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DETERMINATION DU FACTEUR D'INTENSITE DE CONTRAINTE A L'ARRET DE FISSURE DE PIECES FORGEES EN ACIER 16MND5 A PARTIR DE LA PROCEDURE ASTM 1221. COMPARAISON AVEC LE CODE RCC-M

DETERMINATION OF CRACK ARREST TOUGHNESS IN A508 CL.3 FORGING STEEL FROM ASTM E1221-88 PROCEDURE. COMPARISON WITH THE VALUES OBTAINED FROM THERMAL LOADING TESTS

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SYNTHÈSE :

Dans le cadre de l'analyse du risque de rupture brutale, en situations accidentelles, des cuves de centrales REP, une étude du concept d'arrêt de fissure est en cours.

Le premier objectif de cette étude est l'évaluation des valeurs de ténacité Kla caractéristiques de l'arrêt de fissure à partir d'expériences sur des éprouvettes de taille réduite. Des essais, sur une pièce forgée en acier 16MND5, ont été effectués conformément à deux méthodes expérimentales, l'une préconisée par l'ASTM, l'autre mise au point à l'Ecole des Mines de Paris. La première méthode consiste à utiliser un chargement mécanique sur des éprouvettes maintenues à température homogène, la seconde est basée sur un chargement thermique.

Les essais effectués ont montré les limitations de la procédure expérimentale ASTM. Les différentes valeurs de ténacité à l'arrêt obtenues ont ensuite été analysées et comparées, entre elles, et avec celles proposées dans le code RCC-M. Les valeurs obtenues par la méthode ASTM sont supérieures aux valeurs Kla déterminées à partir d'essais basés sur un chargement thermique. Ces dernières sont en bon accord avec les valeurs proposées dans le code RCC-M.

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EXECUTIVE SUMMARY :

A crack arrest study is under way at Electricité de France as part of the analysis of the risk of fast fracture of PWR vessels in emergency conditions. The first objective of this study is to evaluate the toughness which caracterizes crack arrest through tests on reduced-size specimens. Some of the tests on a forging steel (A508 cl.3) were conducted in conformity with two experimental methods.

One method recommended by the ASTM calls for the use of an imposed-displacement mechanical loading on specimens kept under homogeneous temperature. Since the stress intensity factor K applied to the outside loading decreases along the crack growth, we can observe the arrest of the crack. In order to obtain brittle crack initiations in cleavage in the whole studied range of temperature and crack propagation of a sufficient length, the application of a weld point at the top of the notch is done.

The other experimental method was developed at the Ecole des Mines in Paris, and is based on a thermal loading. It requires the use of a disk or a cylinder with a longitudinal initial crack of the external surface. We dip this specimen in liquid nitrogen and we heat its internal surface with inducing current. There is a temperature gradient in the thickness of the specimen which produces a stress field which tends to open the crack. When the value of K is reached the crack initiation takes place. Several phenomena act to oppose the crack growth, they even go as far as stopping it. First the value of K, after increasing, gets steady then decreases, then, the rate of energy dissipated by plasticity at the top of the crack increases because the crack meets warmer and warmer areas on its way.

The arrest toughness values which were obtained were then analyzed and compared to one another and with values proposed by RCC-M code.

The tests conducted showed that the experimental process described by the ASTM standard is relatively easy to implement. Test static analysis does not reveal any major problem. However this experimental method reveals 2 important limitations :

- the implementation of a weld point at the top of the notch introduces residual stresses
- we note that the imposed displacement loading cannot be controlled correctly.

Values obtained with the ASTM method are superior to the ones obtained through thermal shock. Moreover we observe that values obtained through thermal shock tests are the only ones that correspond to those recommended by RCC-M code ; ASTM test values are considered as being too optimistic.

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ASTM WORKSHOP ON USER'S EXPERIENCE IN CRACK ARREST TESTING, ATLANTA, MAY 17TH 1993.

1 - INTRODUCTION

A crack arrest study is under way at Electricité de France as part of the analysis of the risk of fast fracture of PWR vessels, in emergency conditions. Crack arrest can be studied from the classical approach of fracture mechanics. We want to evaluate a material-characteristic criterion called arrest toughness KIa.

So, the purpose of the study is to evaluate the toughness values KIa from experiments with small-sized specimens. For this aim, two schemes are possible (figure 1):

- either to increase the toughness of the material,
- or to decrease the stress intensity factor K during the growth of the crack already under way.

Some tests on a forging steel (A508 cl.3) were conducted in conformity with two experimental methods. One method recommended by the ASTM calls for the use of an imposed-displacement mechanical loading on specimens kept under homogeneous temperature. The other experimental method was developped at the Ecole des Mines in Paris, and is based on a thermal loading.

The purpose is to analyse and to compare these two methods in order to determine KIa. At the end we will compare the different results with the ASME standard curve, which is based on an increase of the material toughness.

2 - STUDIED MATERIAL

The studied material is a low alloyed steel of the A508 Cl3 type taken from a forging sample. The chemical composition and the main mechanical characteristics are presented in tables I and II.

The temperature RTNDT was set according to the RCCM method. This determination was based on the Charpy tests and on the Pellini tests. We have :

