EFFECT OF SPECIMEN GEOMETRY ON DYNAMIC FRACTURE TOUGHNESS OF 15H2MFA REACTOR PRESSURE VESSEL STEEL

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ABSTRACT

The effect of specimen size and geometry on the dynamic fracture mechanics properties of 15H2MFA reactor pressure vessel steel was investigated using instrumented Charpy impact experiments combining with magnetic emission measurement at different temperatures. Pre-cracked Charpy-V specimens and half-size miniature Charpy specimens of 15H2MFA steel, with and without side-groove have been used in the experiments. The critical value of the dynamic stress intensity factor (K_{Id}) have been determined using different methods depending on the type of the fracture. In the lower shelf region the impact response curve method was applied. In the case of higher impact velocities due to the strong oscillation of the force signals, the magnetic emission signals had to be used for determining the time-to-fracture. In the transition region - when brittle crack initiation was occurred after significant plastic deformation – the K_{Id} was determined on the basis of the J_{id} value at initiation. In the upper shelf region K_{Id} was calculated from the J_{md} value belonging to the maximum force. The comparison of the transition behaviour of the different specimen types showed that the side-grooving could increase the constraint and shifts the transition curves toward higher temperatures with 7÷10 °C. The transition temperatures of the half-size miniature specimens were lower with 29÷32 °C than of the standard pre-cracked Charpy specimens.

INTRODUCTION

Due to the limited availability of archive material of nuclear reactor, evaluating the residual life of service exposed nuclear plant components requires the assessment of the mechanical properties using small sample material. Usually pre-cracked Charpy specimens are used for fracture mechanics testing, but research has been done on the applicability of miniaturised Charpy specimens as well [1,2]. The aim of our work was to study the effect of specimen size and geometry on the dynamic fracture properties of the 15H2MFA pressure vessel steel.

EXPERIMENTS

Instrumented Charpy impact experiments have been performed on pre-cracked Charpy-V specimens and half-size miniature Charpy specimens of 15H2MFA steel, with and without side-groove. The chemical composition and the mechanical properties of the investigated steel can be seen in Table 1. The side-groove was 10% of the specimen width on both sides. The specimen dimensions are summarised in Table 2.

TABLE 1

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF 15H2MFA STEEL

C, %	Si, %	Si, %	P, %	S, %	Cr, %	Mo, %	V, %
0.18	0.45	0.33	0.01	0.01	2.85	0.64	0.25

Yield stress, MPa	Ultimate tensile strength, MPa	Elongation, %
444	593	21

TABLE 2

SPECIMEN GEOMETRIES AND DIMENSIONS

Dimension	Full-size	Half-size
Length, mm	55	27.5
Width, B, mm	10	5
Height, W, mm	10	5
Notch depth, mm	2	1
Depth of side-groove, mm	1	0.5
Net specimen thickness, B_n, mm	8	4
Relative crack length, a_0/W	0.43-0.55	0.38-0.55

The impact experiments were performed on a 300 J and a 25 J instrumented impact pendulums. The bigger pendulum was additionally instrumented with magnetic emission probe [3, 4]. The force (F) and the magnetic emission (ME) signals have been registered during the experiments. In the case of Charpy specimens two different impact velocities were applied: v_0=2.55 m/s and v_0=5.5 m/s. In the case of miniature specimens the impact velocity was 3.7 m/s. The impact experiments were performed in the temperature range from –60 °C to 100 °C. The pre-cooling of the specimens were done in liquid medium.

EVALUATION METHODS AND RESULTS

The critical values of dynamic stress intensity factor (K_{Id}) have been determined using different methods depending on the type of the fracture. In the *upper shelf region* the critical value of J integral was calculated from the energy absorbed up to the maximum load (U_m) with Eqn. 1 [5]:

$$J_{md} = \frac{2 \cdot U_m}{B_n \cdot \left(W - a_0\right)} \tag{1}$$

where U_m was calculated by integrating the force-displacement (F-f) curve using Eqn. 2:

$$U_m = \int_{f=0}^{f_m} F(f)\,df \tag{2}$$

Then the relevant K_{Id} value can be determined for plain stress condition using Eqn. 3:

$$K_{Id} = \sqrt{E \cdot J_{md}} \tag{3}$$

where E=210000 MPa was considered as the Young modulus of the investigated steel.

