The Transferability of Brittle Fracture Toughness Characteristics

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ABSTRACT

In this paper, the use of the Weibull stress as a measure of the failure probability of cracked body is tested. The Weibull stress model for cleavage fracture of cast steel requires calibration of two micromechanics parameters (m, σ_u). Weibull stress seems to be a parameter for prediction of cleavage failure of cracked bodies and the study is focused on the assessment of the effects of constraint loss on cleavage fracture toughness (J_c). To quantify the effects of constraint variation on the cleavage fracture toughness the form of the toughness-scaling model based on the Weibull stress σ_w is investigated. Local material parameters have been calculated arising from Beremin approach and calibration is based on the Gao and Ruggieri approach. Method is based on weakest link assumption and incremental fracture probability, which depends not only on the maximum principal stress, but also on the equivalent plastic strain. Accepting this approach 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 types of geometry too. The aim of the paper can be seen in fracture toughness transfer and correction from pre-cracked specimens to small scale yielding (SSY) represented by 1T (SENB) specimens. The fracture resistance has been assessed using data from static tests of the bend specimens. The standard finite element method package Abaqus was applied and the manganese cast steel considered for storage and transport container for spent nuclear fuel (SKODA) was selected as an experimental material.

INTRODUCTION

The tendency for catastrophic fracture initiated by cleavage is key aspect for assessments of industry structures. 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 the 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 a new design of container for spent nuclear fuel. The cast design is based on thick walled pipe with bolted lids, both fabricated from cast low-alloyed steel with ferritic microstructure.

Crack-like defects that can be developed in such structures and therefore knowledge of its behaviour seems to be very important for the life prediction. For safe enclosure of the radioactive material during transportation it must be shown that the crack extension 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 small specimens to the component of much larger dimensions. 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.

CLEAVAGE FRACTURE AND WEIBULL STRESS

The transgranular cleavage fracture is a sequential process involving crack initiation and propagation. In most steels crack nucleation occurs at brittle grain boundary particles (e.g. carbides) due to stress concentration caused by the dislocation pile-ups at these particles. This explains the experimental fact that local plastic deformation always preceded cleavage fracture. The local approach for cleavage is based on the weakest link concept that postulates that failure of the body of a material containing a large number of statistically independent volumes is triggered by the failure of one of the reference volume [1]. Due to microstructural inhomogeity of material, volume-sampling effects play a important role to quantify the large scatter in the fracture toughness data. For initially sharp cracks, the probability sampling effects becomes tightly coupled with near-front constraint, which governs the volume of material subjected to stresses sufficiently large to initiate fracture. In Ref. [2], the reference volume V_o was identified as a material volume related to likelihood of finding cracked carbide. In a finite element analysis it is kept to be constant and to be computed Weibull stress independent of the finite element mesh used the size of the element in the plastic zone ahead the crack tip must be smaller that size of V_o. A connection between microcracking process, a continuum view of material and mathematical formulation follows by assuming a random distribution of microscale flaws. Carbide particles seem to be eligible for cleavage initiation for many ferritic steels.

In the local approach to cleavage fracture, the probability distribution (P_f) for the fracture stress of a cracked body at a global level K_J or J is assumed to follow a two-parameter Weibull distribution [1,2] in the form:

$$P_f(s_w) = 1 - \exp\left[-\left(\frac{s_w}{s_u}\right)^m\right]. \quad (1)$$

The stress integral over the fracture process zone is denoted σ_w and is termed the Weibull stress. This stress is defined by

$$s_w = \left[\frac{1}{V_0}\int s_1^m dV\right]^{1/m}, \quad (2)$$

where m is so-called Weibull slope, V_0 is a reference volume, the integral is computed over the plastic zone, and σ_1 is the first principal stress. The parameters σ_u and m of the Weibull stress σ_w at fracture are material parameters, i.e. independent of the stress state of materials, but may depend on the temperature.

The determination of two parameters m and σ_u has to be performed iteratively as σ_w depends on the parameter m. This can be done by the least square method or preferably by the maximum likelihood procedure, e.g. [2,3], σ_u can be determined by the following equation

$$s_u = \left(\frac{1}{N}\sum_{j=1}^{N}\left(s_w^{(j)}\right)^m\right)^{1/m}. \quad (3)$$

The most important problem is if is it possible to use this parameters received on the notched specimens directly to specimens with cracks. Recently published papers prefer to use calibration of Weibull stress using fracture toughness data (ed. [3]).

TOUGHNESS SCALING MODEL BASED ON WEIBULL STRESS

The application of the Charpy pre-cracked specimens indicates to be very useful for valuation of material degradation in the nuclear industry. The development of methodology for prediction of fracture behaviour of components and structures has great practical meaning. One can suppose the new European norms setting and standard procedures for valuation of integrity of construction.

