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Comparative Analysis of Defect Assessment Methods Using Fracture Toughness from Small Charpy-V Specimens

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ABSTRACT

Fracture toughness determination shall be performed by standard test methods using specimens with valid geometry. Frequently, required specimen size can not be obtained the material thickness to be characterize so in this case is possible to obtain fracture parameters from small specimens fracture mechanics techniques or it using indirect methods from Charpy – V impact energy obtained by means of standard or subsize V-notch specimens.

This paper presents a comparative evaluation between fracture defect assessment methods applied to pressure vessel where the material fracture mechanics parameter has been obtained either Charpy standard specimens or small ones. The results are evaluated with actual values of pressure vessel fracture failures induced by pressurized cycle tests .The analysis verifies an acceptable agreement in terms of engineering determinations.

INTRODUCTION

The structural integrity assessment of nuclear reactor pressure vessels, conventional pressure vessels, pipe lines and associate systems might be evaluated according to fracture mechanics methods such as CEGB R6, BSI 6493,WES 2805 and ASME XI.This methods are based on deterministic approach where the fracture toughness parameter is an essential input value to structural integrity or fitness for purpose flaw evaluation.

The fracture toughness parameters are obtained by means of standard test methods using specimens with a recommended or valid geometry. Frecuently, specimen size requirements can not be obtained from the material to be characterized due to the actual thickness of the pressure retaining component is thiner than the minimum required one by the standard fracture toughness test methods. Examples of these cases can be pointed out when archive material is not available or small samples corresponding to reactor pressure vessels survillance programs should be tested. Furthermore, the modern TM and HSLA steels, applied to pressure components, allow selecting thin plates less than 10 mm in thickness, which are under standard specimen size criteria.

Therefore it is possible to obtain the fracture toughness parameters, in terms of J, CTOD, or Kc values, such from small specimens fracture mechanics techniques as it may be using indirect methods from Charpy-V impact energy. The last one may be carried out by means either standard or subsize V notch specimens.

This paper presents a comparative evaluation between fracture defect assessment methods applied to pressure vessel where the material fracture toughness parameter has been estimated from Charpy-V impact energy tests which ones have been conducted using standard specimens and subsize ones. The results of this comparative work are evaluated with actual values of pressure vessel fracture failure induced by pressurized cycle tests.

MATERIAL AND METHOD

In order to make a comparative evaluation three kind of steels were used. One type corresponds to well known hot rolled fine grain C-Mn steel widely applied on pressure retaining components (Steel A) which chemical and mechanical properties are showed in Tables 1 and 2.The other ones are AISI 1045 and API 5L X60 respectively.

Table 1: Chemical Properties of Steel A.

Element	%
C	0.34
Si	-----
Mn	1.47
P	0.019
S	0.012

Table 2: Mechanical Properties of Steel A.

Yield Stress	Tensile Strength
{MPa}	{MPa}
624	721

Charpy-V impact tests to several temperatures have been made according to standard specification ASTM E23 in order to obtain the ductile to brittle transition curve.Charpy –V tests were made with three size of specimen thickness:standard B= 10mm(B=1T),B= 5mm(B=1/2T) and B=7.5mm(B=3/4T).

The fracture toughness values,in terms of K_{IC} or K_C, have been determined by indirect methods from the results of Charpy-V impact tests using Eq.1 ASME/PVRC[3,4],Eq.2 BSI PD6493[3,5] and Eq.3,Barsom[3].

$$K_{IR}=1.333 \exp(0.0261(T-RT_{NDT} + 88.9)) + 29.18 \qquad \{MPa\sqrt{m}\} \qquad (1)$$

Where:
RT_{NDT}= Neil ductility transition temperature in °C according to ASME.

$$K_{IC}=1.333 \exp(0.0261(T- T(40J) + 88.9)) + 29.18 \qquad \{MPa\sqrt{m}\} \qquad (2)$$

Where:
T(40J)= transition temperature in °C at 40J Charpy-V impact energy.

$$K_{IC}= 45.1 (C_V^{1.5}) \qquad \{MPa\sqrt{m}\} \qquad (3)$$

Where:
C_V= impact energy (J).

For subsized Charpy-V(B=1/2T and 3/4T) a transition temperature correction suggested by Wallin[6] was used and which is expressed as Eq.4.

$$\Delta T=51.4 \ln(2 (B/10)^{0.25}-1) \qquad \{^{\circ}C\} \qquad (4)$$

Where:
B=thickness in mm.