$$RTNDT = -40°C$$

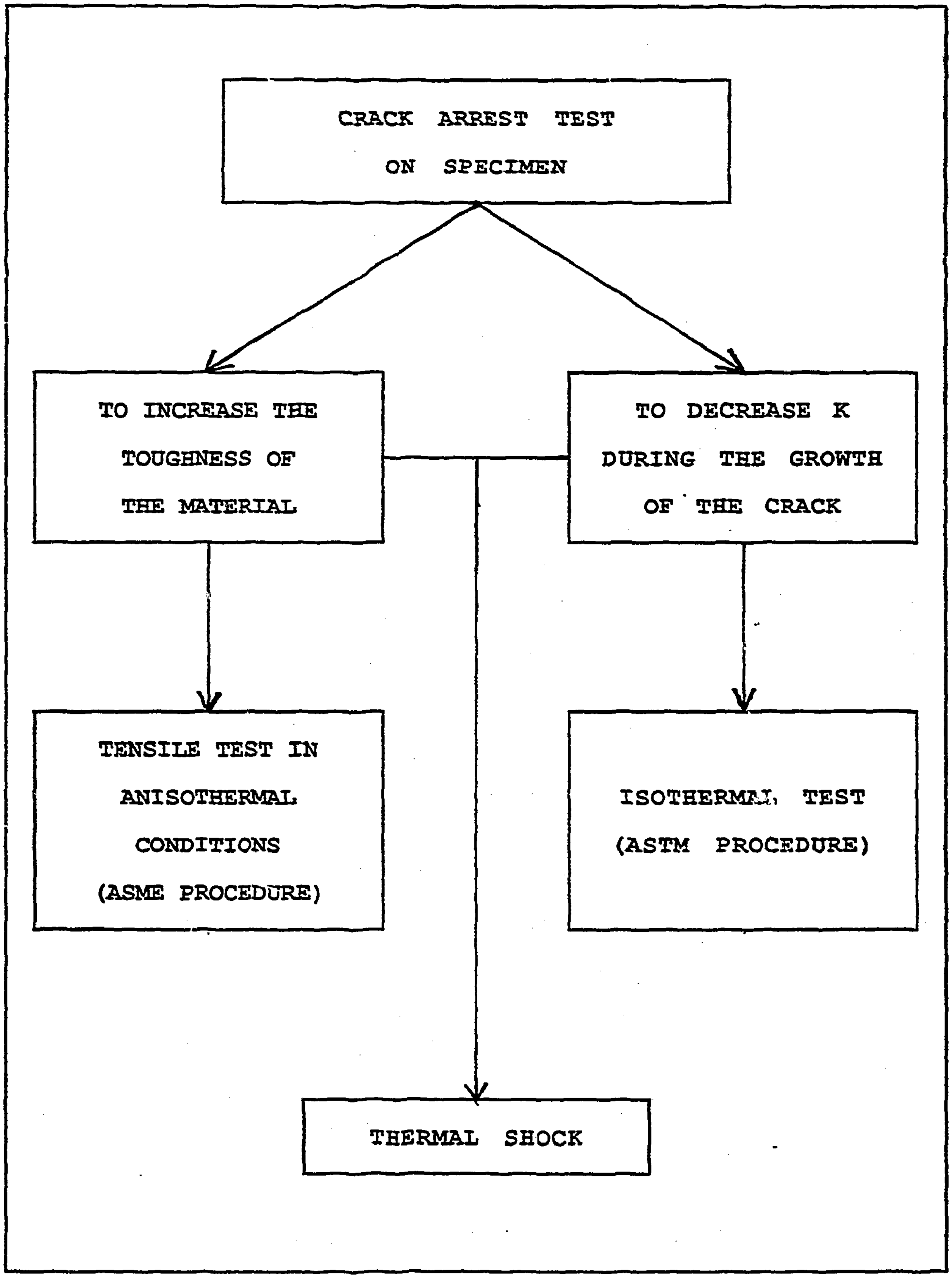


Figure 1: How to determine the crack arrest toughness values.

	C	S	P	Si	Mn	Ni	Cr	Mo	Cu	V	Al
RCC-M spécification	≤0,22	≤0,020	0,10 / 0,30	1,15 / 1,60	0,50 / 0,85	≤0,30	0,40 / 0,60	0,40 / 0,60	≤0,20	≤0,01	≤0,04
Casting analysis	0,19	0,003	0,007	0,20	1,26	0,76	0,20	0,48	0,07	<0,001	0,02

Table I: Résults of chemical analysis done on studied material (% weight) [1].

Temperature (in °C)	0,2% offset yield strength (in MPa)	Tensile strength (in MPa)	Young modulus (in MPa)
20	444	594	209000
0	453	608	213000
-20	461	625	208000
-40	469	641	208000
-60	483	661	210000

Table II: Main mechanical caracteristics of studied material [1].

3 - ISOTHERMAL TESTS

The determination of KIa is regulated by an ASTM norm [2]. This method calls for the use of an imposed-displacement mechanical loading on small sized specimens kept under homogeneous temperature. The stress intensity factor K applied to the outside loading decreases during the growth of the crack already under way, and we can observe the arrest of the crack [3, 4].

The loading consists of the quasi-static depression of a wedge between two split pins which rest on a Compact Crack Arrest specimen (figures 2 and 3). The opening of the notch lips is increased until a crack jump happens. This fixed system helps limit the exchanges of energy between the sample and the machine during the propagation stage.

The shape of the specimens is advocated by ASTM (CCA). The standard dimension called W was set at 200 mm. In order to obtain brittle crack initiations in cleavage in the whole studied range of temperature and crack propagation of a sufficient length the area at the top of the notch is made brittle with a weld point (figure 4). Thus, we can control the elastic energy which is stocked in the specimen.

Each specimen has a plane side where some gauges are stuck in order to measure the propagation rate. The other side has a lateral notch in order to guide the crack during its propagation (figure 5). Temperature is measured where the weld point is.

The loading device forbids any access to the loads applied to the specimen. This is due to the uncontrolled rubbing phenomena between the wedge and the two split pins. So to analyse the test we have to use the notch lip displacement of the specimen. The ASTM procedure advocates a simplified static approch introduced by Crosley and Ripling [5, 6] which evaluates KIa from the length of the arrest crack and from the critical loading. These values are measured after the propagation stage. The values of the K factor are obtained from the following formula:

$$K = \frac{E}{\sqrt{W}} (\delta) \; f(a/W) \sqrt{\frac{B}{B_n}} \qquad \text{(in MPa}\sqrt{\text{m}}\text{)}$$

Where :

δ: displacement of the notch lips at 0.25 W of the loading line.

E is the Young modulus; W is the standard dimension and B is the thickness of the specimen

a is the length of the initial crack (a_0) or during arrest (a_f), (a_f is measured after the rupture of the specimen).

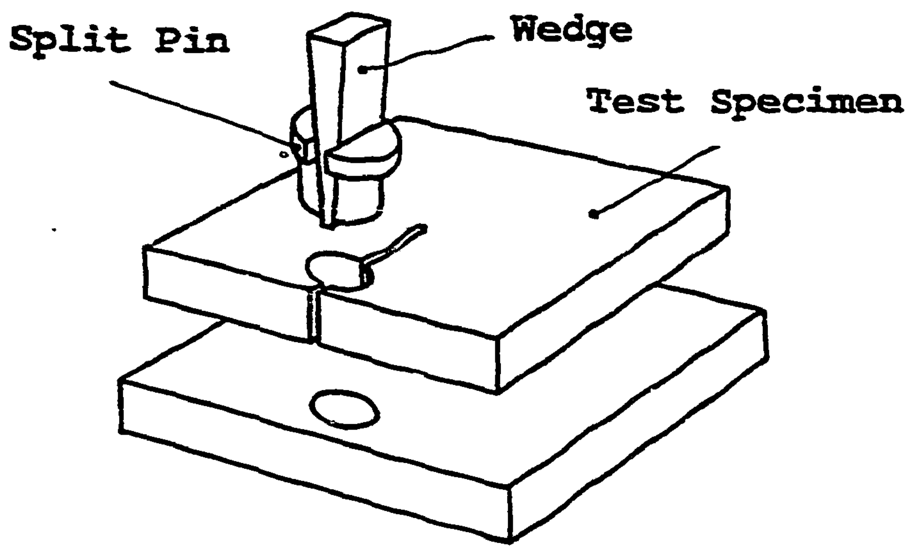
B_n is the minimal thickness of the specimen in the crack plan.

15 specimens were tested at temperature varying between -60°C et 0°C [7]. The different results which were obtained are presented in figure 6. All the tests conform to the validity conditions dictated by the ASTM procedure.

