatment may result into a rise in crack-initiation temperature in the order of magnitude of 50 to 100^{o}C. It may easily rise so much that it becomes higher than Pellini's Nil Ductility Transition temperature or even the isothermal Robertson crack-arrest temperature of the weld metal. In that case a static C.O.D.-test has not much meaning (if leakage is no serious problem). One should simply rely upon the Pellini N.D.T. temperature because that is the temperature above which small running cracks are arrested at relatively light loads. Unfortunately Pellini's drop weight test is not suited for thick plates and the brittle weld necessary for creating a running crack influences the quality of the weld metal.(In many welds made with high heat-input the brittle weld will improve the test-weld locally). How to account for this aspect will be treated later.

3. Estimation of the resistance to crack propagation.

From the foregoing it will have become clear that one philosophically sound approach for weld metal and H.A.Z. testing is the estimation of the temperature above which a small brittle crack will certainly arrest. This temperature is mostly appreciably lower than the Robertson isotherm arrest temperature, because that one concerns arresting of relatively large running cracks. In fact, both from abundant experimental and service experience, and from an appraisal of the test procedures proper, there is every reason to accept that the N.D.T. temperature determined with Pellini's drop weight test is the one we have to look after.
In that test the brittle weld provides for a running crack which either or not is immediately arrested in the test metal. This situation conforms to that in a Wells wide plate test where the hot-strained metal at the notch's tip provides for a small running crack.

W.G. 2912 has given serious consideration to the difficulty how to estimate the N.D.T. in a more reliable way than with the old Drop-weight test. The main difficulty is to get a crack starter which does not influence in a favourable way the test metal. (For instance: coarse grained H.A. Zones are very much improved by a brittle weld on top; the N.D.T. may be wrong up to $40^{\circ}C$).

The first thoughts went in the direction of the side bend test by Marquet /7/, which is comparable to the Drop weight tear test developed by the N.R.L. (Pellini, Puzak and co-workers). Figures 2, 3 and 4 of /7/ show the test method, evaluation and results. For our purpose the relation between the N.D.T. and the side bend test results is important (fig. 4). It must be concluded that with the side bend test the N.D.T. cannot be determined satisfactorily accurate.

Girardi and Cepolina /8/ have studied relations between N.D.T., side bend test results and Charpy-, Schnadt- and van der Veen-results. In fact the only satisfactory correlation they found was between N.D.T. and Charpy 70% crystalline fracture appearance,

Fracture appearance of course is a very good parameter when evaluating the resistance of a material to crack propagation.
~~What disturbs the picture is, that any shearlip at the tip of the notch is~~ also taken into account as "shear area" although it has no influence on the arresting of the crack. Therefore pressed notched or Schnadt notched Charpy specimens might serve the purpose better. The influence of plate thickness of course should be estimated empirically.

Returning to the problem of finding an improved Pellini Drop Weight Test. Mr. van den Blink in a letter (2912-183-73) proposed to use the side bend test, applying low energy. In order to prevent that too much energy would be required for initiation, the material at the pressed notch's tip should be aged at $250^{\circ}C$ for 30 min. Then static instead of impact-testing might even be sufficient, which of course can be far easier controlled (for instance by limiting deflection as proposed by Girardi and Cepolina) than impact testing.
Pursuing this line of thinking Nibbering carried out drop weight experiments with specimens of small height (= plate thickness) containing fatigue cracks.

The latter are excellent crack starters under impact conditions.
The reduced height was chosen in order to obtain a specimen, which can deflect as much as a few mm's before the crack starts.
(In the higher side bend specimens the deflection is too small to be controlled sufficiently accurate). In fact the specimens conformed closely to the standardized C.O.D. ones.
The results are shown in fig. 5. It is obvious that a clear estimate of the N.D.T. is not yet possible. Nevertheless the approach looks promising and