The fracture mechanics defect assessment has been evaluated taken into consideration a circumferential crack, which was detected and measured on pressure vessel, undergoes to pressurized cycle testing, an schema of the evaluated case is showed in Figure 1.

For defect assessment two criteria were applied, one of them correspond to limit load analysis according to relationships given by Chell and Kastner[7] so the other one is the well known CEGB R6 method (Option 1 – Category 1)[8] ongoing the fracture toughness input from the value calculated by indirect method according to BSI[3].

RESULTS

In Figure 2 a complete scatter band of Charpy-V impact energies are showed. These values belong to steels A, AISI 1045 and API 5L X60 tested with specimens B= 1T, 1/2T and 3/4T.

The Table 3 shows the fracture toughness values obtained from indirect methods and transition temperatures determined according to Wallin, ASME and BSI.

Figure 3 shows the results of defect assessment calculated by limit load and R6 method while in Figure 4 a validation of fracture assessment analysis on R6 method is showed such to Kc from small specimens as from standard ones.

Table 3: Fracture Toughness Values from Indirect Method, and Transition Temperature Values.

Material	K_{IR}	$K_{IC\,BSI}$	K_{ICB}	$To_{35J/cm2}$	T_{CV68J}	To_{40J}
	{MPa√m} (20° C)			{°C}		
Steel A 1/2T	111	139	107	-77	-49	-60
1045 1/2T	---	39	212	16	---	32
1045 1T	---	34	68	40	---	61
Steel A 1/2T(To+ΔT)	---	95	---	---	---	---
1045 1/2T(To+ΔT)	---	35	---	---	---	---
X60 1/2T	128	---	---	---	-56	---
X60 3/4T	179	---	---	---	-72	---
X60 1T	195	---	---	---	-76	---
X60 1/2T(To+ΔT)	195	---	---	---	-76	---
X60 3/4T(To+ΔT)	208	---	---	---	-79	---

DISCUSSION AND CONCLUSIONS

The results of fracture toughness parameters, in terms of Kc, such as it is showed in Table 3 allows to observe that those Kc values calculated from Cv energy corresponding to subsized Specimens (B=1/2T and 3/4T) are lowers than ones obtained from standard 1T specimens.

The response of this behavior can be explained by differences in constraint between small and large specimen thickness. In this sense Eq.4 allows to correct toughness parameters from small Charpy-V specimens through an increasing of the transition temperature, defined as the temperature corresponding to the 28 J of impact energy or its equivalent of 35J/cm^2 ($To_{35J/cm2}$). Therefore, for steel A Eq.4 gives a correction of 20 °C ($\Delta_{Calculated}$) at temperature $To_{35J/cm2}$, Table 3.Following this methodology it is evaluated the applicability of Wallin's correction to transition temperatures values defined according to ASME and BSI PD6493 such is showed in Table 3.The differences between $To_{35J/cm2}$ and $To_{40J/cm2}$ for AISI 1045 transition curves obtained with specimens B=1T and 1/2T are respectively 24°C and 29°C.Therefore a first conclusion would be indicating that Eq.4 correction shows a higher difference with the measured ΔT for impact energy level closer to upper shelf of the transition curve. On the other hand for X60 steel the transition temperatures T_{CV68J} values corresponding to B=1/2T and 3/4T, that were corrected by Eq.4, show a good agreement with the 1T transition temperature value, considering the same impact energy level at material transition curve. According to these results the correction in transition temperature for subsized Charpy-V specimens by means of Eq.4 could be applied on transition temperatures obtained by ASME or BSI PD6493.

The scatter band of impact energy values for specimens 1T,1/2T and 3/4T corresponding to all evaluated steels, Figure 2, shows a span reduction on the temperature range of the lower shelf of transition curve. Therefore, the Kc parameters using indirect methods could directly be determined from small specimens for lower shelf temperature range.

Table 3 shows that K_{IC} value obtained from indirect method for steel A ,using Charpy-V specimens B=1/2T, given by Eq.3 is more conservative than the ones calculated according to ASME, Eq.1 and BSI, Eq. 2.On the same form K_{IC} value obtained according to BSI with its transition temperature corrected by Eq. 4 it has the same magnitude of the one obtained by Eq.3.The same correction of transition temperature according BSI applied to 1045 steel for B=1/2T specimens allows to obtain a K_{IC} value that is very close to the one calculated for B=1T specimens.