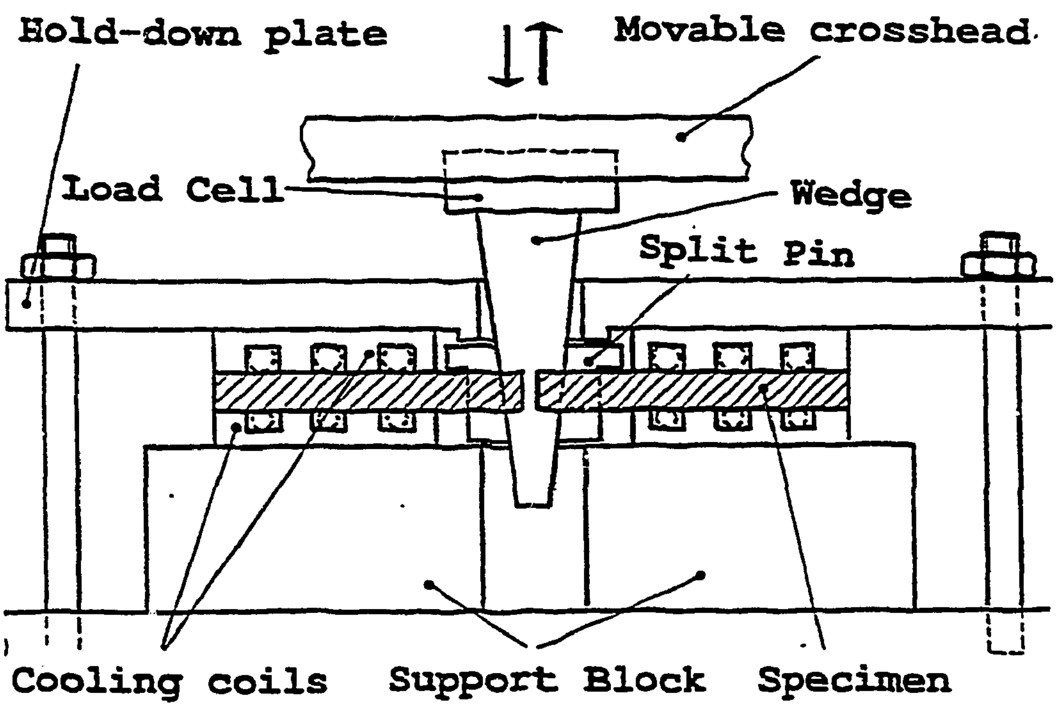
Several problems were encountered during the experiments:

- at the lowest temperatures crack ramifications happened into two branches. For the analyses we considered the largest branche.This behaviour seems to be a characteristic of the tested steel at temperature inferior or equal to -40°C. A deepening of the lateral notch enabled us to correct this problem;

ISOTHERMAL TEST
(ASTM PROCEDURE)



PRINCIPLE OF LOADING DEVICE

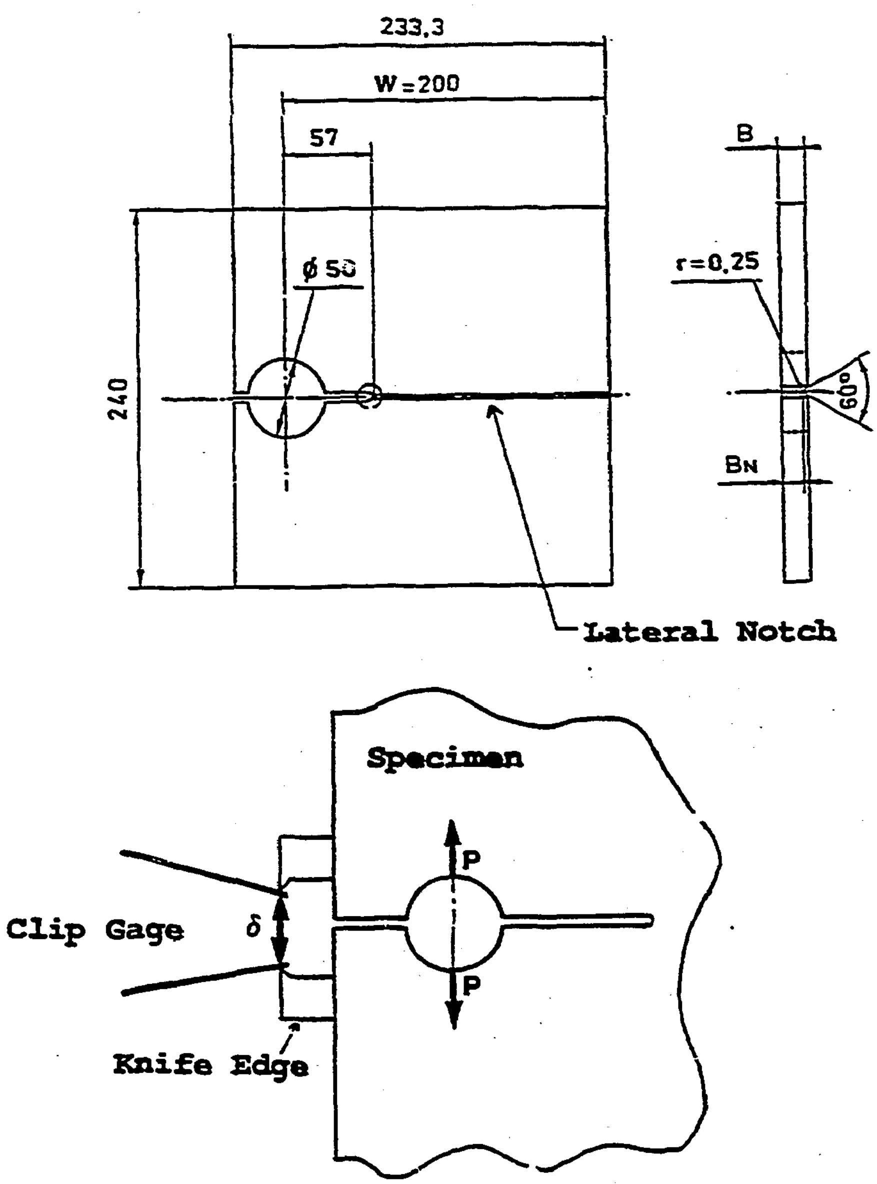


GENERAL PLAN OF LOADING DEVICE

Figure 2

ISOTHERMAL TEST

(ASTM PROCEDURE)



$$K = \frac{E}{\sqrt{W}}\ (\delta)\ f(a/W)\ \sqrt{\frac{B}{Bn}}$$ (in $MPa\sqrt{m}$)

Figure 3: Compact Crack Arrest specimen (C.C.A.)

