FRACTURE TOUGHNESS K_{IvM} MEASUREMENT OF NON-BRITTLE METALLIC MATERIALS BY "CHEVRON NOTCH" SPECIMENS

Dal Re V. and Zucchelli A.

Department of Engineering Mechanics, (DIEM) University of Bologna, ITALY

ABSTRACT

The aim of this research is to extend the K_{IvM} fracture toughness measurement method to non perfectly brittle metallic materials. Many experiments on tough Steels, Aluminium and Titanium alloys showed that the measured K_{IvM} is strongly dependent on specimen size. Increasing specimen size measured K_{IvM} also increases.

This phenomenon is coherent and may be explained by the rising R-curves of these materials. In fact, in a bigger specimen, unstable crack propagation takes place after a larger stable crack propagation. In the cases of materials with rising R-curves, measured K_I values corresponding to larger crack propagations are higher.

In order to obtain in each material an experimental K_{IvM} value not higher than the valid K_{IC} (ASTM E399), the "chevron notch" specimen size must not exceed a certain value. A validity condition about the maximum size of "chevron notch" specimens to obtain measured K_{IvM} values not higher than the valid K_{IC} in Steels, Aluminium and Titanium alloys is proposed. This validity condition is based on the concept that, in order to obtain a $K_{IvM} \leq K_{IC}$, the stable crack propagation in K_{IvM} measurement must not exceed the admissible stable crack propagation in the valid K_{IC} measurement. It brings to the condition that the thickness B of the "chevron-notch" specimen must not exceed the value:

$$B \leq C\,(K_{IvM} / \sigma_{ys})^2$$

where: C is a constant ranging from 0.215 to 0.538, depending on the toughness of the material and σ_{ys} is the 0.2% offset tensile yield strength.

Many tests have been performed on Steels, Aluminium ad Titanium alloys in order to obtain, for each material, a correlation between the fracture toughness and the value of the constant C. A linear correlation between the constant C and the plastic zone radius has been found.

1 INTRODUCTION

Fracture toughness K_{IvM} measurement using "chevron-notch" specimens, according to [1], is a very useful and simple method in order to obtain quick results, avoiding the long and tiring pre-cracking procedure. In brittle materials, K_{IvM} [1] and K_{IC} [2] values are similar and quite independent on specimen size. The aim of this research is to extend K_{IvM} fracture toughness measurement method [1] to non perfectly brittle metallic materials; a new validity condition, based on "Chevron-notch" specimen size, in order to obtain K_{ivM} results not higher than valid K_{IC} is proposed. In the case of non-brittle materials, the validity condition, involving specimen size, proposed in [1]:

$$B \geq 1.25 (K_{IvM} / \sigma_{ys})^2$$

has no mean and carries to obtain fracture toughness K_{IvM} values much higher than corresponding valid K_{IC}.

Many tests on tough Steels, Aluminium and Titanium Alloys showed that the measured K_{IvM} is strongly dependent on specimen size. Increasing specimen size, measured K_{IvM} also increases [4],[5],[6]. This phenomenon is coherent and may be explained by the rising R-curves of these materials.

2 R-CURVE EFFECT ON K_{IvM} MEASUREMENT

In a bigger "chevron-notch" specimen, unstable crack propagation takes place after a larger stable crack propagation. In the case of materials with rising R-curves, K_I values corresponding to larger crack propagations are higher. In order to obtain a K_{Iv} [1] value coherent with a valid K_{IC} [2], stable crack propagation must to by about the same in both tests. If we wont that the measured value of K_{Iv} don't' exceed the valid K_{IC} of each material we must impose that the stable crack propagation in the "chevron-notch" specimen don't' exceed the one of the valid K_{IC} specimen. This condition may be written in the form:

$$\Delta a_{critic}(K_{IvM}) \leq \Delta a_{critic}(K_{IC}) \qquad (1)$$

In a valid K_{IC} test of a quasi-brittle material, the stable crack propagation, corrected by the plastic zone radius and the border effect, must be not greater than 5% of the original crack length a_c:

$$\Delta a_c(K_{IC}) \leq 0.05 \times 2.5(K_{IC}/\sigma_{ys})^2 = 0.125(K_{IC}/\sigma_{ys})^2 \qquad (2)$$