The fracture toughness defect assessment, Figure 3, shows a good agreement between limit load analysis and CEGB R6 ,taken into consideration that in the last one the fracture toughness input has been calculated by BSI indirect method (Eq.2) with transition temperature corrected by Eq.4 (Table 3). In the curves of Figure 3 an acceptable safety margin it can be observed respect of the point that indicates the actual defect size (such as it is described in Figure 1) on failure condition of pressurized component. Therefore, it is possible to obtain an acceptable result in defect assessment, for engineering purpose, using fracture toughness value obtained by indirect method from Charpy-V test using small subsized specimens.

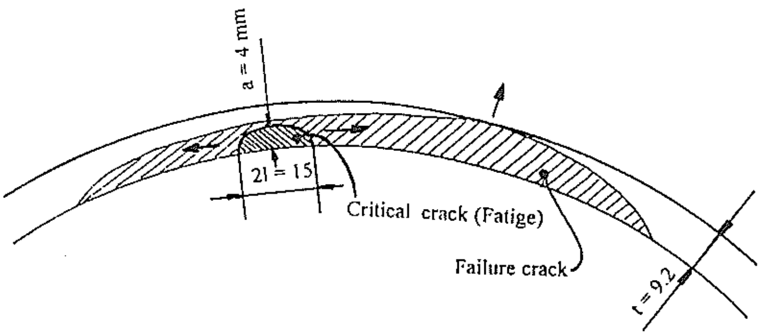

Figure 1: Actual Defect Geometry on Failure Condition of Pressurized Component.

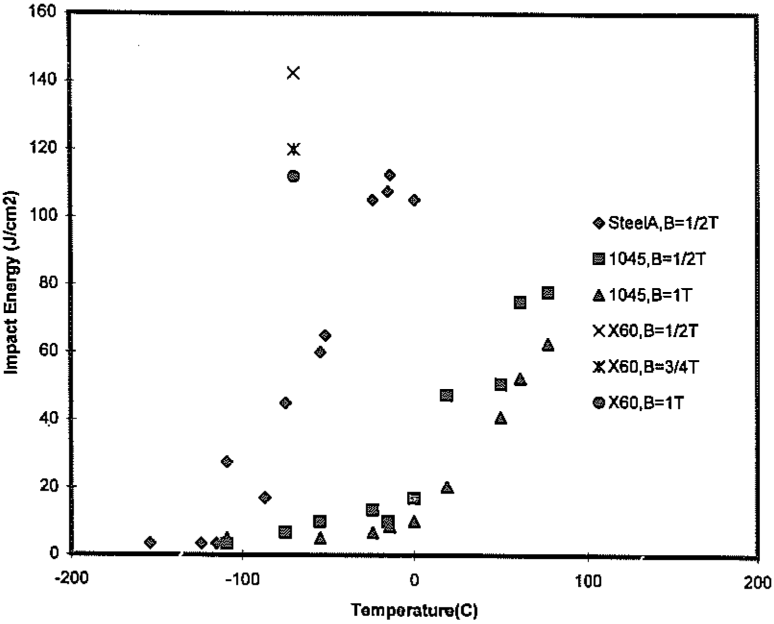

Figure 2: Charpy - V Impact Test Results for Steel Materials Evaluated.

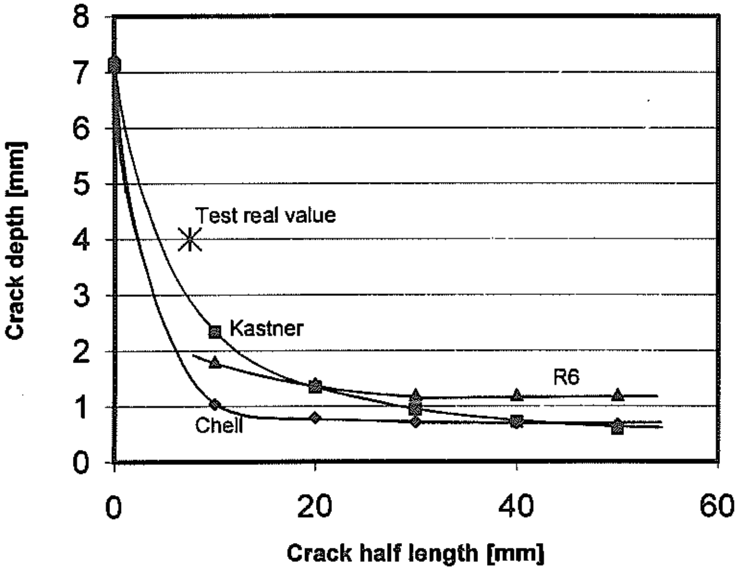

Figure 3: R6 and Limit Load Structural Integrity Assessment for Pressure Component of Steel A under Pressurized Test.