The soundness of structures is usually ensured on the basis of several relatively well-accepted rules. These rules are supposed to be able to assess the integrity for complex engineering applications on the base of exact measurement in laboratory, evaluation of received data according to standards and their transferability to components and structures. The recent investment proved that e.g. the well-used characteristics as the fracture toughness couldn't be generally used to the arbitrary geometry of body. The new methods of experimental and theoretical fracture mechanics should provide the right rules to solve it. Based on this concept, some works from the seventies and eighties are trying to predict values of K_{IC} and relations between K_{IC} and absorbed energy CVN (e.g. [1]). Values developed by linear or elastic plastic fracture mechanics are used for assessment of defect tolerance from a global view. At present, the latest approaches can be characterized mostly by the knowledge of micromechanics and micromechanisms of failure. More recently the approach to the problems has been developed. This is the local approach that relies upon the fact that it is possible to model macroscopic fracture behaviour of defected components in terms of local fracture criteria. This statistical approach, the methodology of local material parameters measurement using notched tensile specimens and some prediction of brittle fracture behaviour prediction were worked out during solution of this problem. It is important to emphasize that local approach has wider spectrum of approaches than were incorporated in Beremin model and others.

The first one method of transferability of the fracture toughness was studied on the pre-cracked Charpy specimens and standard bodies (1T). The Dodds and Anderson [4] have proposed to quantify the relative effects of constraint variation on the cleavage fracture toughness in the form toughness-scaling model. They approached lost of constraint by postulating the material volume ahead of the crack front over which the principal stress exceeds a critical value as a local fracture criterion without respect for the J integral value. The first one studies can be found out in the same works, where as principal can be regarded: (i) the Dodds and Anderson approach, (ii) the Koppenhofer approach, (iii) the Minami and others [5, 6, 7].

(i) The method is based on the philosophy of diagram construction $J_o/b\sigma_o$ versus $J_{FE}/ b\sigma_o$, where b is body thickness and σ_o is yield stress. The principle is to transfer from tested geometry, where the elasto-plastic fracture toughness is measured, to small scale yielding state (SSY). Schematic outline can be seen at Fig. 1. (ii) The method demonstrates the dependence of Weibull stress σ_w on the crack-tip stress triaxility and the transfer diagram σ_w versus computed value of J_{FE} is being

constructed. The idea is to use to same value of probability of failure. In the beginning we have to determine the local parameters, m and σ_u, and compute σ_w of bodies of various geometry. (iii) This approach is modified Koppenhofer method and the construction $\ln(\ln(1/P_f)))$ versus σ_w is generated.

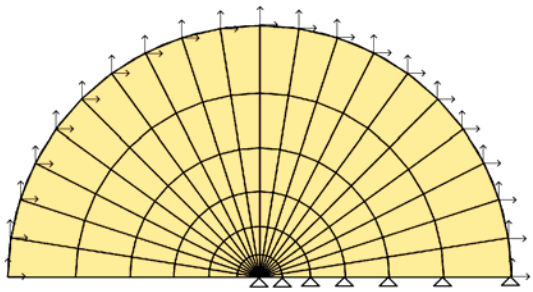

Figure 1. Schematic outline of modified boundary layer method.

EXPERIMENTS

Manganese cast steel has been utilised for experiments. Škoda Company has supplied the material as a component part produced for certification procedures of the container of nuclear spent fuel. To guarantee the microstructure of specimens used for the static test to be the same as that of an inner part of cast body the computer simulation of cooling of semi-product has been used. As the result of this modelling the optimised plate (size 55 x 90 x 250 mm) for fracture mechanics experiments was produced. From this plate three tested bodies were reduced (in size 50 x 25 x 240 mm). The size of semi-product was the compromise between the cooling rate needed for cooling simulation and furnace capacity. Figure 2 shows the typical microstructure.

True stress-strain curves have been measured using cylindrical specimens with a diameter of 6-mm tested over a temperature range of –196°C to -60°C at crosshead velocity of 2 $mm.min^{-1}$. Standard FEA package ABAQUS 5.8 was used to model elastoplastic behaviour.

Fracture toughness data were measured using a 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. Scanning electron microscopy was applied to investigate the fracture micromechanisms.

Figure 2. A micrograph showing carbide distribution in ferritic matrix.

True stress-strain curve at -100 ºC is presented in Fig. 3 and experimental database in shown the next Table 1. The material parameters received then make possible to use the J – Q stress field for the determination of the critical value of J

integral J_c versus Q parameter. This dependence J_c –Q, incorporating the probability of failure, is more precise than the result based on model of critical fracture stress [5].