This condition may be transformed in the well-known formula [2]:

$$B \cong a_c \geq 2.5(K_{IC}/\sigma_{ys})^2$$

where σ_{ys} is the effective yield strength and B is the specimen thickness.
If we take in account only the 2% stable crack propagation, we obtain:

$$\Delta a_c(K_{IC}) \leq 0.02a_c = 0.02 \times 2.5(K_{IC}/\sigma_{ys})^2 = 0.05(K_{IC}/\sigma_{ys})^2 \quad (3)$$

In K_{IvM} tests, the critical crack length a_c, corresponding to the maximum applied load, is: $a_c = 0.5W$. In the bar specimens with standard proportions [1], the initial crack length (distance to chevron tip) is: $a_o = 0.33W$ and the thickness is: $B = 0.69W$. Thus: $a_o = 0.33B/0.69 = 0.48B$; $a_c = 0.5B/0.69 = 0.725B$ and:

$$\Delta a_c(K_{IvM}) = a_c - a_o = (0.725 - 0.48)B = 0.245B \qquad (4)$$

2.1 Quasi-brittle materials.

In K_{IvM} tests, because of the sharp grooves of specimen, the border effect is absent and the plastic zone may be neglected, in this case, while in K_{IC} specimens these effects are present.
Comparing equations (4) and (2), the condition (1) becomes: $0.245B \leq 0.125(K_{IC}/\sigma_{ys})^2$; thus:

$$B \leq 0.51(K_{IC}/\sigma_{ys})^2$$

2.2 Tough materials

In this case, the sharp grooves of "chevron-notch" specimen are not able to avoid an important plastic zone, comparable to the one in the compact K_{IC} specimen. Comparing equations (4) and (3), the condition (1) becomes: $0.245B \leq 0.05(K_{IC} / \sigma_{ys})^2$; thus:

$$B \leq 0.204(K_{IC} / \sigma_{ys})^2$$

The validity condition may be written in the general form:

$$B \leq C(K_{IC} / \sigma_{ys})^2 \qquad (5)$$

where the constant C (varying from 0.2 up to 0.5) depends on material toughness. The aim of experimental tests is to find a relationship between C values and mechanical characteristics of some categories of metallic materials.

3 EXPERIMENTAL RESULTS

Tested materials were: 5 steels, 3 Aluminium alloys and one Titanium alloy.

- Steels: 20CrNi4 (Full anneal), 20CrNi4 (Hardening & Tempering 240°C), 28NiCrMoV12 (Normalized) , C43 (Hardening & Tempering 300°C), 38NiCrMo4;
- Aluminium alloys: 6061 (Anticorodal 61; T6 condition), 6061 (Solution treatment), 6082 (Anticorodal 100; T6 condition);
- Titanium alloy: 550.

For each material, three types of specimens were tested:

i) K_{IC} compact specimens: 1TCT up to 5TCT, [2]
ii) "K_{IvM}" specimens: B = 6.25 (except Al alloys), 12.5, 25, 50 mm, [1]
iii) R-Curve specimens: B = 6.25 and 12.5 mm [3].

Experimental results are summarized in table 1.

Table 1. Experimental results

Chevron 1/4"		Chevron 1/2"		Chevron 1"		Chevron 2"		CT		-
K_{ivM} [MPa√m]	Δa [mm]	K_{ivM} [MPa√m]	Δa [mm]	K_{ivM} [MPa√m]	Δa [mm]	K_{ivM} [MPa√m]	Δa [mm]	K_{IC} [MPa√m]	Δa [mm]	σ_Y [MPa]
20CrNi4 – Full Anneal										
66	1.45	116	2.9	172	5.8	188	11.6	68 (1T)	1.28	470
20CrNi4 – Hardening & Tempering 240°C										
-	1.45	129	2.9	134	5.8	142	11.6	99 (1T)	1.31	1020
28NiCrMoV12										
116	1.45	152	2.9	211	5.8	298	11.6	135 (5T)	3.08	670
C43										
-	1.45	81.6	2.9	108.2	5.8	134.6	11.6	82.3 (1T)	1.26	450
38NiCrMo4 -										
-	1.45	106.5	2.9	128.7	5.8	137.5	11.6	96.8 (1T)	1.28	650
550 Titanium Alloy										
80.7	1.45	98.7	2.9	-	-	-	-	73.5 (1T)	1.32	830
6061 Aluminium Alloy (Anticorodal 61) – (T6 Condition)										
-	-	21.8	2.9	70.8	5.8	53.2	11.6	36.1	1.28	-
6061 Aluminium Alloy (Solution Treatment)										
-	-	21.9	2.9	38.9	5.8	50.0	11.6	27.8	1.35	120
6082 Aluminium Alloy (Anticorodal 100) – (T6 Condition)										
-	-	42.2	2.9	22.3	5.8	58.51	11.6	35.8	1.23	310