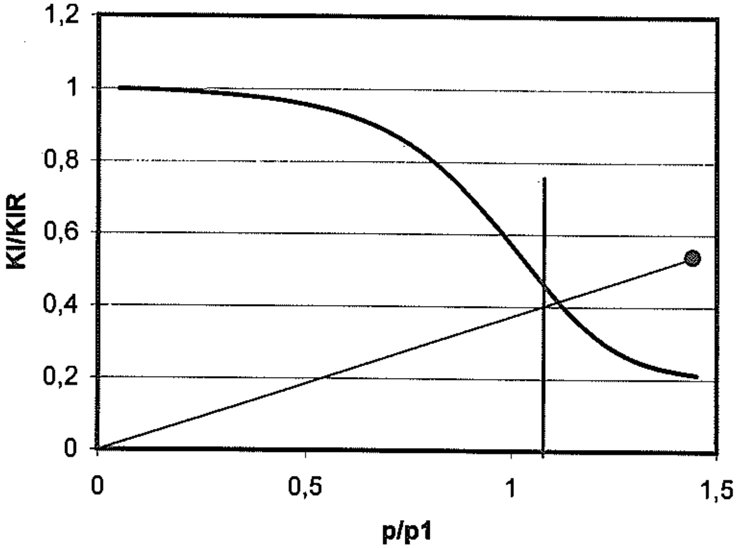

Figure 4: Validation of the Defect Assessment Using R6 Method.

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The Fracture Behaviour of the Cast Steel and Its Prediction Using the Local Approach

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ABSTRACT: The master curve (MC) concept has been used for assessment of the fracture toughness transition behaviour of C-Mn cast steel intended for fabrication of large container for spent nuclear fuel (ŠKODA). Standard fracture toughness tests using bend specimen with various crack lengths, the static tests of the CVN specimens and the axisymmetric notched tensile specimens have been effected. The transferability of results received on the small pre-cracked Charpy specimens is tested here and the methodology MC is applied. For determining the reference transition temperature, T_0, which is taken as a basic material characteristic positioning the MC on the temperature axis, the large (1T) specimen is required. Additionally, the small pre-cracked Charpy type specimens have been used for determining the fracture transition behaviour and for measurement of fracture toughness.

1. INTRODUCTION

Transport and storage containers for spent nuclear fuel have to ensure the safe enclosure of a radioactive material and must meet stringent requirements on safety. They must ensure the storage of radioactive material safely for expected container lifetime and also in the case of the most severe accident loading and earthquake shock. The container should be highly resistant to temperature and radiation embrittlement. Škoda Nuclear Machinery (Czech Republic) has introduced new design of a container for spent nuclear fuel. The cask design is based on thick walled pipe with bolted lids, both fabricated from cast low alloyed steel with ferritic microstructure (see at Fig. 1).

The knowledge, assessment method of fracture mechanics has increased to point where certain structural materials until now not considered for radioactive transport cask constructions are being proposed for these applications. For the safe enclosure of the radioactive material during transportation it must be shown that the extension of non-detected crack after fabrication will not occur. For the safe storage additional embrittling effects should be taken into account. Brittle fracture can occur under specific combination of temperature, mechanical and environmental loading conditions. When assessing if the material satisfies the demand on container resistance against catastrophic failure the following key problems have to be addressed from the fracture mechanical point of view: (i) the transferability of fracture toughness data measured on laboratory specimens to the component of much larger thickness. And (ii) the prediction with a good probability of brittle fracture in case of the most severe accident loading and in case of radiation embrittlement.