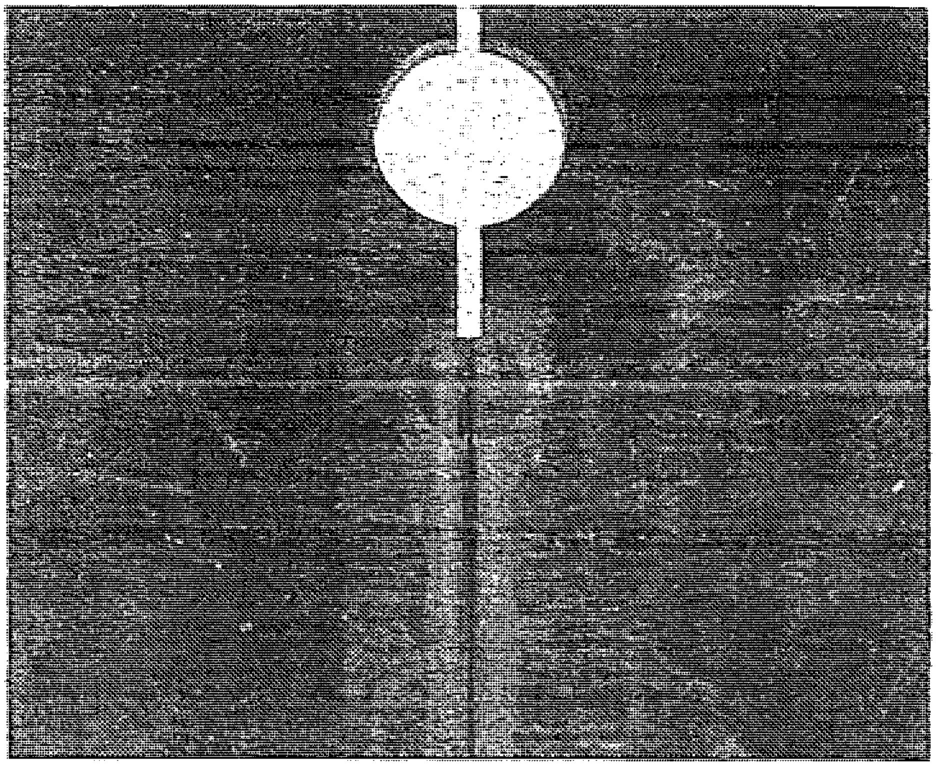


Figure 4: Weld point in order to obtain brittle crack initiation.

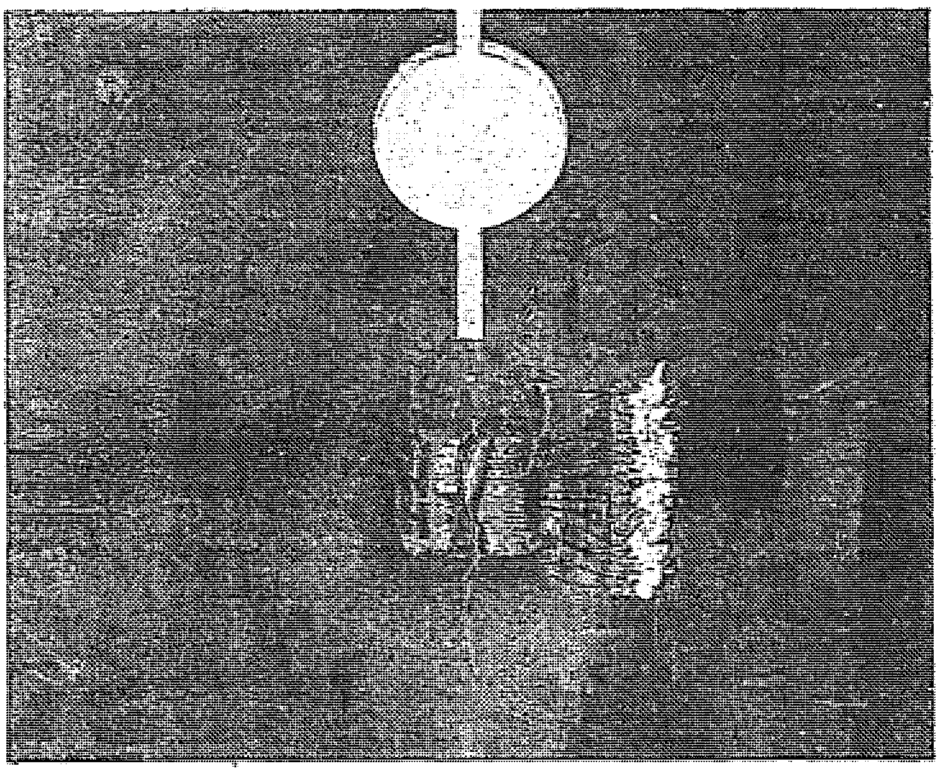


Figure 5: Device to measure propagation rate.

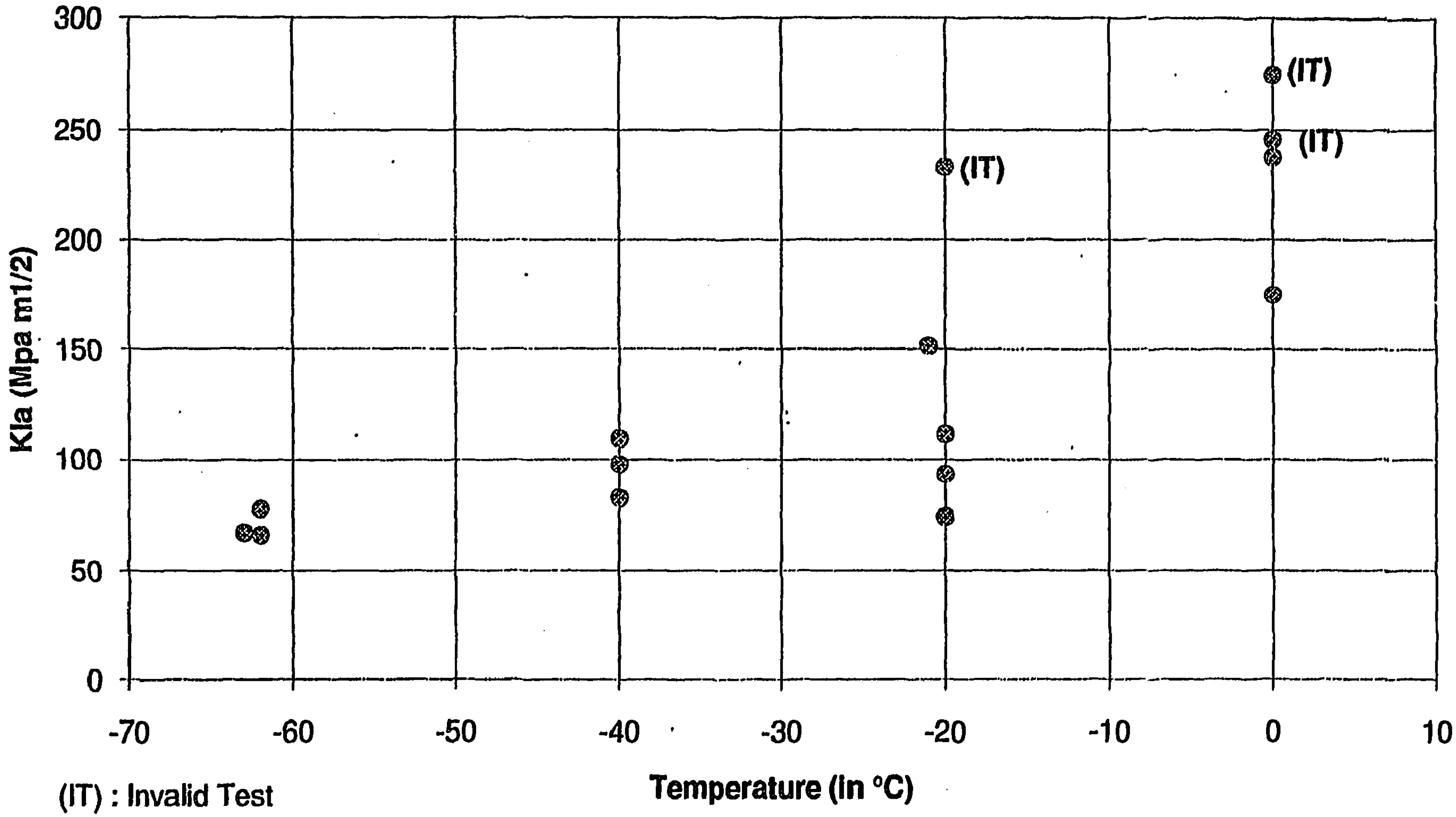


Figure 6: Crack arrest toughness KIa versus temperature.