In all cases, increasing the thickness of "chevron notch" specimens, corresponding measured K_{IvM} value is higher, according to R-curve trends [3]. Some examples of obtained results are shown in figs. 1, 2 and 3. It may be noted that very small "chevron notched" specimens are able to measure the same K_I value obtained by big CT specimens. A limit case is the 28NiCrMoV12 steel; a 12,5 mm thick "chevron notched" specimen gives the same result of a 150 mm thick CT specimen.

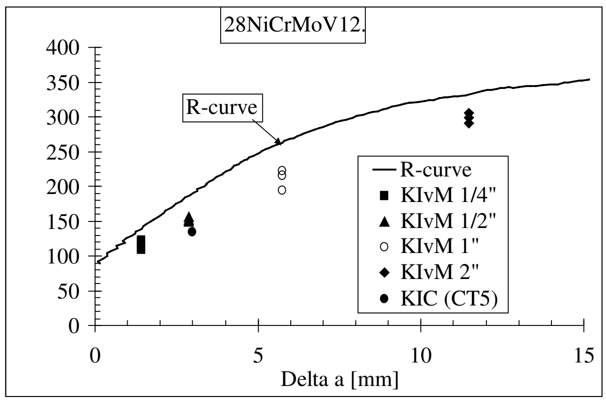

Fig. 1. R-Curve and K_I values of 28NiCrMoV12 Steel.

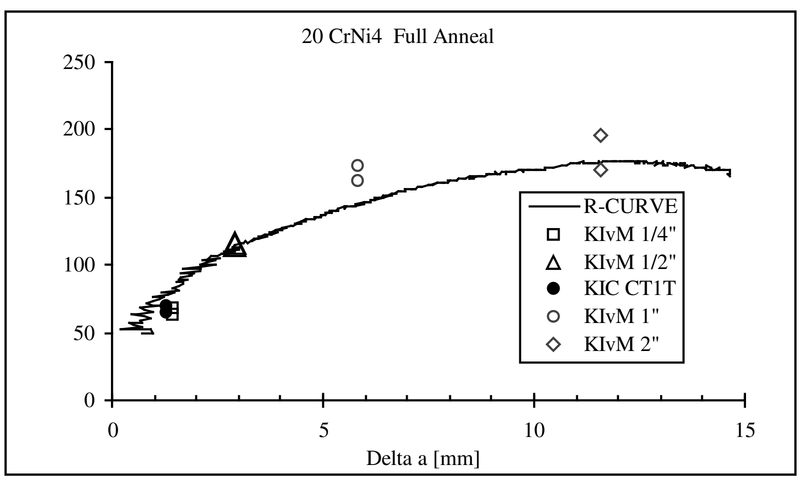

Fig. 2. R-Curve and K_I values of 20CrNi4 Steel.

For each tested material the thickness B* of the K_{IvM} specimen giving the same value of K_{IC} test has been found, by linear interpolation, and the constant C has been calculated as:

$$C = B^* / (K_{IC} / \sigma_{ys})^2 .$$

Obtained C values are plotted vs $(K_I/\sigma_{ys})^2$ in Fig. 4. C values for Steels and C values for non-ferrous materials may be linearly interpolated, and two relations may be found.

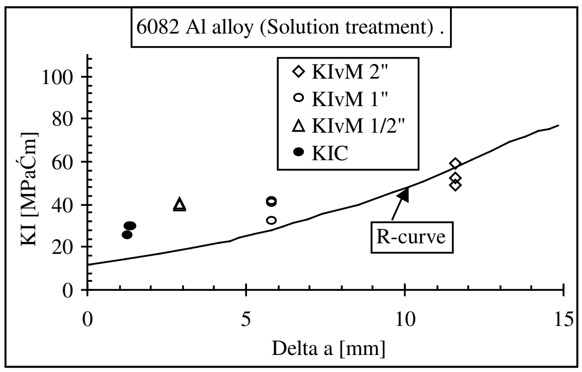

Fig. 3. R-Curve and K_I values of 6082 Aluminium alloy.