2. METHODOLOGY

The methodology of master curve (MC) [1] is currently widely used for transition behaviour evaluation of fracture toughness. The verification of this concept has been performed for steel of pressure vessel and weldments [2-7]. For determining the reference transition temperature, T_0, which is taken as a basic material characteristics localising the MC on the temperature axis, the large (1T) specimens are required. But there are structures (plants) under operation for which the transition behaviour of fracture toughness is of great interest (reactor pressure vessels, rotors etc.) and application of MC concept would be very useful here. For these components only small specimens (Charpy V-notch) can be used for assessment of degradation, however. The effort is now concentrated on application of pre-cracked small specimens for these purposes [8]. Some works, mainly of Wallin [7,9], have shown that the small pre-cracked specimens can be used in determining reference temperature, T_0, and thereby making possible to apply MC concept for the integrity assessment procedure of these components.

Small pre-cracked specimens and 1T SENB specimens were used to measure fracture toughness over wide temperature range. Using the results obtained the reference transition temperatures, T_0, were determined for both types of specimens and compared each other. Having the T_0, the MC may be drawn. Its validity for the cast steel has been discussed. Additionally, the prediction of the fracture toughness scatter of large (1T) specimens through those ones small pre-cracked using Weibull stress concept has been also performed.

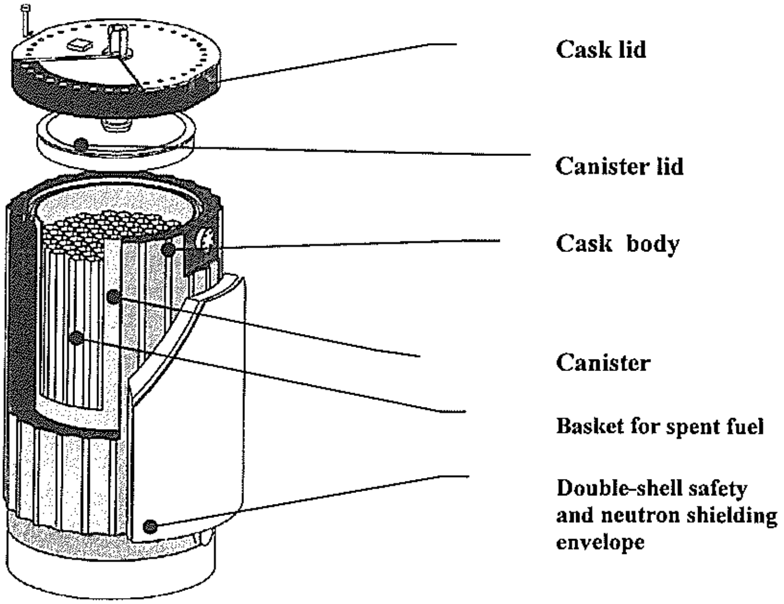

Figure 1: Transport and storage cask
ŠKODA 440/84

3. MATERIAL, EXPERIMENTAL AND CALCULATIONS PROCEDURES

3.1 Material Characterization

Manganese cast steel has been utilised for experiments having chemical composition in wt %: 0.09C, 1.18Mn, 0.37Si, 0.01P, 0.025S, 0.12Cr, 0.29Ni, 0.29Cu, 0.03Mo, 0.028Al. True stress-strain curves have been measured using cylindrical specimens with diameter of 6 mm being loaded over temperature range –196°C to -60°C at cross-head speed of 2 $mm.min^{-1}$. Standard FEA – ABAQUS 5.7 was used to model elastoplastic behaviour for tensile notched specimens.

Fracture toughness data were measured using standard 25 mm thick specimen with a/W ratio of 0.5 loaded in the 3-point bending. Small pre-cracked Charpy type specimens have been also tested in the same temperature range. For one selected temperature in lower shelf region (below temperature t_{GY} at which F_{FR} and F_{GY} coincides on their temperature dependencies) a range of round tensile-notched bars were tested to obtain data for statistical local approach procedure treatment.

Accepting the Beremin approach [10] to the analysis of local criteria for cleavage fracture the location σ_u and shape parameters m were calculated using FEM for notched tensile bars having various type of notch geometry. The first one was the tensile specimen with the same circumferential notch as for Charpy (CVN), the other three types were U-notch geometry with radii 1;0.7;0.2 mm. Statistics were made at least for 20 replicated experiments in all cases. The influence of geometry is presented in the Table 1. Prediction was calculated for standard cell size and for notch geometry that is the most close to the crack. Different size of process zone has small influence on computed local parameters. Values used for the MC are: $m = 56$ ($V_o = (100.e\text{-}6)^3\ m^3$) see Tab.1 (the best fit).