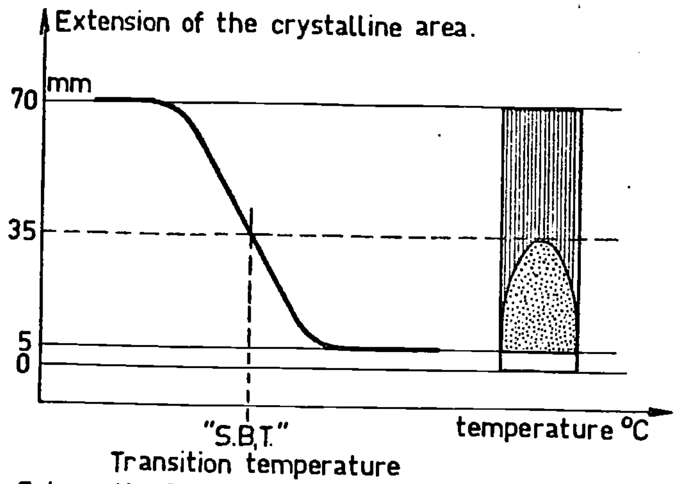

Fig. 2 Schematic function "extension of the crystalline area–temperature".

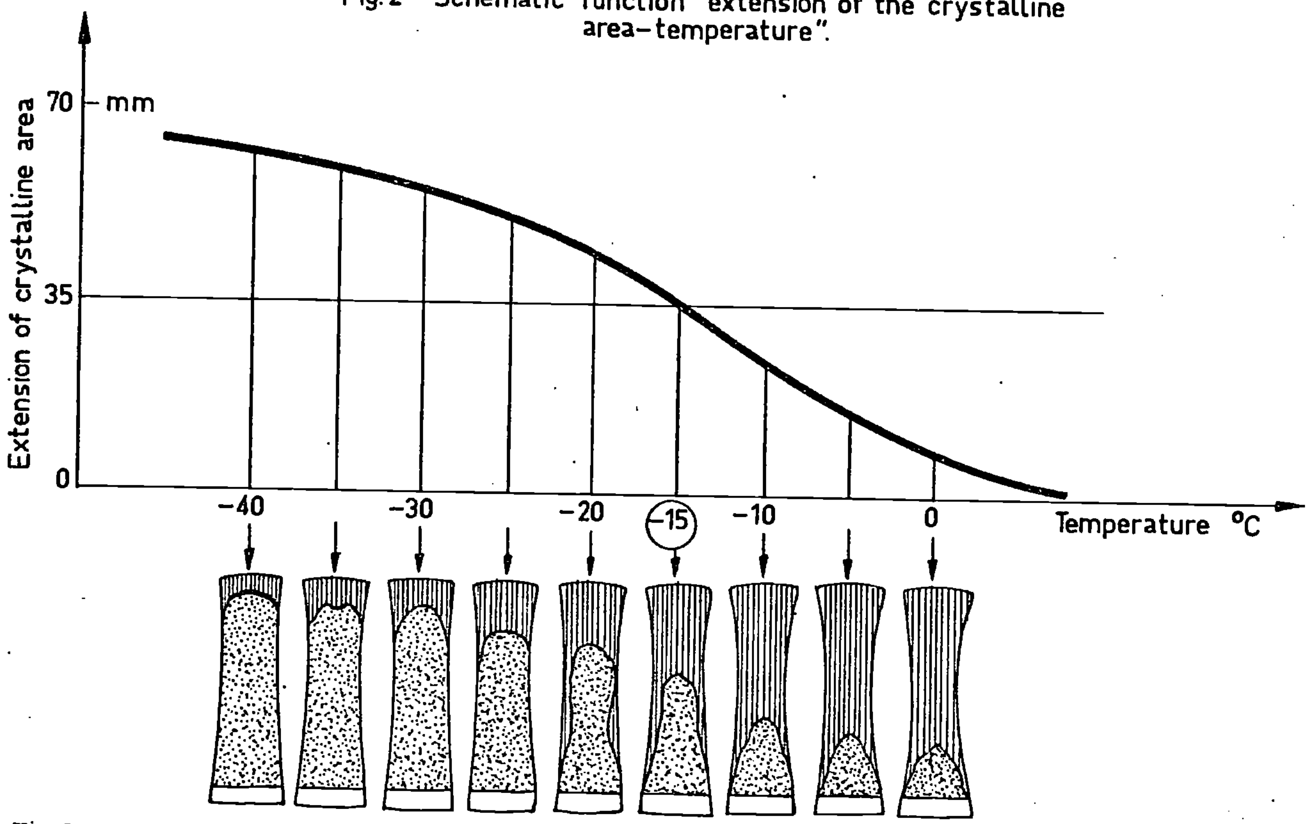