Table 1. Database for 1T (SENB) and PCVN specimens (*the values can be used directly without TSM)

Rank	P_f N=24	P_f N=23	$J_{c\ 1T}$ [MPam]	$J_{ssy\ 10}$ 1T	PCVN a [mm]	J_Q [MPam]	$J_{ssy\ 10}$ PCVN
1	0,029	0,030	0,0229	0,035	5,3	0,0317	*
2	0,071	0,074	0,0235	0,036	5,1	0,0331	*
3	0,110	0,117	0,0235	0,0360	5,2	0,040	*
4	0,154	0,160	0,0234	0,0367	5,1	0,0446	*
5	0,196	0,20	0,0276	0,0426	5,2	0,0447	*
6	0,234	0,25	0,0293	0,0453	5,3	0,0479	0,0301
7	0,280	0,29	0,0310	0,0481	5,2	0,0645	0,0423
8	0,320	0,335	0,0319	0,0492	4,6	0,0677	0,0421
9	0,360	0,380	0,0325	0,0500	5	0,0677	0,0427
10	0,400	0,420	0,0335	0,052	4,8	0,0741	0,050
11	0,0446	0,465	0,0335	0,052	5,3	0,0764	0,0513
12	0,487	0,510	0,0357	0,0554	5	0,085	0,0564
13	0,530	0,550	0,0368	0,0570	4,9	0,0867	0,057
14	0,570	0,595	0,0399	0,0621	4,7	0,0892	0,0601
15	0,612	0,640	0,0404	0,0630	5,1	0,0907	0,0608
16	0,654	0,680	0,0432	0,0670	5,1	0,1089	0,0722
17	0,695	0,725	0,0442	0,0688	5,3	0,114	0,0746
18	0,740	0,770	0,0472	0,0736	5,3	0,116	0,0789
19	0,780	0,810	0,0488	0,0761	5,1	0,119	0,0798
20	0,820	0,856	0,0503	0,0785	5,3	0,128	0,0855
21	0,860	0,9	0,0550	0,0851	5,5	0,140	0,0881
22	0,900	0,940	0,0586	0,0916	5,2	0,142	0,0893
23	0,946	0,986	0,0782	0,122	5,2	0,151	0,0998

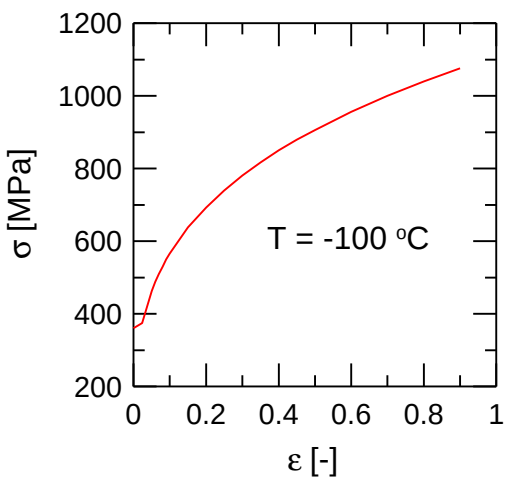

Figure 3. True stress-strain curve at –100 °C

NUMERICAL PROCEDURE

The three-dimensional computation using finite element package Abaqus was done. For the following step of modelling the right setting of determined material characteristics of the cast steel is necessary. As can be seen in Fig. 3, at the test temperature the stress – strain curve has the region where the Lüders deformation is dominating. Therefore the standard relation seems to be not appropriate for the modelling. Incorrectness of standard Ramberg-Osgood or exponential description

and then necessity to use piecewise linear description is expressed in case of modelling the body with a crack. The real measurement of the true stress true strain provides the information below the values of deformation 0.15-0.2. After some numerical tests and their comparison with experiments, the next expression was applied.

In interval ε <0,0017512 – 0,02429> $\sigma = 562{,}2*\varepsilon + 361$ (4)

ε <0,02429 – 0,9> $\sigma = 1110* \varepsilon^{0{,}2921}$ (5)

Test two sets of specimens with different crack configuration from Table 1 can be compared using rank probability diagram in Fig. 4, where P_f is expressed using $P_f=(i-0.3)/(N+0.4)$.

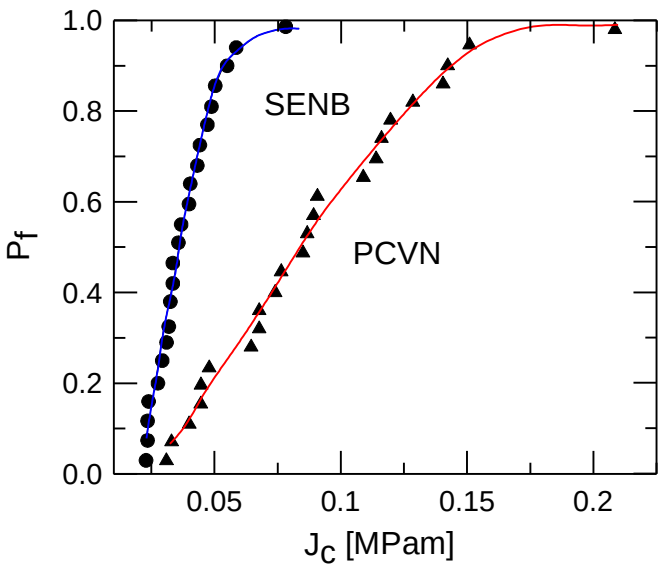

Figure 4. Rank probability diagram for J_c values.