Geometry	$V_o = (100e\text{-}6)^3\ m^3$
	$\sigma_{th} = 500$ MPa
V r=0.25 mm	σ_u=1409, m= 45.4
U r=1.00 mm	σ_u=2102, m= 18.6
U r=0.70 mm	σ_u=2486, m= 17.0
U r=0.20 mm	σ_u=1350, m= 56.0

Table1: Local parameters received for various geometry (the best fit).

3.2 Tensile Properties

The temperature dependence of common tensile characteristics is given in Fig. 2. As seen the cast steel examined exhibits relatively low values of lower and upper yield stress and with decreasing temperature these characteristics increase very slowly. (E.g. at –100 °C Re is equal to only 380 MPa). With respect to small pre-cracked specimen this fact resulted in the necessity to test small specimens at very low temperatures in order to fulfill the validity condition for valid determination of K_{Jc}.

The testing at very low temperature, far below the expected reference temperature T_0 determined by means of larger 1T specimens, can lead to uncertain determination of T_0 [3].

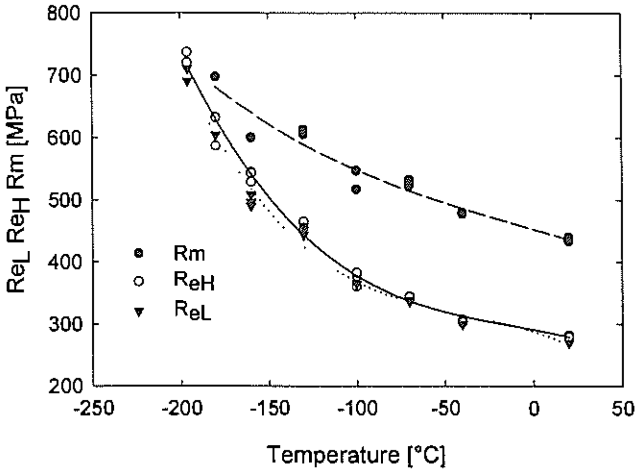

Figure 2: Tensile properties of the cast steel.

3.3 Fracture Behaviour of 1T SENB Specimens

On the basis of preliminary measurement of the fracture toughness using this type of specimen the temperature of –100 °C has been chosen for determining the reference temperature T_o. Six SENB specimens were used to measure the fracture toughness values at this temperature. The K_{Jc} results obtained are given in Fig. 3. This figure serves as a check whether the basic assumption included in ASTM Standard E1921 [1] for determining the reference temperature T_o, i.e. whether the cast steel obeys the three parametric Weibull distribution with the Weibull modulus m is equal to 4,

$$P_f = 1 - \exp[(K_I - K_{MIN})/(K_O - K_{MIN})]^m \qquad (1)$$

describing the fracture toughness scatter in transition region.

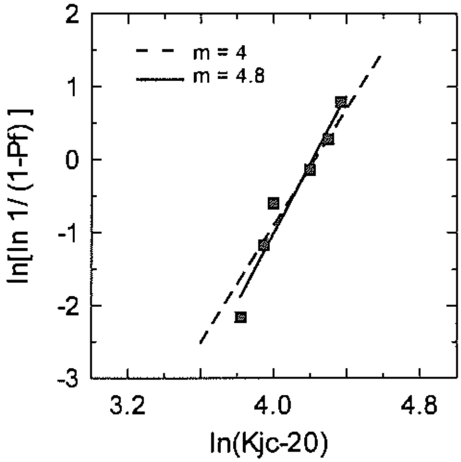

Figure 3: Scatter of fracture toughness data.

