# RESULTS OF ROUND ROBIN TESTS OF FRACTURE MECHANICS PARAMETERS WITHIN CMEA COUNTRIES

M. Brumovsky+

Results of the CMEA Round Robin Testing Programme of Fracture Mechanics Parameters is presented and discussed. Three phases of this programme have been finished with aim to the determination of static plain fracture toughness $K_{Ic}$, critical value of J-integral $J_{Ic}$ for mild and medium yield strength steels and of fracture toughness for dynamic initiation $K_{Icd}$

Analysis of received results from 15 laboratories from 6 CMEA countries shows that all used recommendations are sufficient to receive correct and comparable results of measurements.

## INTRODUCTION

Determination of correct fracture mechanics parameters needs not only new testing methods and evaluation of results but also strong requirements on testing equipments and measuring technique. Both part must be taken into account during preparation of national/international standards for material testing.

Within the CMEA Working Group in Brittle Fracture /22K.o3/ during several last years a great effort has been given to the preparation of international recommendations for the determination of fracture mechanics parameters by static /$K_{Ic}$, $\delta_c$ and $J_{Ic}$/ as well as dynamic /$K_{Icd}$/ loading and also to their verification by round robin testing.

In this experimental programme 15 organizations from 6 CMEA countries /as shown in Table I/ took part.

+ SKODA Concern Enterprise, Power Machinery Plant, 316 oo Plzen, Czechoslovakia

TABLE I - Laboratories involved with the round robin programme, listed in alphabetical order

| Laboratory | Chief Scientific Investigator | Phase |
|---|---|---|
| Centralny ośrodok badań i rozwoju techniki kolejnictwa, o4-275 WARSZAWA, Poland | Z. Gmur | I,II |
| Czech Technical University Building Institute, 16o oo PRAHA, CSSR | R.Stárek | I,II |
| Institut de sudura si incercari de materiale, 19oo TIMISOARA, Romania | T.Moise | I,II,III |
| Institut Mashinovedenia AN SSR, MOSCOW, USSR | N.A.Makhutov<br>P.F.Koshelev | I,II,III |
| Institute of Physical Metallurgy ČSAV, 616 62 BRNO, CSSR | J.Mann<br>B.Vlach | I,II<br>III |
| Nuclear Research Institute 25o 68 ŘEŽ, CSSR | R.Havel<br>B.Stoces | II<br>III |
| Research Institute of Chemical Apparatus 6o2 oo BRNO, CSSR | J.Podhora | III |
| Research Institute of Iron Metallurgy 739 51 DOBRÁ, CSSR | J.Kucera | II |
| ŠKODA k.p., Central Research Institute 316 oo PLZEŇ, CSSR | R.Janda | I,II,III |
| ŠKODA k.p. Power Machinery Plant 316 oo PLZEŇ, CSSR | M.Brumovsky | I,II |
| State Research Institute of Materials 113 12 PRAHA, CSSR | V.Koula<br>F.Hajsky | I,II |
| Technische Universität "Otto von Guericke" 3o12 MAGDEBURG, GDR | E.Schick | I,II,III |

| Laboratory | Chief Scientific Investigator | Phase |
|---|---|---|
| Vasipari Kutató Intézet<br>1116 BUDAPEST, Hungary | A.Fehérvári | I,II,III |
| VITKOVICE k.p.<br>Research Institutes<br>7o6 o2 OSTRAVA, CSSR | M.Tvrdy | I,II |
| Welding Research Institute<br>894 23 BRATISLAVA, CSSR | P.Polák | I |

Main effort of this programme have been given to:

Phase I - Determination of $K_{Ic}$

- comparison of accuracy of fracture mechanics parameters received from standard hydraulic and well equiped mechanical or servohydraulic machines and in different laboratories;

Phase II - Determination of $J_{Ic}$

- comparison of $J_{Ic}$ values for steels with different dJ/da values with/without experimental determination of blunting line;
- comparison of different methods for evaluation of subcritical crack growth initiation;

Phase III - Determination of $K_{Icd}$

- elaboration and verification of standard force calibration and measuring methods; comparison of results from different laboratories received by standard specimens;
- comparison of accuracy in dynamic fracture toughness determination in different laboratories.