Fig. 3 Example of a function "extension of the crystalline area–temperature".

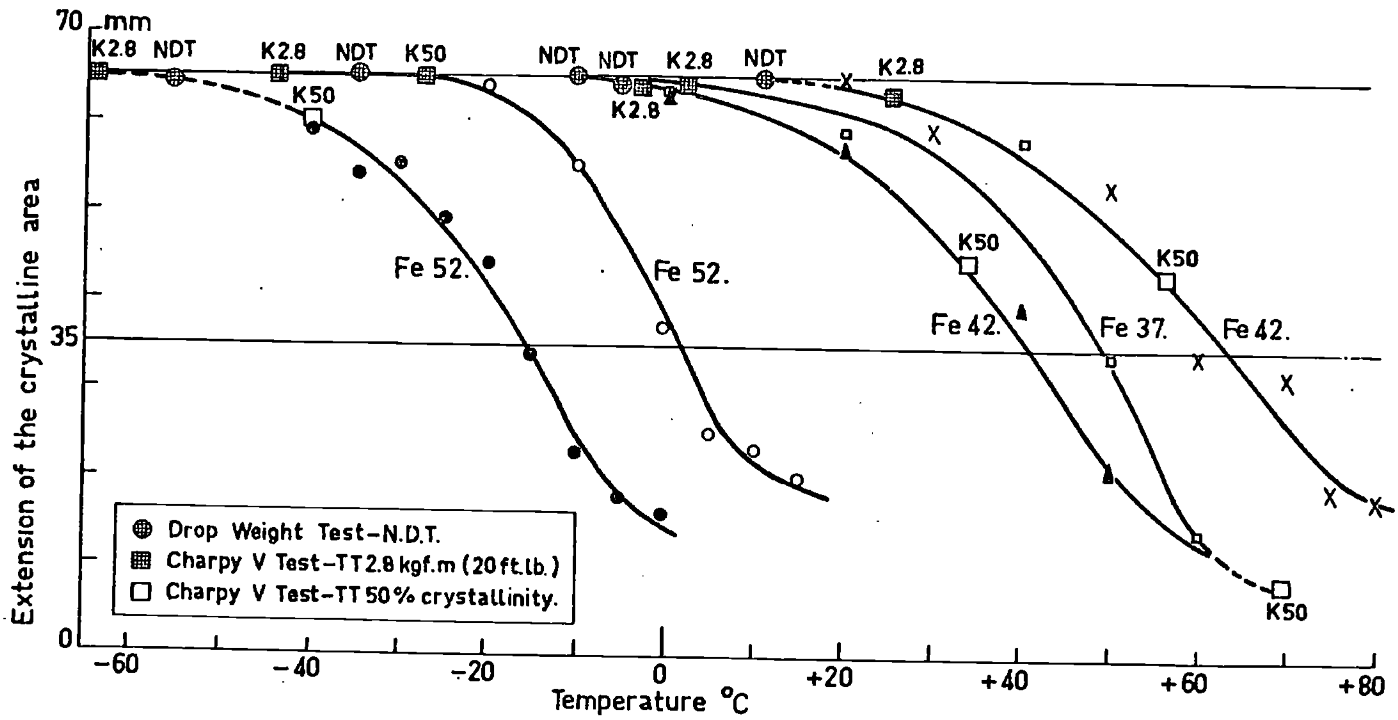

Fig. 4 Examples of Side Bend Test transition curves of five structural steels.