In the *transition region,* if brittle crack initiation occurred after significant plastic deformation, the critical J integral and K values at crack initiation was determined using Eqn. 1-3. One example for this fracture behaviour is shown in Fig. 1.

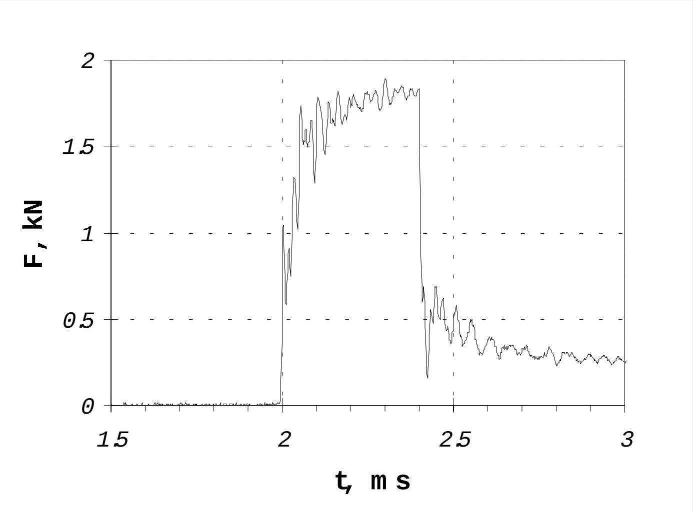

Figure 1: Force-time record of a pre-cracked half-size Charpy specimen (T= -20°C, v_0=3.7 m/s)

In the *lower shelf region* and in some cases in the transition region brittle crack initiation occurred preceding by no any macroscopic plastic deformation (Fig. 2 and Fig. 3) In these cases the „3τ" criteria - proposed by Ireland [6] - was usually not fulfilled therefore the quasi-static evaluation methods cannot be used any more for determining K_{Id}. In these cases the impact response curve method - proposed by Kalthoff [7] - was applied when the time-to-fracture (t_F) is to be determined. In the case of lower impact velocities (2.55 m/s and 3.7 m/s) the instant of brittle crack initiation could be determined directly from the force signals, since unstable crack propagation is indicated by a force drop (Fig. 2 and Fig. 3). But in the case of higher impact velocity (5.5 m/s) due to the strong oscillation of the force signals, it was impossible to determine the instant of the brittle fracture from the force-time curves when brittle crack initiation occurred. In these cases the magnetic emission signals were used for determining t_F using the observation that the rapid crack jump usually is accompanied by a sharp peak of the magnetic signal (see in Fig. 4). As it can be seen in Fig. 4, at very low temperature the completely brittle fracture occurred during the inertia peak, and the force based analyses was impossible. Even the sudden change in the magnetic signal due to the rapid crack jump was overlapped by the mechanically induced Barkhausen noice [4].

With the measured time-to-fracture the dynamic fracture toughness can be determined with Eqn. 4:

$$K_{Id} = R \cdot v_0 \cdot t'' \qquad (4)$$

where t''= f(t') is given in tables of reference [7]

and

$$t' = g(t) = t_F \cdot \left\{ 1 - 0.62\left(\frac{a_0}{W} - 0.5\right) + 4.8\left(\frac{a_0}{W} - 0.5\right)^2 \right\} \qquad (5)$$

where R=301 GN/$m^{5/2}$ for a machine with c_M=8.1x10^{-9} m/N machine compliance. If the machine compliance differs from this value, a first-order correction factor should be used in calculating R that is: 1.276/(1+0.276c_M/8.1x10^{-9} m/N). The machine compliance were c_M=2.335x10^{-8} m/N for the bigger pendulum, and c_M=3.3 x10^{-8} m/N for the smaller one.