## EXPERIMENTAL PROCEDURE

Materials used within this round robin programme were delivered by Czechoslovak /CSN/, German /TGL/ and Poland /9o P/ members; main characteristics are summarized in TABLE II.

Static fracture toughness testing were carried out according to the INTERATOMENERGO standard /1/ elaborated on the bases of Recommendations from the CMEA Working Groups 22K.03 and 06.S-12.

TABLE II - Characteristics of experimental materials

| Steel /mass %/ | C | Mn | Si | P | S | Ni | Cr | Mo |
|---|---|---|---|---|---|---|---|---|
| ČSN 115o3.1o | .16 | 1.17 | .33 | .o16 | .o15 | .o5 | o.11 | |
| ČSN 11149 | .15 | 1.15 | .34 | .o18 | .o17 | .o5 | | |
| ČSN 15313.5 | .13 | o.6o | .19 | .oo9 | .oo7 | .o9 | 2.29 | o.98 |
| TGL 15198 | | | | | | | | |
| 16CrMo4.4V | .19 | o.7o | .33 | .o23 | .o17 | | 1.1o | o.43 |
| 9o P | .68 | 1.16 | .25 | .o25 | .o1o | | | |

| Steel | $R_p0.2$ /MPa/ | $R_m$ /MPa/ | $A_5$ /%/ | KCV/+2o$^oC$ /J.cm$^{-2}$/ |
|---|---|---|---|---|
| ČSN 115o3.1o | 395 | 526 | 26.3 | 11o |
| ČSN 11149 | 365 | 516 | 29.o | 1oo |
| ČSN 15313.5 | 391 | 552 | | 29o |
| 16CrMo4.4V | 447 | 586 | 24.8 | 23o |
| 9o P | 518 | 99o | 13.6 | |

Dynamic fracture toughness testing were carried out with respect to the Recommendations of the CMEA Groups 22K.03 and o6.S-12 /2/. Both recommendations are in main requirements very close to the ASTM ones.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Phase I

The main purpose of testing within this phase was to compare testing procedures in different laboratories equipped by different testing techniques. Tests were carried out within plain strain loading conditions.

Three point bend /TPB/ testing specimens of 25 mm thickness were tested at these conditions:

- steel ČSN 115.o3 : between -196$^oC$ and -8o$^oC$ ;
- steel 9o P : at +2o$^oC$ and -4o$^oC$.

Main results are shown in TABLE III.

Analysis of these results shows that:

- there is a very small difference between mean values, determined for Gauss or Weibull type of distribution /38.5 for Gaussian and 41.0 MPa.m$^{1/2}$ for Weibull type for ČSN 115o3 type steel at -196 C/;
- mean square error of results in individual laboratories depends on experimental equipment: for hydraulic machines it represents about 1o% for mechanical and servohydraulic machines only 5% of mean value; in absolute values it represents 4, resp. 2 MPa.m$^{1/2}$ all these values are valid for the area of lower shelf of fracture toughness;

- for higher temperatures /i.e. in transition region/ it was also obtained that relative mean square error in determination of $K_Q$ or $K_{max}$ values are similar to those ones obtained for lower shelf /i.e. 1o,resp.5%/; thus, there is no difference in accuracy in determination of $K_{IC}$ and $K_C$ values.

TABLE III - Results of Phase I testing /in $MPa.m^{1/2}$/

| Steel | ČSN 115o3.1o | 9o P | | Machine |
|---|---|---|---|---|
| Laboratory | $K_{Ic}$/-196°C | $K_{Ic}$/2o°C | $K_{Ic}$/-4o°C | |
| 1 | 4o.o±o.9 | | | SH |
| 2 | 34.3±4.6 | | | H |
| 3A | 38.1±1.7 | | | M |
| 3B | | 45.1±2.4 | 39.7±3.o | M |
| 4 | | 38.6±2.1 | | SH |
| 5 | 33.7±2.o | | | M |
| 6 | 36.3±3.7 | | | H |
| 7A | 43.9±4.1 | | | M |
| 8A | 34.5 | 44.6±2.8 | 35.8±1.7 | H |
| 8B | | 39.9±2.7 | 38.8±3.8 | H |
| 9 | 45.8±1.o | | | M |
| 1o | 45.4±2.7 | 4o.1±1.2 | 34.1±1.8 | H |
| mean | 38.5±6.o | 41.4±3.5 | 37.2±3.6 | |

H - hydraulic SH - servohydraulic M - mechanical

Phase II

The main purpose of testing within this phase was to compare testing procedures for determination $J_{IC}$ values using method of several specimens in different laboratories and also with other methods using only one specimen. Moreover, two steels with quite different dJ/da values were used.