- in the case of several tests done at 0°C as well as for one test done at a temperature of -20°C the crack stopped when it reached the basic metal just outside of the brittle area. Thus this test cannot be considered valid. The increasing of the radius up to 1 mm at the top of the notch in order to increase the initial loading enabled us to resolve this problem.

- in the case of one test performed at 0°C and three tests performed at -20°C, we measured very high crack arrest toughness values. It seems that, for these specimens, the ligament was plastified, and the loading was near its maximum value.

4 - ANISOTHERMAL TESTS

Another kind of test is based upon the applying of a thermal shock on a specimen; the arrest of the crack is then made possible by the increasing of toughness as the crack is developping. As part of this method, l'Ecole des Mines de Paris and EDF have perfected an original test method and results are available [1, 3, 8 - 10].

It involves using a disk or a cylinder with a longitudinal initial crack on the external surface. We dip this specimen in liquid nitrogen and we heat its internal surface with inducing current (figure 7). At this point there is a temperature gradient in the thickness of the specimen which produces a stress field which tends to open the crack. When the value of toughness KIC is reached the crack initiation takes place. Then several phenomena act to oppose its spreading, they can go as far as stopping it. In figure 8 the variation of the stress intensity factor K and of the temperature according to the thickness of the disk is represented. We can see that :

- the value of K after increasing gets steady then decreases (static calculations),

- the rate of energy dissipated by plasticity at the top of the crack increases because the crack meets warmer and warmer areas on its way.

Three tests on cylinder (height 200mm) and two tests on disk (height 20 mm) were conducted at the Ecole des Mines. Table III shows the results which were obtained (the reference temperature was measured at the top of the crack). Only one specimen was precracked by fatigue.

5 - THE DATA OF THE RCCM CODE

The RCCM code uses the standard curve of the ASME code. It is important to note that the latter was determined from tensile tests on large plates into which a temperature gradient was imposed (figure 9). With this configuration the crack is initiated in a material which is colder, that is more brittle and is spreading towards a warmer area with a better toughness. The analysis which is done to determine the standard curve is a static one [9].

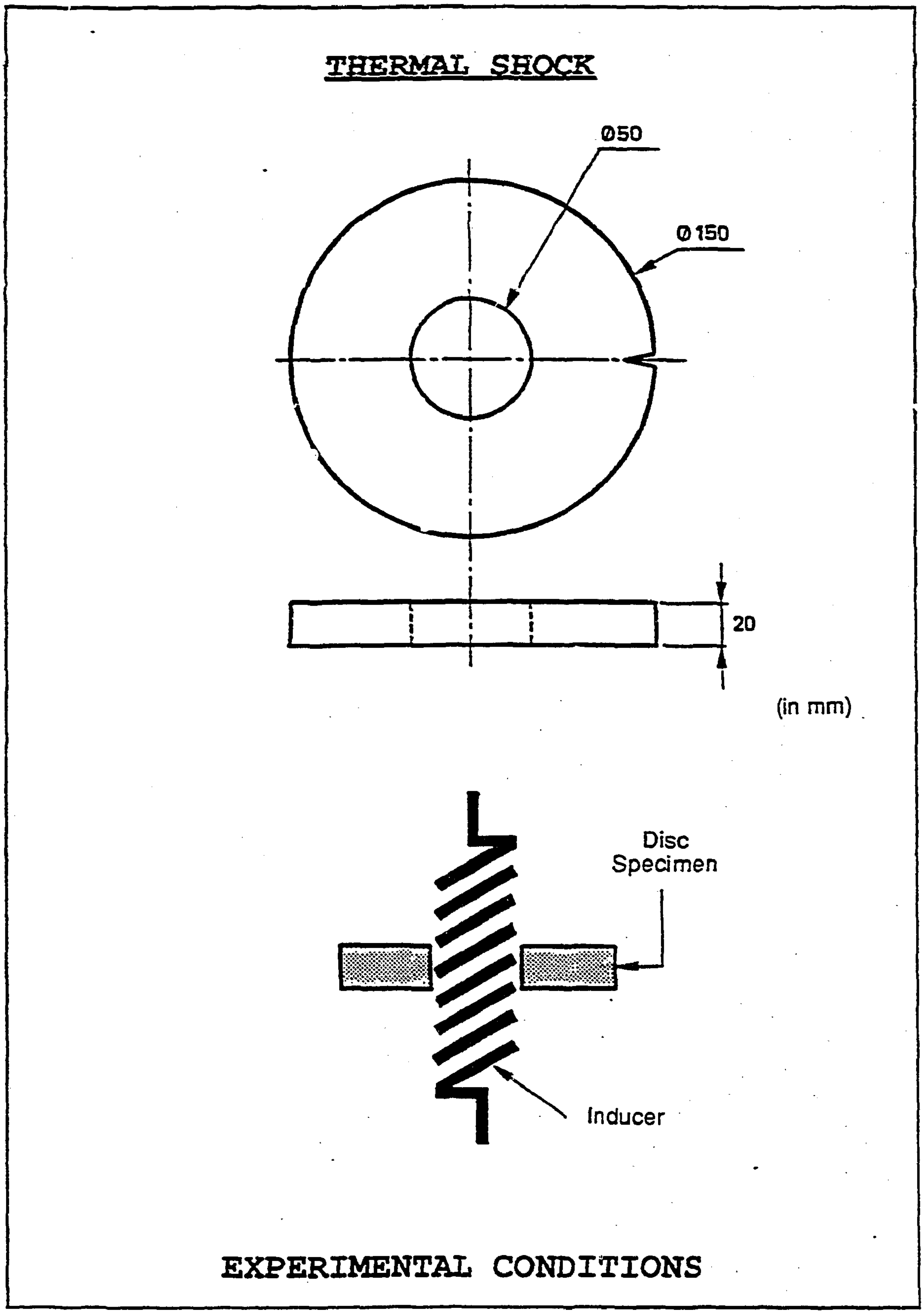


Figure 7: Experimental conditions of thermal shock test.