The evaluated results are summarised in Fig. 5-9. As it can be seen in Fig. 5 the impact velocity does not have any significant effect on the position of the transition range. But large scatter of the fracture behaviour and of the fracture toughness values was obtained in the transition region, between 0 °C and 60 °C. Thus

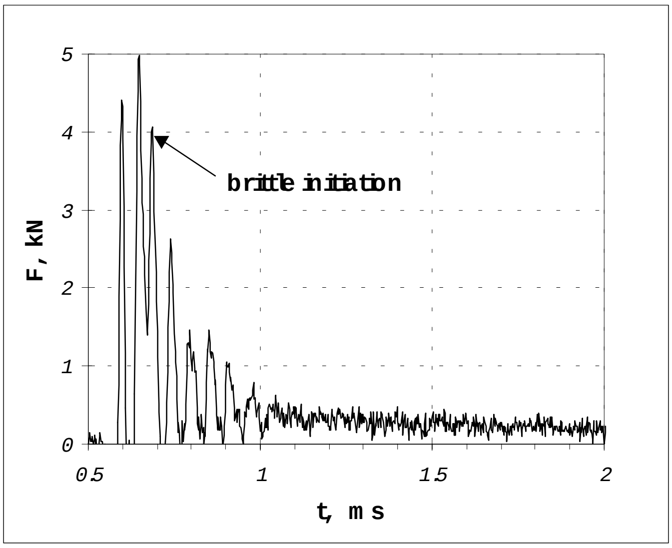

Figure 2: Force-time record of a pre-cracked Charpy specimen (T= -60°C, v_0=2.55 m/s)

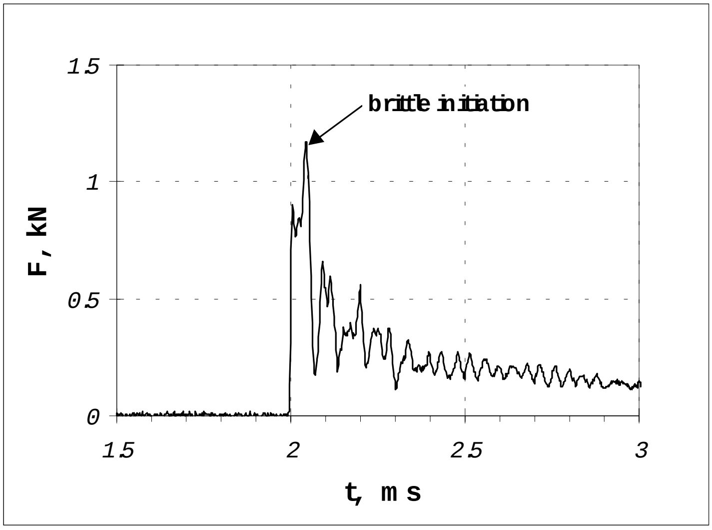

Figure 3: Force-time record of a half-size pre-cracked side-grooved Charpy specimen (T= -20°C, v_0=3.7 m/s)

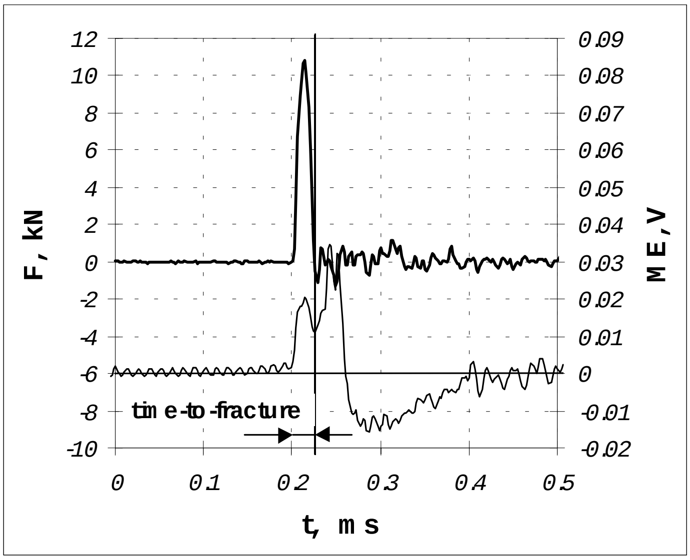

Figure 4: Force and magnetic emission signals of a pre-cracked side-grooved Charpy specimen (T= -20°C, v_0=5.5 m/s)