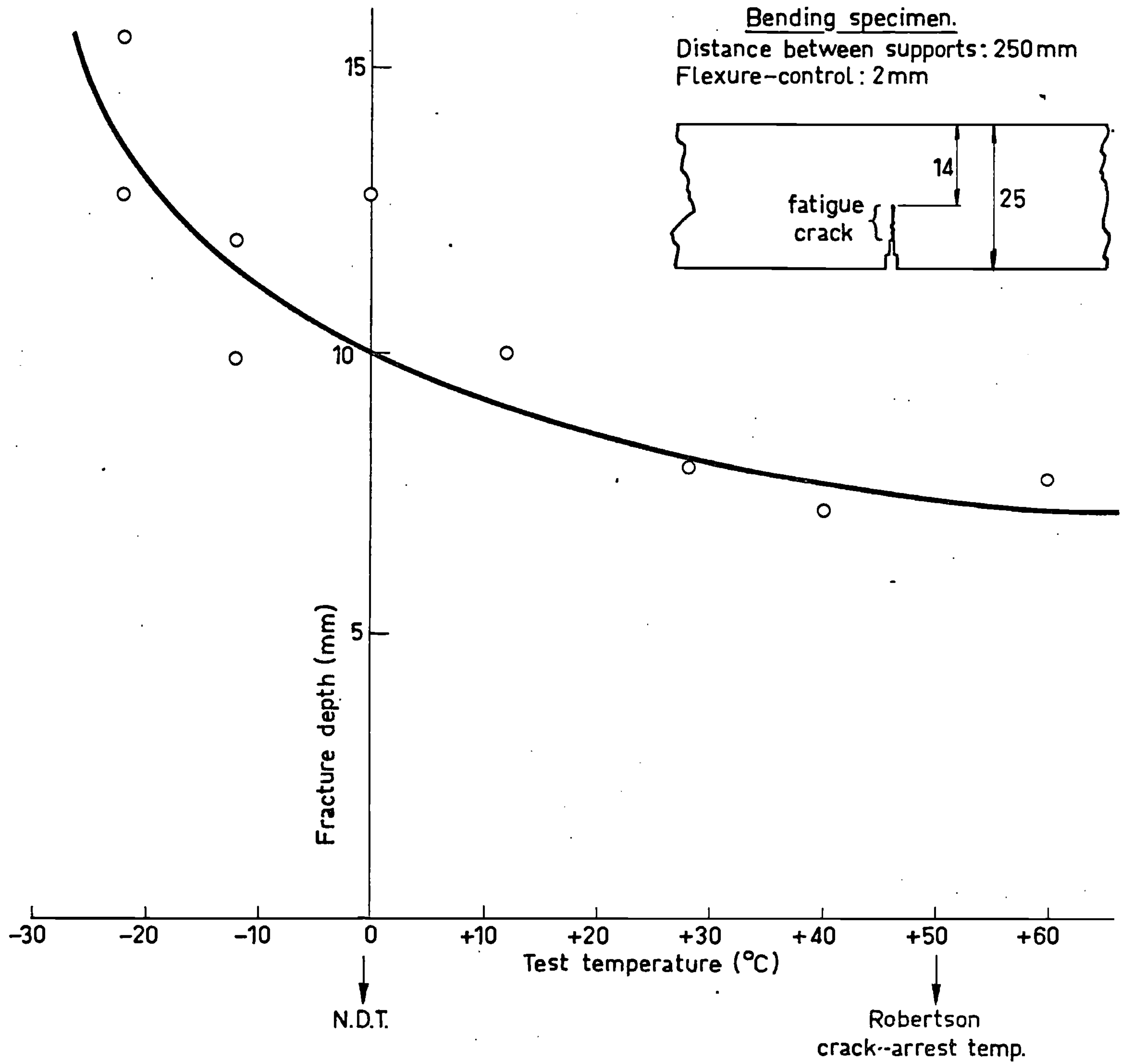

Fig.5 Results of impact tests with specimens containing fatigue-cracks.

may after systematic variation of the test parameters finally lead to something useful.
If not, another idea, which is already studied in the Ship Structures Laboratory at Delft may also become successful.