Therefore the dependence of ln[ln 1/(1-Pf)] versus ln ($K_{Jc} - K_{min}$) for six measured K_{Jc} values was plotted in Fig. 3. As seen, the obtained value of modulus m is equal to 4.8, which is little different from the value 4. To determine this dependence more preciously additional experiments are being in progress. However, in spite of small difference in m, for assessment of reference temperature T_0 the procedure given in the Standard E1921 was used for the present

$$K_O = [\sum_{i=1}^{N} (K_{Jc(i)} - K_{\min})/(r - 0.3068)]^{1/4} + K_{\min} \tag{2}$$

$K_{min} = 20$ MPam$^{1/2}$, one gets for K_o the value $K_o = 85.6$ MPam$^{1/2}$. $K_{Jc(med)}$ is given by:

$$K_{Jc(med)} = (K_o - K_{\min})[\ln(2)]^{1/4} + K_{\min} \tag{3}$$

After substituting K_o and K_{min} the value of $K_{Jc(med)}$ = 79.8 MPam$^{1/2}$. Finally, utilising the equation:

$$T_o = T - \frac{1}{0.019} \ln[\frac{K_{Jc(med)} - 30}{70}] \tag{4}$$

the reference temperature T_0 may be established to be T_o = -82 °C.
The master curve for C-Mn cast steel investigated is described by:

$$K_{Jc(med)} = 30 + 70 \exp[0.019(T + 82)] \tag{5}$$

Figure 4 shows the master curve together with the tolerance bounds 5% and 95%. In this diagram the measured fracture toughness values in temperature range –100 to – 40 °C are plotted. Full point represents data keeping the validity condition:

$$K_{Jc(LIMIT)} = [(Eb \, \mathrm{Re})/50]^{1/2}. \tag{6}$$

The value of constant in Eq.6 was taken to be 50 instead of 30 in Standard [1] based on work of Ruggieri et al [12] and the discussion in subcommittee of ASTM [11].

Some peculiarities of fracture behaviour of cast steel follow from the Fig. 4:

- Only for the fracture toughness values being below T_0 + 15 °C the master curve methodology may be used to predict the fracture toughness behaviour.
- At the temperature T_0 + 26 °C the sharp transition of fracture toughness too much higher values of K_{Jc} occurs. But it must be emphasised that for those specimens having these high values of K_{Jc}, the fracture was initiated by cleavage indicating that the C-Mn cast steel has large intrinsic resistance against ductile tearing.

3.4 Fracture Behaviour of Small Pre-cracked Charpy Specimen-PCVN

For PCVN specimens the temperature dependence of fracture toughness is given in Figure 5. The line representing the validity condition Eq. 6 is plotted in the graph. Only small number of fracture toughness data, especially the data at the temperature -100°C, that were intended for establishing T_0, fall below the line. Therefore data not meeting the K_{Jc}(limit) was firstly constraint adjusted, using Dodds and Anderson toughness scaling model [13, 14].

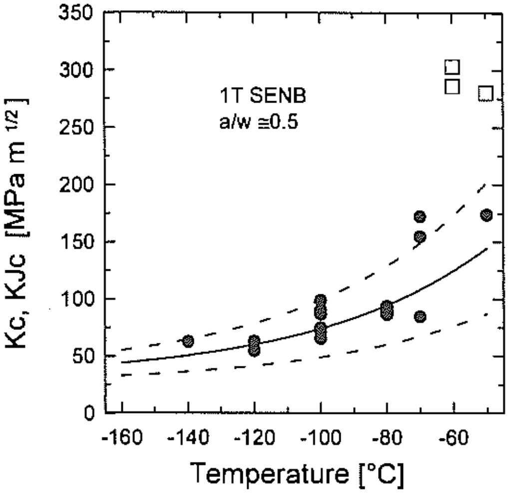

Figure 4: Fracture toughness temperature diagram for 1T specimen.

But only for data lying below the line labeled K_{Jc}(max)DA this concept may be used, as this line represents the end of FE-3D calculation of Dodds and Anderson model as performed by Nevalainen and Dodds [15]. All constraint adjusted and size corrected data using

$$K_{Jc(1T)} = 20 + (K_{Jc(10)} - 20)\left(\frac{B_{10}}{B_{1T}}\right)^{1/4} \qquad (7)$$

are plotted in Fig. 6 in which MC $K_{Jc(med)}$ and tolerance bounds for 5 and 95% are replotted. All fracture toughness data of small pre-cracked specimens processed in such a way fall inside the scatter band of larger 1T specimens, verifying so the potency of utilising small pre-cracked specimens for the fracture toughness evaluation in the transition region.