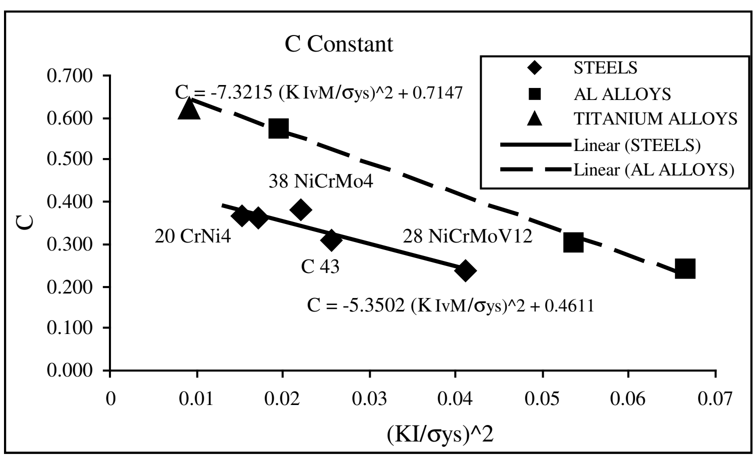

Fig. 4. Constant C vs $(K_I/\sigma_{ys})^2$ for Steels and for Aluminium or Titanium alloys.

It means that constant C, depending on fracture toughness of each material, is linearly dependent on the radius r_y of the plastic zone, proportional to $(K_{IC}/\sigma_{ys})^2$. Increasing the fracture toughness of material, also increases the plastic zone radius, that is the factor $(K_{IC}/\sigma_{ys})^2$, and the value of the constant C tends to the one supposed: C = 0.204.

After each K_{IvM} test, with a B thick "chevron-notch" specimen, the validity condition must be checked:

$$B \leq C(K_{IvM} / \sigma_{ys})^2,$$

where C may be calculated as:

$C = -5.3502(K_{IvM} / \sigma_{ys})^2 + 0.4611$ for steels, and

$C = -7.3215(K_{IvM} / \sigma_{ys})^2 + 0.7147$ for Al and Ti alloys.

If it occurs, the K_{IvM} is not greater than the valid K_{IC}.

4 CONCLUSIONS

- In the case of brittle materials, with a flat R-curve, increasing the thickness of "chevron notch" specimens, measured K_{IvM} decreases or remains constant and is near to the "true" K_{IC}. Validity condition about the specimen thickness, proposed by ASTM [1] is meaningful.
- In the case of tough materials, measured K_{IvM} increases with specimen thickness. This is coherent with the rising R-curve of these materials.
- In this case, proposed validity condition about specimen thickness: $B \le C(K_{IvM} / \sigma_{ys})^2$, allows to obtain K_{IvM} measured values not greater than a valid K_{IC} for each material.
- The constant C is linearly dependent on the radius r_y of the plastic zone, proportional to $(K_{IC}/\sigma_{ys})^2$.
- The extreme values experimentally found for the constant C are coherent with theoretical values supposed in relation to different fracture toughness of materials.
- In many cases, required "chevron-notch" specimen size is very small. This can be an advantage in terms of saving of material but a limitation in terms of difficulty in working and testing specimens.
- Further tests on other Steels, Aluminium, Titanium and Copper Alloys, must be performed to confirm these first interesting results.

5 REFERENCES

[1] American Society for Testing and Materials, "Standard Test Method for Plane-Strain (Chevron-Notch) Fracture Toughness of Metallic Materials", ASTM E 1304-97.

[2] American Society for Testing and Materials, "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials", ASTM E 399-97.

[3] American Society for Testing and Materials, "Standard Practice for R-Curve Determination", ASTM E 561-94.

[4] Kevin, R. Brown, "The use of the chevron-notched short-bar specimen for plane-strain toughness determination in Aluminium alloys", ASTM STP 885, 1983.

[5] J. Eschweiler, G. Marci, D. G. Munz, "Fracture toughness of an Aluminium alloy from short-bar and compact specimens", ASTM STP 885, 1983.

[6] J. L. Shannon, Jr., D. G. Munz, "Specimen size and geometry effects on fracture toughness of Aluminium oxide measured with short-rod and short-bar chevron-notched specimens", ASTM STP 885, 1983.