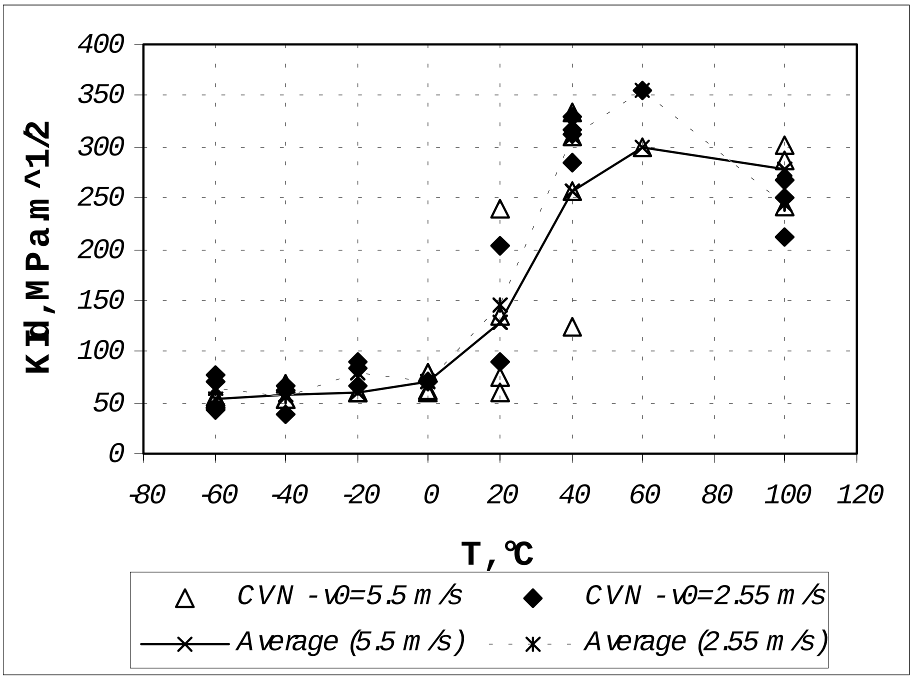

Figure 5: Dynamic fracture toughness values of full-size Charpy specimens (CVN)

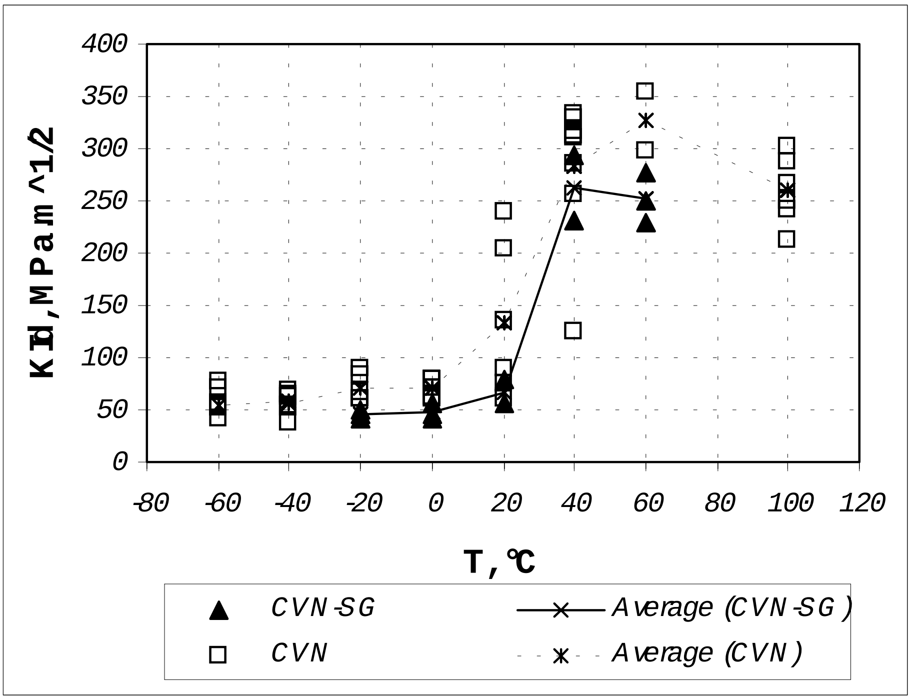

Figure 6: Dynamic fracture toughness values of full-size Charpy specimens (CVN) and side-grooved Charpy specimens (CVN-SG); v_0=5.5 m/s

for more accurate determination of the transition temperature would require testing of larger number of specimens in this region.