For all specimens of TPB type with 25 mm thickness were again used. Main results are summarized in TABLE IV.

Analysis of received results show that:

- more consistent results are received using mean value of subcritical crack growth $\overline{\Delta a}$, in comparison with its maximum value, $\Delta a_m$ : scatter of $J_{Ic}$ values are smaller for the first one /between 175 and 253 $kJ.m^{-2}$ , i.e. 5o% / in comparison with the latter one /between 126 and 212 $kJ.m^{-2}$, i.e. 7o% /;

TABLE IV - Results of phase II testing /in $kJ.m^{-2}$/

| Steel | ČSN 115o3.1o | | | 16CrMo4.4V | | |
|---|---|---|---|---|---|---|
| Laboratory | $J_{IC}$/+2o °C | | $J_i$ | $J_{IC}^{/2/}$ | $J_{IC}^{/3.5/}$ | $J_{0.2}$ |
| | $\overline{\Delta a}$ | $\Delta a_m$ | | $\overline{\Delta a}$ | $\overline{\Delta a}$ | $\overline{\Delta a}$ |
| 1 | 242 | 153 | 1o2 $U_A$ | | | |
| 2 | | | | 21o | | |
| 3A | 233 | 17o | | 41o | | |
| 3B | | 1o2 | 1o2 $U_A$ | 184 | 1o4 | 195 |
| 4 | 238 | 212 | | 1o37x | 879x | 79ox |
| 5 | | 172 | 155 $U_D$ | | | |
| 6 | 186 | | | 134 | | |
| 7A | 175 | 167 | | | | |
| 7B | 253 | 126 | | | | |
| 8A | | | 38 AE | 293 | 187 | 24o |
| 8B | | | | 332 | 257 | 24o |
| 1o | | | | 45o | 175 | 336 |
| 11 | | | | 765x | 662x | 615x |
| 12 | | | | 292 | 19o | 241 |
| 13 | | | | 469 | 287 | 3o9 |
| mean from all $J_{IC}$ | 221 ± 29 | 157 ± 34 | | 3o8 ± 112 | 2oo ± 59 | 26o ± 48 |
| mean from J-Δa pairs | 212 | 178 | | 519 | 38o | 373 |

x - values are not taken into account as they do not fullfil all requirements of standard;
$U_D$- electrical potential drop method, direct current;
$U_A$- electrical potential drop method, alternating current;
AE- acoustic emmission method

- mean square error of $J_{Ic}$ for all laboratories is less than 15%, which is close to errors in $K_{Ic}$ determinations;
- one specimen methods for crack growth initiation give much smaller values of $J_i$ in comparison with standard multiple specimen method /$J_{Ic}$/;
- determination of $J_{Ic}$ becomes problematic if dJ/da value is smaller or close to $\sigma_Y$ as it is shown in Fig.2 for 16CrMo4.4V type of steel; for this case a large scatter of results were received:
  mean value of all $J_{Ic}$ values is not consistent with mean value of all J-Δa pairs /Fig.2/;

- for this type of steel a blunting line is steeper than with $\alpha = 2$ /experimentally was determined to be equal to $\alpha = 3.5$/ : large differences between $J_{Ic}^{(2)}$ /according to standards/ and $J_{Ic}^{(3,5)}$ are seen;
- value of $J_{0.2}$ is close to the experimentally determined $J_{Ic}$ from stretch zone measurement: 255 $MPa.m^{1/2}$

Phase III

Mean aim of this phase was to compare calibration and method of dynamic testing using pre-cracked Charpy specimens from CSN 11149 /calibration/ and CSN 15313 /$K_{ICd}$ determination/. Main results are shown in Fig.3 and Fig.4, from which the following conclusions can be made:

- tests, made at -196°C have shown that not in all laboratories the calibration /static/ of force was made with appropriate accuracy: even though scatter within one laboratory is relatively small /up to ± 1o%/ differences between laboratories have reaches even 5o % ;
- similar results have been received for tests of $K_{Icd}$ in temperature interval between -12o°C and -4o°C, where mean square errors of sets of results have been between 6 and 8 $MPa.m^{1/2}$ for all testing temperatures /similar errors have been reached by individual laboratories/.