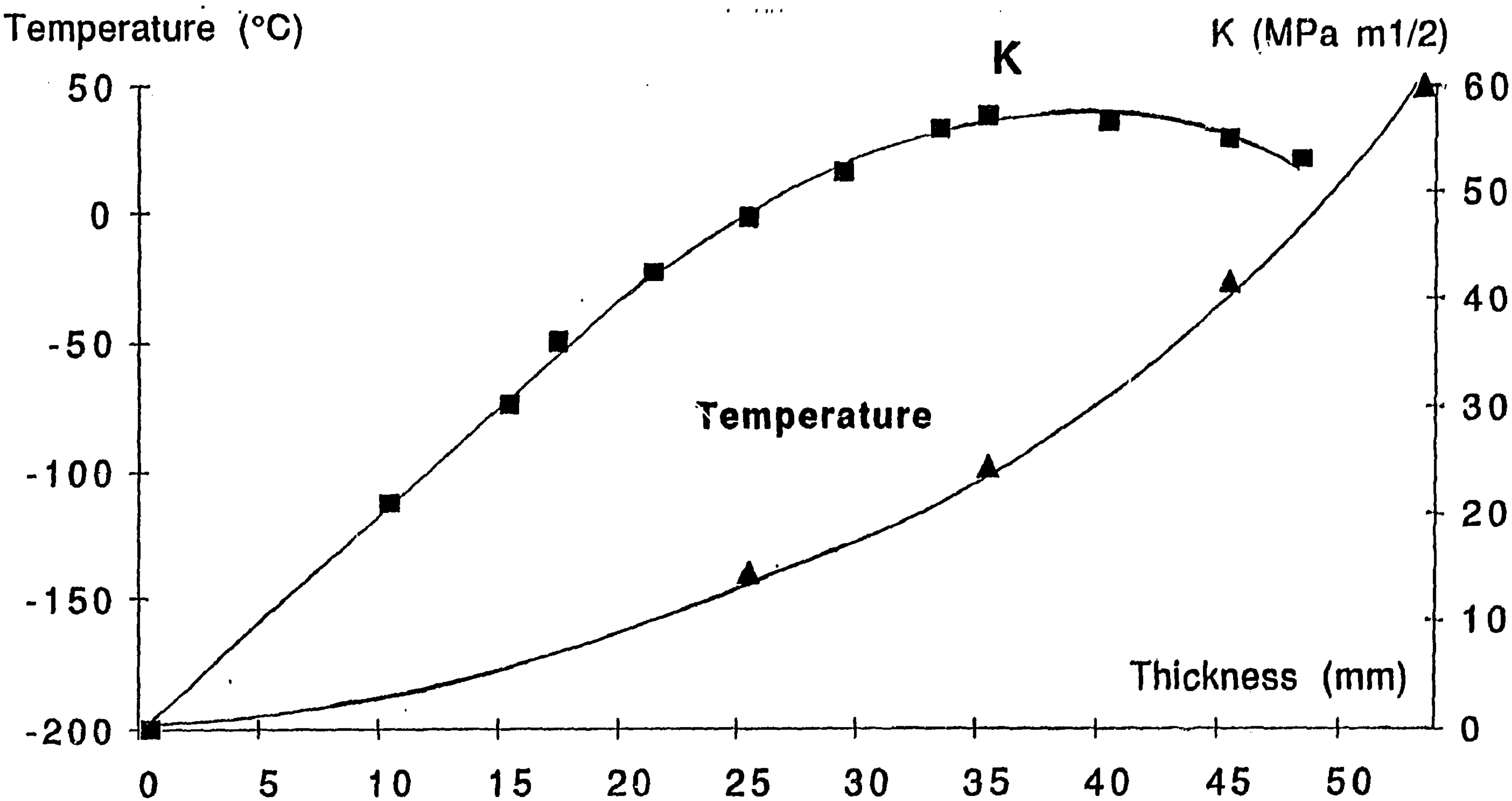
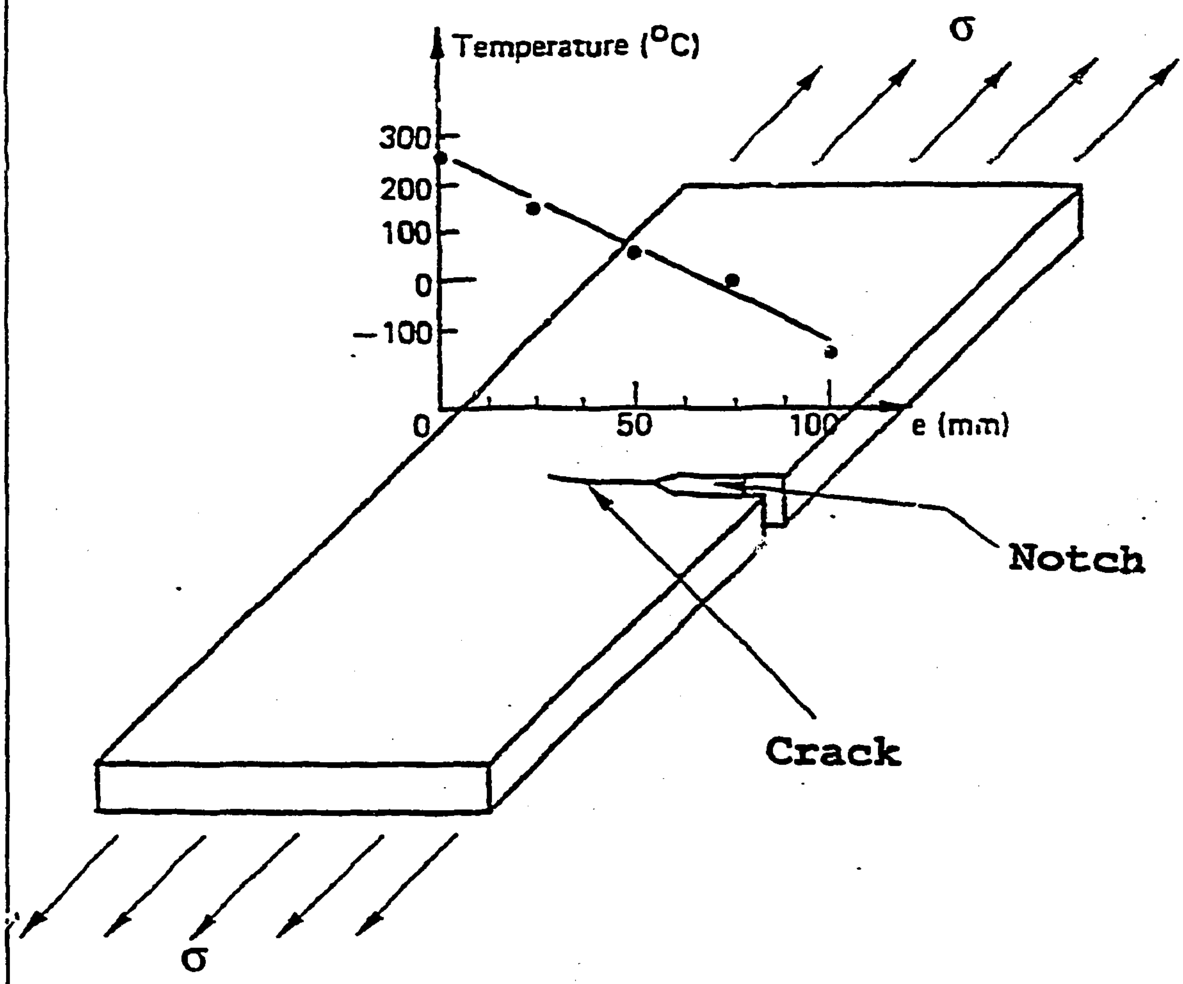


Figure 8: Stress intensity factor and temperature versus thickness of the specimen (thermal shock test).

ASME METHOD



RCC-M CODE:

$$K_{Ia} = \min \left| \begin{array}{l} 29,43 + 1,355 \, EXP[0,026(T - RT_{NDT} + 88,9)] \\ 220 \ MPa\sqrt{m} \end{array} \right.$$

Figure 9: Crack arrest test performed on large plate put through a temperature gradient and tensile loading.