Fig. 6 and 7 show that the side-grooving shifted the transition curves toward higher temperatures in the case of both full-size and half-size specimens. For the half-size specimens same large scatter can be seen in the transition region. Comparing the results of full-size and half-size specimens it can be seen, that half-size specimens had significantly smaller transition temperature (Fig. 8 and 9). There is no significant difference between the lower shelf values of the fracture toughness of the full-size and half-size specimens, but the validity condition (size criteria) cannot be fulfilled for K_{Id}. The upper shelf values of the dynamic fracture toughness for the miniature specimens are smaller than of the full-size ones.

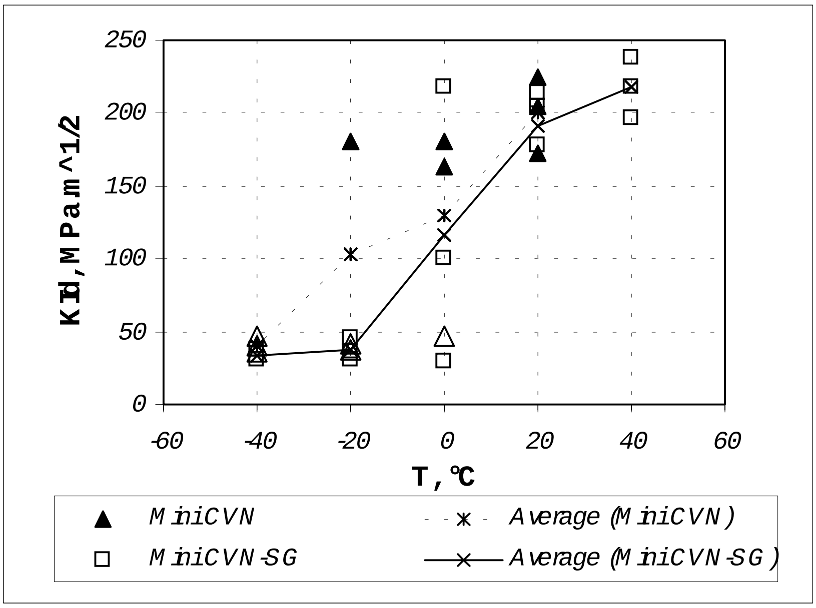

Figure 7: Dynamic fracture toughness values of half-size Charpy specimens (Mini CVN) and half-size side-grooved Charpy specimens (Mini CVN-SG); v_0=3.7 m/s

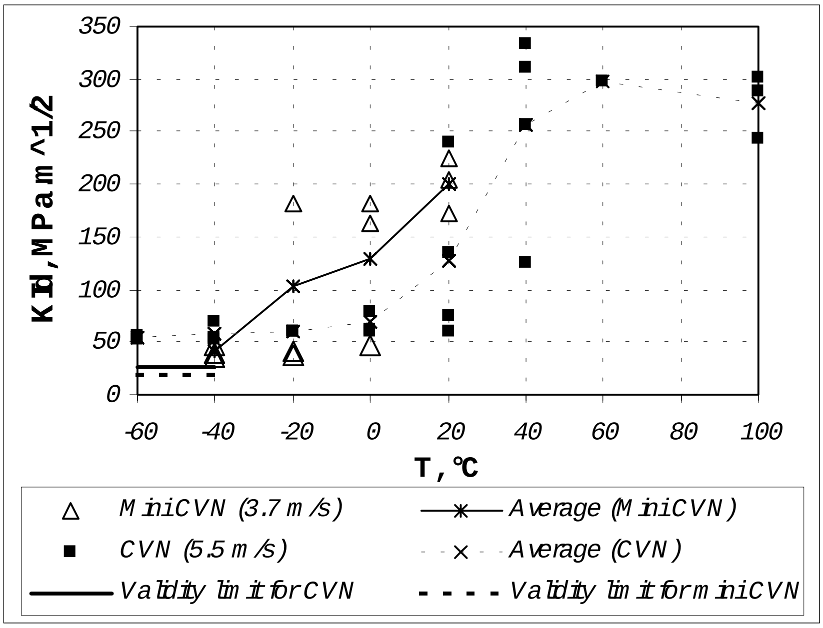

Figure 8: Dynamic fracture toughness values of full-size (CVN) and half-size (Mini CVN) Charpy specimens