## CONCLUSIONS

1/ Testing and determination of plain strain fracture toughness KIC does not represent any serious problem: in all laboratories were received very close results; accuracy in its determination lies between 5 and 1o% with respect to the type of testing machine.

2/ Testing and determination of JIC values using multiple specimens technique is more realistic using mean values of subcritical crack growth; accuracy in its determination is for normal structural steels close to accuracy in determination of KIC, i.e. about 15%.

3/ Method for determination of JIC value for steel with high resistance against crack growth /i.e. with low value of dJ/da/ needs further validation and improvement.

4/ Determination of $J_i$ values using one specimen techniques /potential drop or acoustic emmission methods/ gives substantially lower values in comparison with standard $J_{Ic}$ method.

5/ Determination of $K_{Icd}$ depends in great portion on the accuracy of force calibration which reaches even 25% of measured values.

## REFERENCES

/1/ "Determination of characteristic of base materials, welding joints and melted metal of devices and piping of nuclear power plants. Resistance against brittle fracture".
Standard INTERATOMENERGO - 38.443.56-81.

/2/ "Testing and evaluation of dynamic fracture toughness".
Recommendation o6.S-12-UFM-85 of CMEA Working Groups o6.S-12 and 22K.o3.

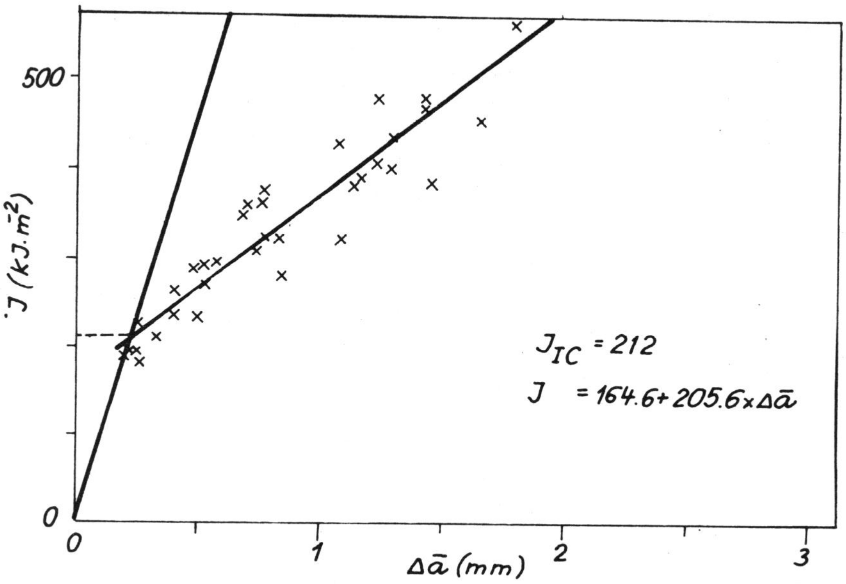


Figure 1 Results of Phase II testing: determination of $J_{Ic}$ value for ČSN 115o3 type of steel at +2o°C

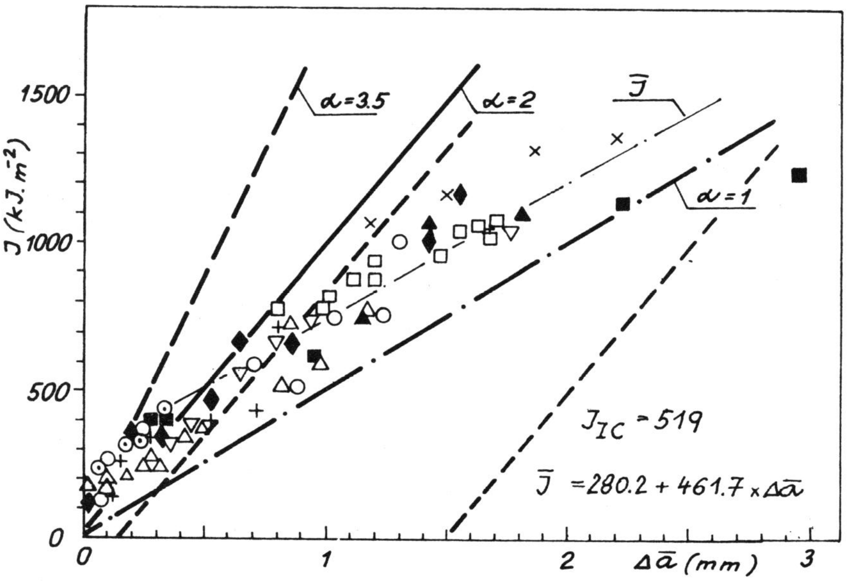


Figure 2 Results of Phase II testing: determination of $J_{Ic}$ value for 16CrMo4.4V type of steel at + 2o°C