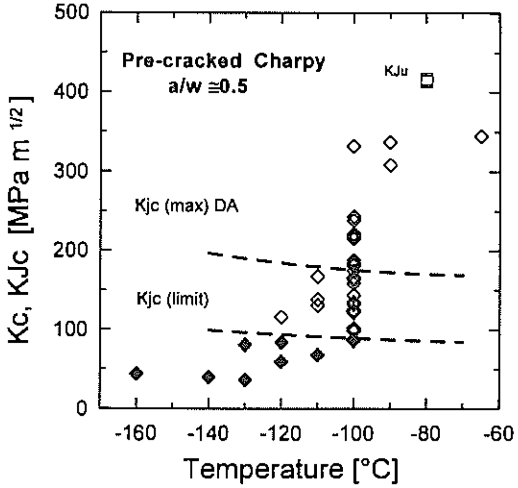

Figure 5: Fracture toughness data from pre-cracked specimens.

Additionally, the reference temperature T_0 was established. The set of twelve PCVN specimens was used, from which only two had valid K_{Jc} values (see Fig. 5) and were only size corrected. The others were constraint adjusted and size corrected. The data obtained are shown in Fig. 6. Following above-mentioned procedure the reference temperature T_0 was estimated to be –78.2°C, which is in good agreement with the value of T_0= -82°C established by means of larger 1T specimens.

It is to be noted, that the recommendation for testing the PCVN specimens for purpose of T_0 determination given in Standard E1921 is effectively impossible for cast steel examined. To obtain valid K_{Jc} data required for PCVN specimens the testing would have to be carried out at very low temperature (Fig.5), deep below the expected reference temperature T_0. This aspect could lead to the uncertainty in the estimation of T_0. The above procedure involving constraint adjustment seems to be very promising and should be verified with other steels.

Using data described in Tab.1, the local approach methodology applied by Koppenhoefer and Dodds in [16], was used to transfer values of K_{Jc} received on the Charpy pre-cracked specimens to 1T specimens. After determining the local parameters, as it is mentioned in the beginning of the paper, it is important to compute variation σ_w as a function of J integral for both types of specimens. Then from a given value of J integral in pre-cracked Charpy specimen it is necessary to find its corresponding σ_w. This value has to be transfered into the diagram for SSY specimen. The transformation diagram was computed and the data are plotted in Fig. 7. Having used the corrected data, calculating the average values $K_{Jc(mean)}$ and substituting into Eq.(4) one can get T_0= -90°C as was presented in [17].

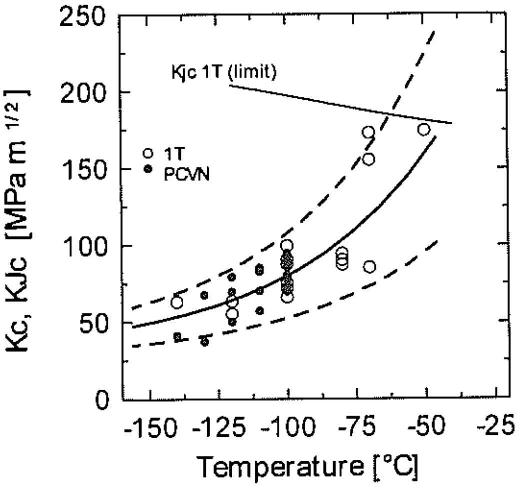

Figure 6: FTTD from 1T and corrected PCVN data

4. CONCLUSION

The main conclusions are as follow:

- Master curve concept has been shown to be valid in the lower transition range for C-Mn cast steel.
- Fracture toughness was measured using small pre-cracked Charpy specimens and results were constraint and size corrected to the 1T SENB specimens.

- Reference temperature T_0 determined using constraint adjusted and size corrected invalid PCVN data was little different from T_0 evaluated using 1T SENB specimens.

5. ACKNOWLEDGEMENTS

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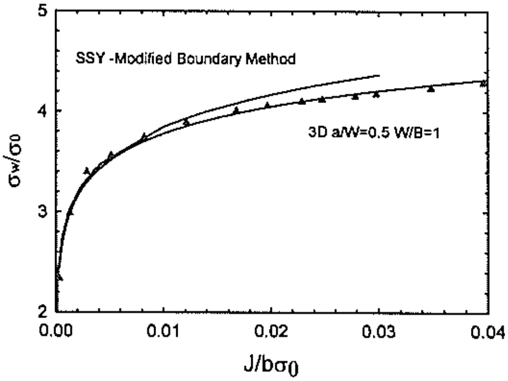

Figure 7: Relation between local σ_W and the global J parameters.

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