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

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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 $\sigma_{ys}$ 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:

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

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 $a_c$:

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

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

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

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

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

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: $0.245B \le 0.125(K_{IC}/\sigma_{ys})^2$; thus:

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

*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: $0.245B \le 0.05(K_{IC} / \sigma_{ys})^2$; thus:

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

The validity condition may be written in the general form:

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

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] | $\sigma_Y$ [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.

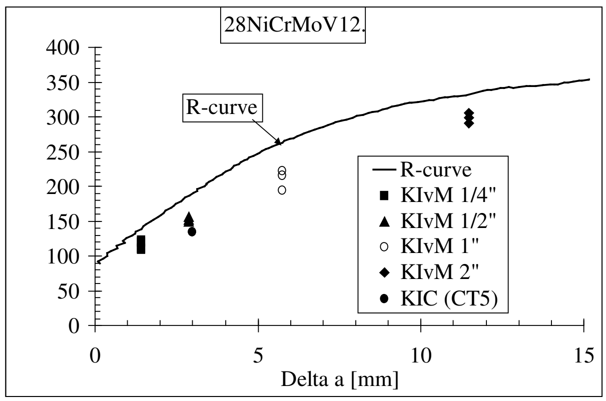


Fig. 1. R-Curve and $K_I$ values of 28NiCrMoV12 Steel.

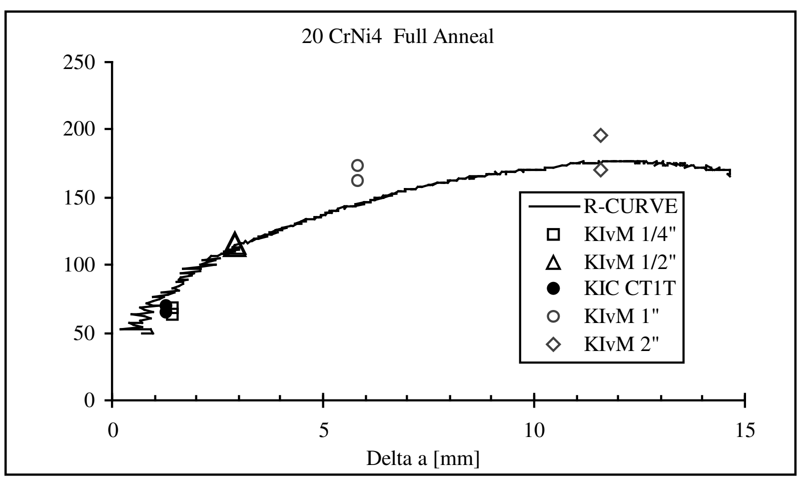


Fig. 2. R-Curve and $K_I$ values of 20CrNi4 Steel.

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.

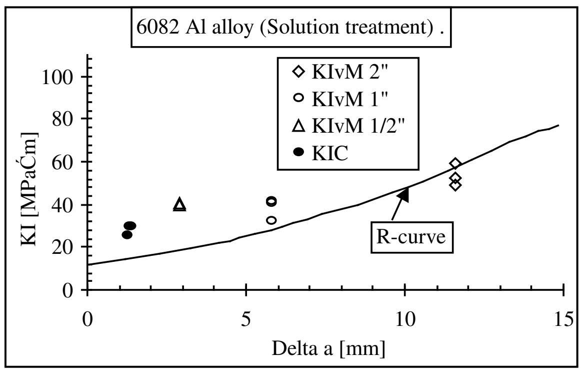


Fig. 3. R-Curve and $K_I$ values of 6082 Aluminium alloy.

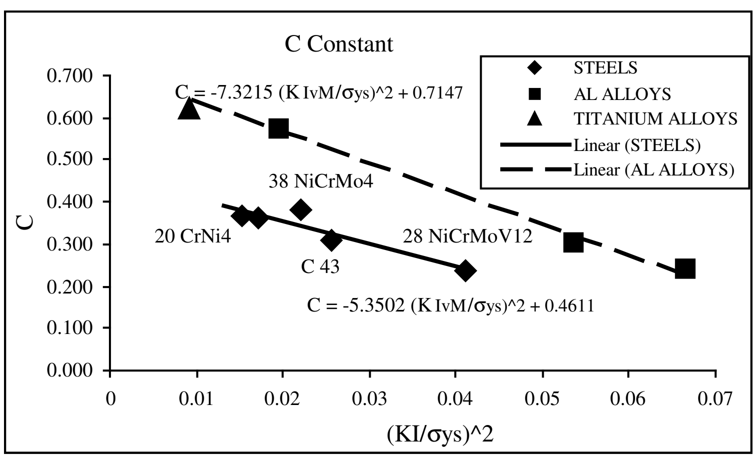


Fig. 4. Constant C vs $(K_I/\sigma_{ys})^2$ for Steels and for Aluminium or Titanium alloys.

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:

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

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.

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