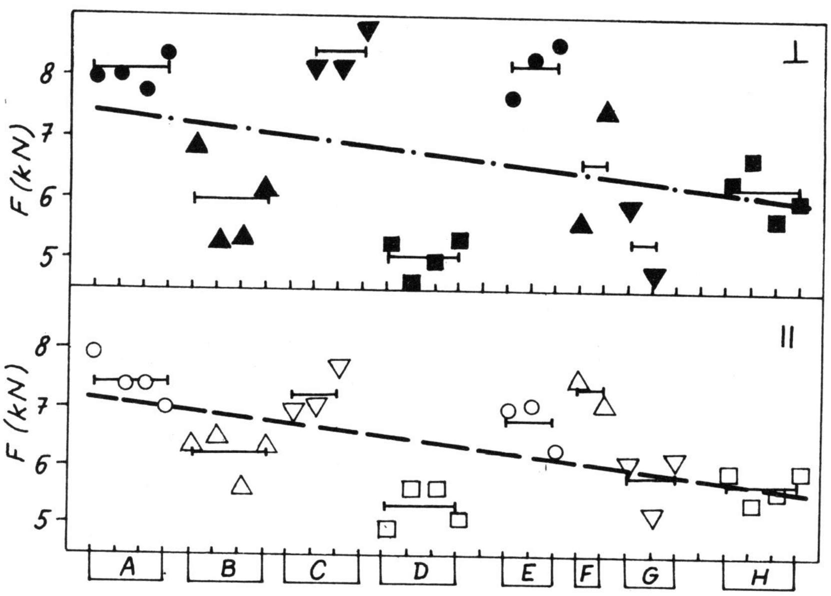


Figure 3 Results of Phase III testing: dynamic calibration at -196 °C using specimens from ČSN 11149 steel

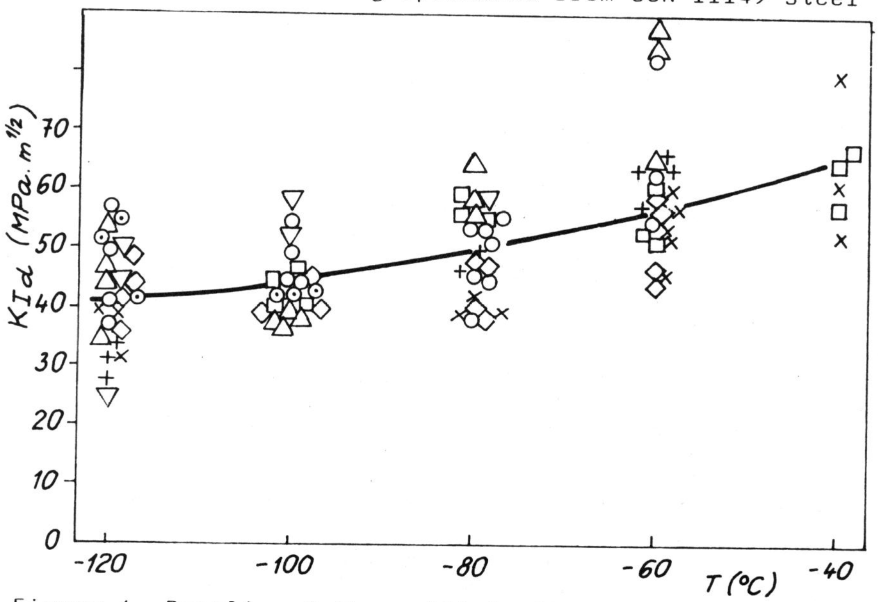


Figure 4 Results of Phase III testing: determination of KICd temperature dependence for ČSN 15313 steel