Test	Specimen	Notch or Precrack	Temperature at crack arrest (in °C)	K_{Ia} (in $MPa\sqrt{m}$)
A1	Cylinder	Notch	11	75
A2	Cylinder	Notch	-13	54,6
D1	Cylinder	Notch	-74	32,3
D2A	Disc	Notch	-36	51,2
D2B	Disc	Precrack	-53	45,1

Table III: Thermal shock tests : values of crack arrest toughness.

6 – COMPARAISON OF ARREST TOUGHNESS VALUES OBTAINED THROUGH THE VARIOUS TESTS.

Figure 10 shows the different results obtained by isothermal tests (standard ASTM) and thermal loading, and compares them with the reference curve of RCC-M code [1].

Two populations of results seem to be very distinct: one is composed of isothermal test results, the other one of test results with temperature gradient. Several points may explain the duality.

Difference in methodology

Isothermal tests present important limitations. Indeed a local metallurgic modification of material is necessary to obtain a cleavage initiation. The implementation of a weld point introduces residual stresses whose future influence on a crack behaviour is not known. Furthermore loading is not adequately controlled. We noted out an additionnal recess of the wedge after initiation. The range of the consequent perturbations is not known.

In the experiment on thermal shock loading conditions are mastered during the propagation phase. Indeed thermal gradients introduced into the specimen have evolved very little during the 100 ms which correspond to the crack jump.

Scale effect

A scale effect (specimens A1, A2 and D1 have a 200mm thickness) can hardly explain the difference between the different method results since specimens D2A and D2B have a 20 mm thickness (same value as for the C.C.A. specimens).

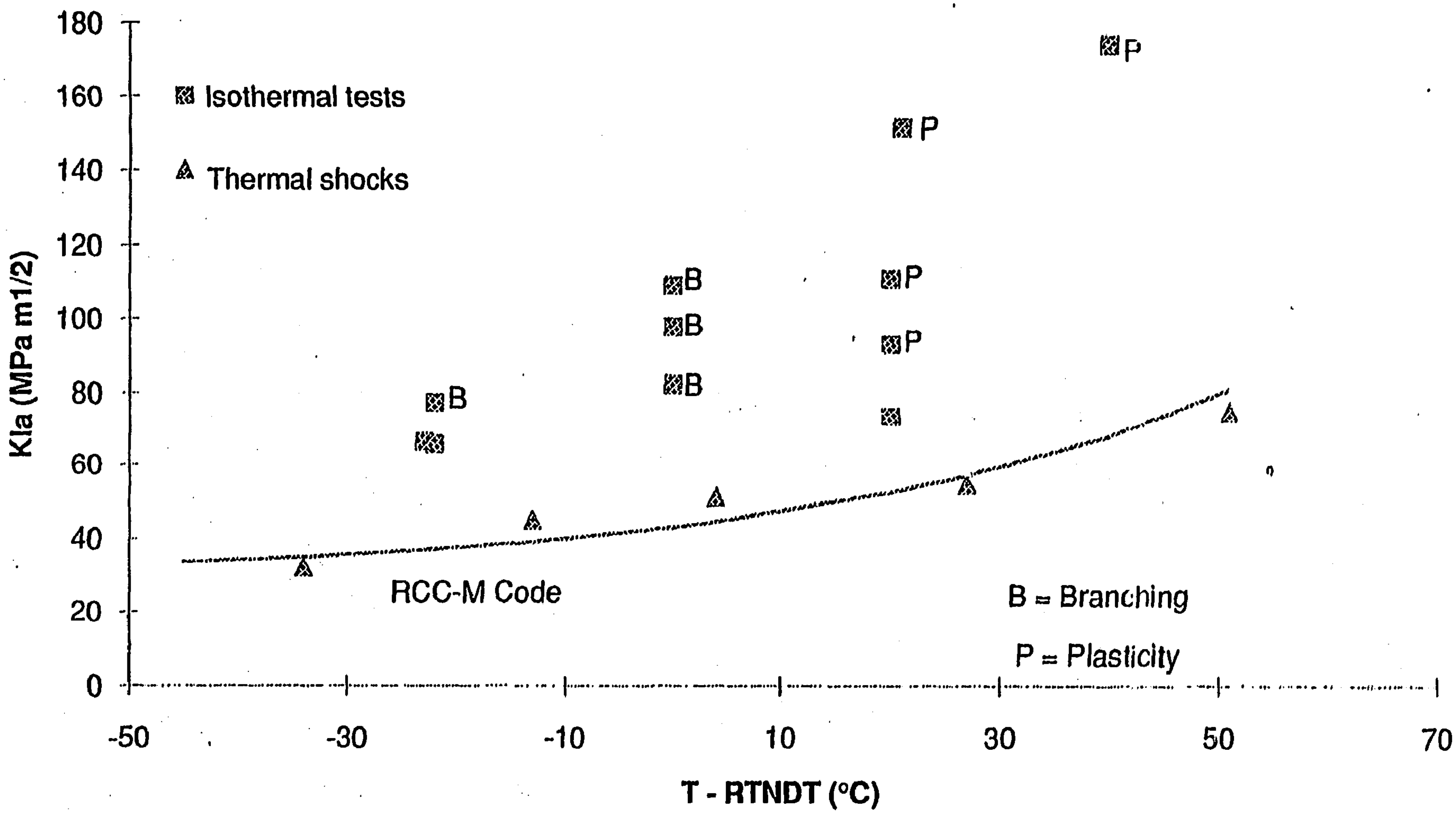


Figure 10: Comparaison between the different values of KIa and the RCC-M code.

Mechanical reasons

What is probably the most important has to do with the difference of the physical situations in the different experiments.

Isothermal tests are based upon a purely mechanical loading (with imposed displacements) with a decrease of the stress intensity factor during the propagation of a beforehand-initiated crack, whereas the tests of a thermal shock type are based upon a thermal loading with an increasing toughness during propagation.

The A.S.M.E. typed tests offer a mechanical loading (but with an imposed stress) as well as a thermal loading. So we can note the closeness of the results obtained with thermal loading.

Moreover it is important to note that the RCC-M code values are realistic: they do not include a safety margin.

Literature Results

We must note that an identical comparison on a E36 steel did not make it possible to differentiate 2 populations. But the study included only 2 experimental results obtained from thermal shock tests.

Importance of dynamic effects

Experiments were interpreted with a static approach taking no account of inertia forces in the mechanical analysis. The rate of crack growth measured at temperatures of -60°C and -40°C (respectively 762 and 670 m/s) are far from being insignifiant if we compare them to the rate of tranverse waves. So, a dynamic analysis would be justified but studies showed that on the one hand it is possible to decrease the dynamic effect by modifying the geometry of C.C.A. specimens [11], on the other hand the static analysis is proven to be always conservative [12].

7 - THERMAL SHOCKS FOR DETERMINATION OF KIa

In that chapter a comparaison between different results of crack arrest tests done by thermal shock is presented. In figure 11, the results of ORNL, FRAMATOME, University of Pisa and EDF-ENSMP are presented. Tested materials are quite similar: A508 C13 *for* FRA and EDF, A508 C12 *for* ORNL and A533 for University of Pisa.

We can notice that FRAMATOME and EDF-ENSMP results are very similar and in good agreement with RCC-M reference curve. On the other hand, the latter is very conservative compared to ORNL and University of Pisa results.