For characterising the brittle to ductile transition behaviour of the material the following mathematical function was used to fit the experimental data:

$$K_{Id} = A_0 + A_1 \cdot \tanh[\frac{1}{A_2} \cdot (T - A_3)] \tag{6}$$

where A_0, A_1, A_2, A_3 are empirical constants. One example for the result of fitting procedure can be seen in Fig. 10. The temperature at a fracture toughness level of 100 MPa√m is often used for characterising the brittle-ductile transition region of ferritic steels. The transition temperatures (TT) based on this interpretation evaluated with Eqn. 6 are summarised in Table 3.

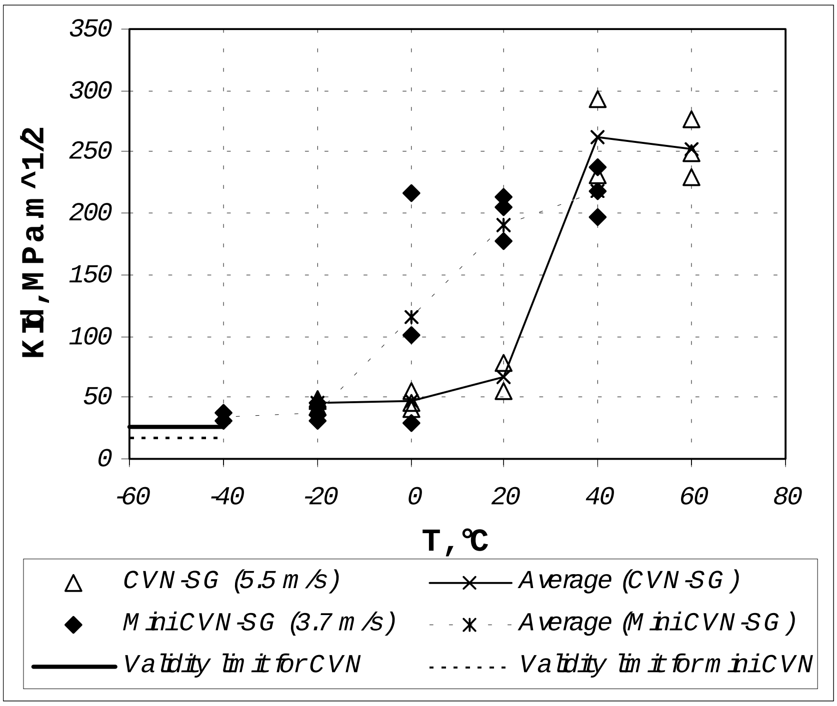

Figure 9: Dynamic fracture toughness values of full-size (CVN) and half-size (Mini CVN) side-grooved Charpy specimens