The specimen is shown in fig. 6.

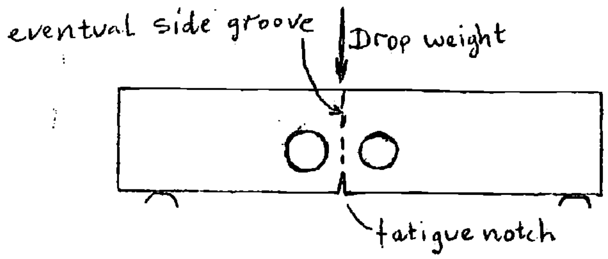

fig. 6

With this specimen Pellini's principle: arresting of a small running crack in a lowly (elastically) stressed field may be realized.
One initial difficulty is that the fractures tend to deviate in the direction of one of the holes. But it is probable that this can only happen above the N.D.T. temperature. Below it, the fractures seem to follow a straight path all over the height of the specimen. Above NDT a crack-guiding groove might be effective.
A third possibility to estimate the N.D.T. is by high stress fatigue bending as mentioned already in 2.
Often during such fatigue bending at low temperature tiny brittle steps occur. They cut through the plastic zone at the fatigue-crack's tip and then are arrested. When they occur the material proofs itself to be able to arrest small running cracks, and that is what we need.
A problem is that the material in the plastic zone should have been sufficiently damaged for allowing the initiation of a brittle crack. The results obtained up to now are not discourageing.

In conclusion it can be said that when the principle of the N.D.T. is accepted to be valid for certain (or perhaps all!) weld metals and H.A. Zones the search for a satisfactorily accurate test method has had an encourageing start.

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4. Final observations.

The main principles stated before have been discussed with the chairman of sub-committee IX-F, mr. W. Bonhomme, because IX-F is looking for realistic acceptance tests for H.A. Zones. He largely agreed with them.

In IX-F and 2912 a document written by Vrbenský and Müncner /9/ has obtained serious consideration. The document starts with basic theses which can be fully supported by 2912. (An exception is their statement that an adequate security against brittle fracture propagation is not economically feasible for most structures. Most modern normalised steels are certainly able to arrest long cracks at sub-zero temperatures, which is of utmost importance for ships, oil-rigs etc.).

Vrbenský and Müncner have abandoned the idea of proposing one single test procedure and evaluation for all cases to be met in practice.

They distinguish between the temperature approach and the fracture mechanics approach. The latter aims at the estimation of critical defect sizes.

In connection to this it should be observed that most lower strength and many medium strength steels are far more sensitive to changes of temperature than to differences in defect- and crack-size. For these the temperature approach is mostly quite satisfactory. Often such steels are also very sensitive to speed of loading and show a large capacity for plastic deformation. It is thought to be wise to take advantage of that plastic deformability and to use these steels at temperatures where that quality can manifest itself to the full.

The following is taken from /9/.

"Following test methods for static loading conditions correspond with the above mentioned criteria:

a) K_{IC} - for testing of high tensile, heavy section steels, where LEFM is valid.

b) COD - for testing of steels showing a pronounced plastic deformation in the notch tip vicinity before fracture, e.g. where EPFM is valid.

A simple test method for impact loading conditions based on fracture mechanics approach is not at our disposal at present. Nevertheless, the Niblink test, enabling the temperature approach to the evaluation of test results and applying similar test specimen geometry as those of K_{IC} or COD can be recommended.

Finally, for determination of CAT of the unaffected BM the dynamic-tear test seems to be most suitable."

The authors apparently have sufficient confidence in the mentioned test methods. In this connection recently obtained results by Düren /10/ and Rosendahl and co-workers /11/ should be mentioned.
Both focus attention on the relatively large scatter in Niblink- and static C.O.D.-tests. This is not so alarming because it will be connected to the heterogeneity of the welds.
More important were the differences observed between test results obtained in two different laboratories /11/.
The results will be subjected to further analysis.

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