8 - CONCLUSION

The tests conducted showed that the experimental process described by the ASTM standard is relatively easy to implement. Test·static analysis does not induce any major problem. However this experimental method reveals 2 important limitations :

- the implementation of a weld point at the top of the notch introduces residual stresses,
- the imposed dispacement loading cannot be controled correctly.

Values obtained with the ASTM method are superior to the ones obtained through thermal shock. Moreover we observe that values obtained through thermal shock tests are the only ones that correspond to those advanced by RCC-M code; ASTM test values are considered as being too optimistic.

At the present time, tests are done according to ASTM procedure, but with a duplex specimen made with two different materials welded by electron beam in order to limit the HAZ. There, the crack initiation happens in a brittle steel, and the arrest in the studied steel.

The determination of KIa from thermal shocks is still under way. The effect of loading conditions, materials properties and crack location are studied.

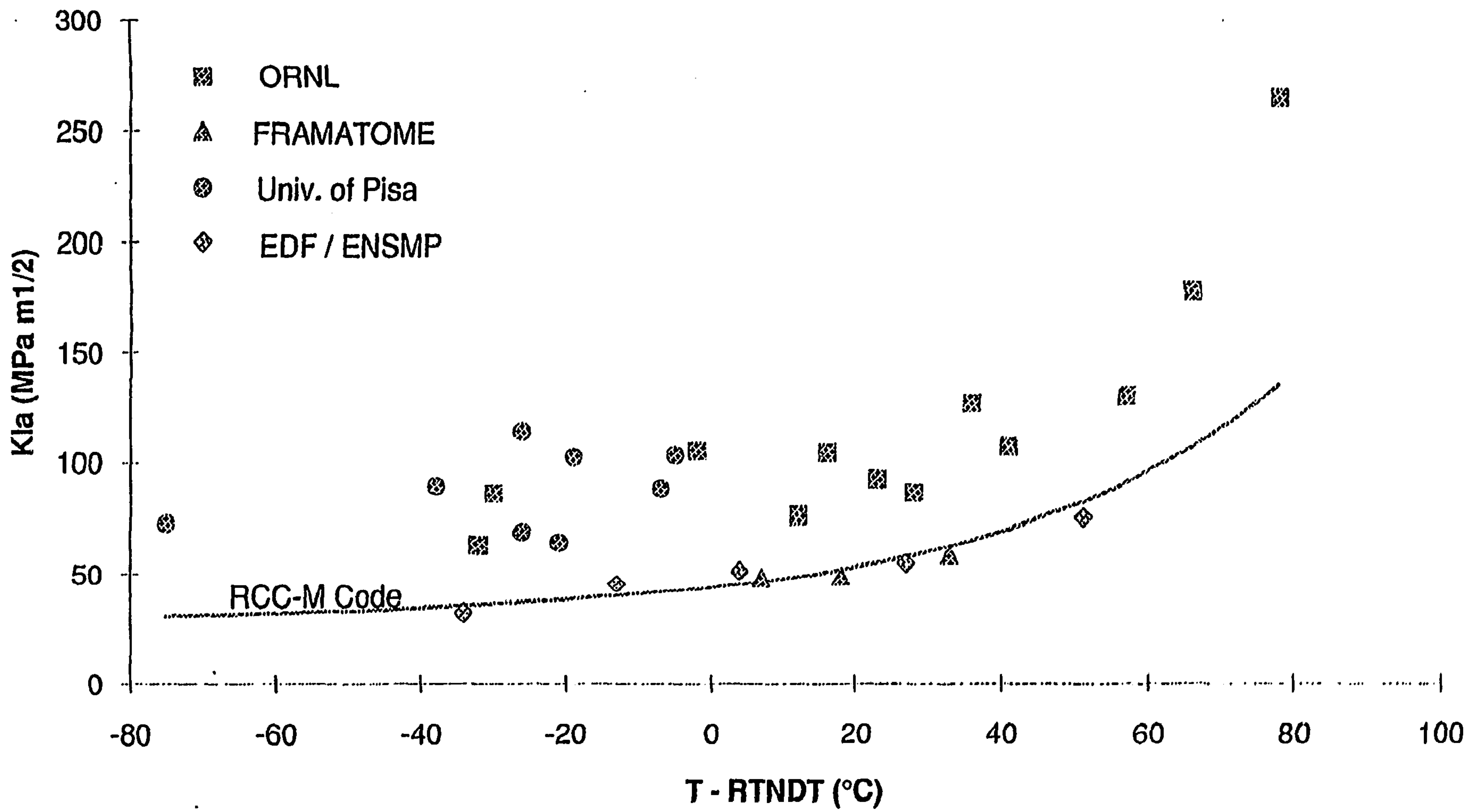


Figure 11: Comparaison between different values of KIa determined from thermal shock loading tests.

REFERENCES

[1] - J.M. FRUND - "Détermination du facteur d'intensité de contrainte à l'arrêt de fissure de pièces forgées en acier 16MND5 à partir de la procédure ASTM 1221. Comparison avec les valeurs issues d'essais de choc thermique ou prévues par le code RCC-M", EDF/DER/EMA document HT-46/NTE 1371-A, january 1992.

[2] - Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steel. ASTM E1221 - 88.

[3] - M. DI FANT - "Mécanique et mécanismes de la rupture dynamique dans un acier peu allié", Thesis in "Sciences et Génie des Matériaux", Ecole des Mines de Paris, december 1990.

[4] - M. DI FANT - A. FONTAINE - A. PINEAU - C. ROUX - "Conditions d'arrêt de fissures de clivage dans un acier de construction métallique", IRSID document RE 89317, july 1989.

[5] - P. B. CROSLEY - E. J. RIPLING - "Crack arrest toughness of pressure vessel steels", Nuclear Engineering and Design, vol. 17, p. 32-45, 1977.

[6] - P. B. CROSLEY - E. J. RIPLING - "Towards development of standard test for measuring K_{Ia}", Fast Fracture and Crack Arrest, ASTM STP 627, p.372-397, 1977.

[7] - M. DI FANT - E. LESUEUR - "Compte rendu d'essais de mesure de ténacités à l'arrêt d'un acier forgé 16MND5", IRSID document PE5780/MDF/LT, november 1991.

[8] - A. GENTY - "Etude expérimentale et numérique de l'amorçage et de l'arrêt d'une fissure sous choc thermique dans un acier faiblement allié (16MND5)", Thesis in "Sciences et Génie des Matériaux", Ecole des Mines de Paris, 1989.

[9] - D. BUISINE - M. BETHMONT - "Evaluation du risque de rupture brutale des cuves REP en situation accidentelle : des défauts dans les veines sombres à l'arrêt des fissures", EDF document HT-46/COM 1189-A, february 1991.

[10] - J.M. FRUND - "Définition d'une méthode d'analyse d'arrêt de fissure dans les cuves REP. Bilan des connaissances", EDF/DER/EMA document HT-46/NTE 1549-B, april 1993.

[11] - J. BEINERT - J.F. KALTHOFF - "The development of a crack arrest test specimen with reduced dynamic effects", Application of Fracture Mechanics to Materials and Structures, Martinus Nijhoff Publishers, 1983.

[12] - J.F. KALTHOFF - "Interpretation of crack arrest fracture toughnesses measured with various steels", 7th International Conference on Fracture, Houston, 1989.

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Auteurs : **FRUND J.M./DI FANT M./BETHMONT M.**

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