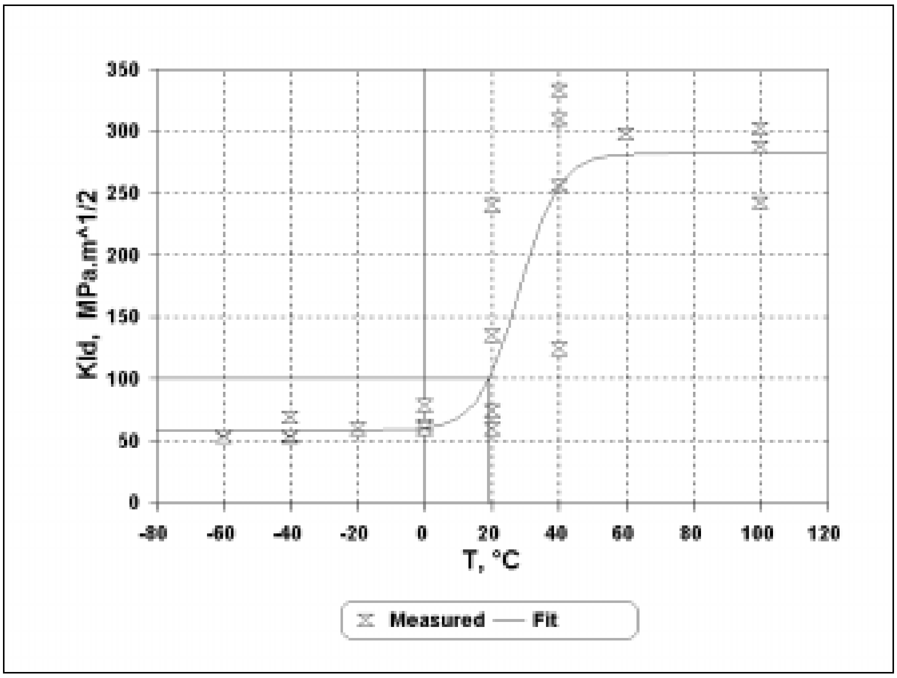

Figure 10: Dynamic fracture toughness vs. temperature for full-size pre-cracked Charpy specimens (v_0=5.5 m/s)

SUMMARY AND CONCLUSIONS

Instrumented impact experiments have been performed on different types of specimens of 15H2MFA steel material: full-size and half-size pre-cracked Charpy specimens with and without side-grooving. Dynamic fracture toughness values have been determined. From the results the following can be concluded:

TABLE 3

PARAMETERS OF THE FITTING FUNCTION AND TRANSITION TEMPERATURES AT K=100 MPA√M

Specimen type	A_0	A_1	A_2	A_3	Transition temperature, °C
Full-size pre-cracked Charpy (5.5 m/s)	170.5	112	11.85	28	19.1
Full-size pre-cracked side-grooved Charpy (5.5 m/s)	156	102.7	5.47	30	26.2
Half-size pre-cracked Charpy (3.7 m/s)	138.9	119.6	38.55	0	-13.1
Half-size pre-cracked side-grooved Charpy (3.7 m/s)	123.8	96.6	17.16	1.6	-2.8

1. The loading rate in the order of 1 m/s has no significant effect on the brittle to ductile fracture transition behaviour of the investigated 15H2MFA reactor pressure vessel steel.
2. In the case of higher impact velocities the magnetic emission signal can be applied for measuring the time-to-fracture when completely brittle fracture occurs.
3. The comparison of the transition behaviour of the different specimen types showed that the side-grooving shifts the transition curves toward higher temperatures with 7÷10 °C.
4. The transition temperatures of the half-size miniature specimens were lower with 29÷32 °C than of the standard pre-cracked Charpy specimens.
5. There is no significant difference between the lower shelf values of the fracture toughness of the full-size and half-size specimens, but the validity condition (size criteria) cannot be fulfilled for K_{Id}. The upper shelf values of the dynamic fracture toughness for the miniature specimens are smaller than of the full-size ones.

ACKNOWLEDGEMENT

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REFERENCES

1. Lucon, E (1996) *Evaluation Material Properties by Dynamic Testing*, ESIS Publication 20, pp.149-164.
2. Manahan, M. P., Stonesifer, R. B. (1996) *Evaluating Material Properties by Dynamic Testing*, ESIS Publication 20, pp. 125-148.
3. Winkler, S. R.(1989) In: *ASTM STP 1074*, pp. 178-192.
4. Lenkey, Gy. B., Winkler, S. (1997) *F. and F. of Eng. Mat. and S.* **20**., No. 2., 1997, pp. 143-150.
5. Blumenauer, H., Push, G. (1982) *Technische Bruchmechanik*, Deutscher Verlag für Grundstoffindustrie, Leipzig
6. Ireland, D. R. (1976) *Proceeding of the Int. Conf. On Dynamic Fracture Toughness*, London, pp. 47-57.
7. Kalthoff , J. F. (1995) In: *ASM Handbook, Volume 8*, ASM, pp. 269-271.