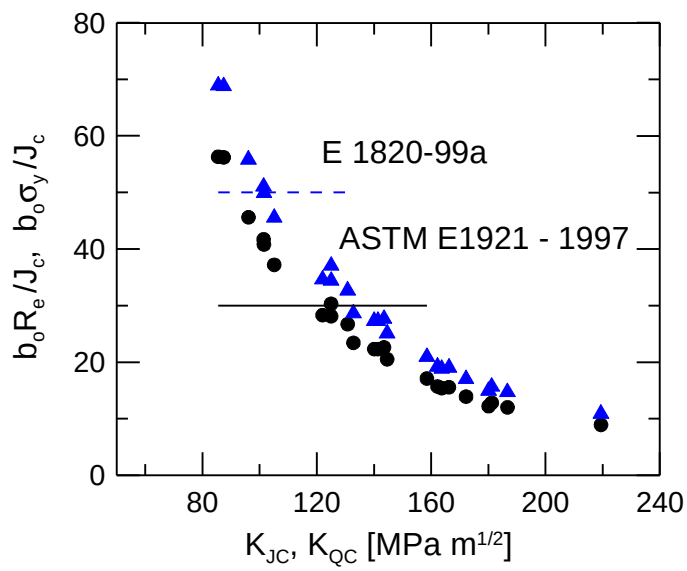

Figure 5. Validity diagram for K_{JC} of PCVN specimens.

The first step of transformation is to determine which data can be only size corrected. Results are presented in the Fig. 5, where two standards are applied (Re=380 MPa, σ_y = (Re+Rm)/2). As can be seen the first five values can be used in both cases directly.

The plane-strain, modified boundary layer model [3] simplifies the generation of numerical solution for stationary cracks under SSY conditions with varying levels of constraint in Fig. 6, where the reference volume V_o equals 1mm^3 for convenience in all calculations.

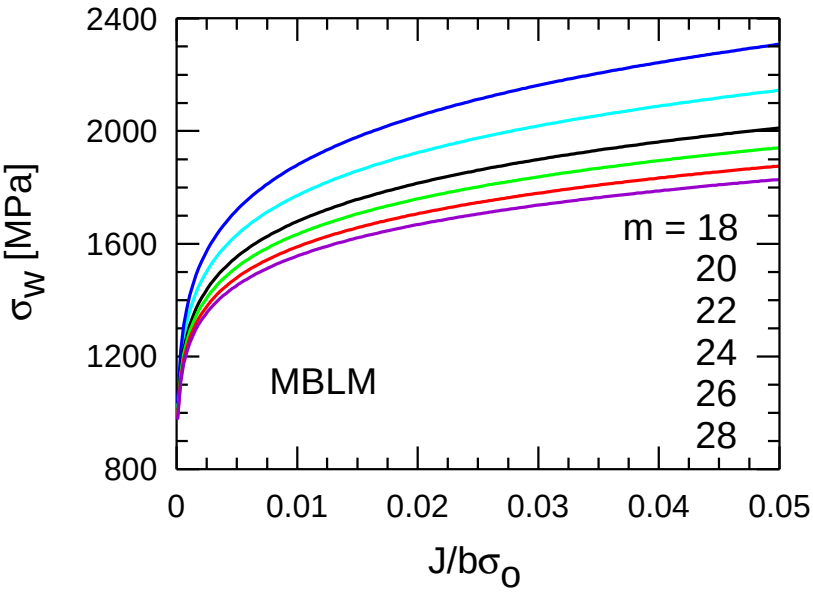

Figure 6. Diagram of Weibull stress determined by modified boundary layer method (MBLM).

To determine toughness-scaling diagram based upon the Weibull stress with varying Weibull moduli a set of experiments for PCVN specimens was done and the finite element model was constructed for analysis. The model includes small notch above sharp fatigue crack. The PCVN specimen has a square cross-section with B=W=10 mm and a span of 40 mm. A conventional mesh having 35 focused rings of elements surrounding the crack front is used with small-blunted tip (radius= 1μm). The mesh has 15 thickness layers and quarter-symmetric 3D model for PCVN contains 17 000 nodes. Using results of FEM modelling one can construct the following diagram in Fig. 7.

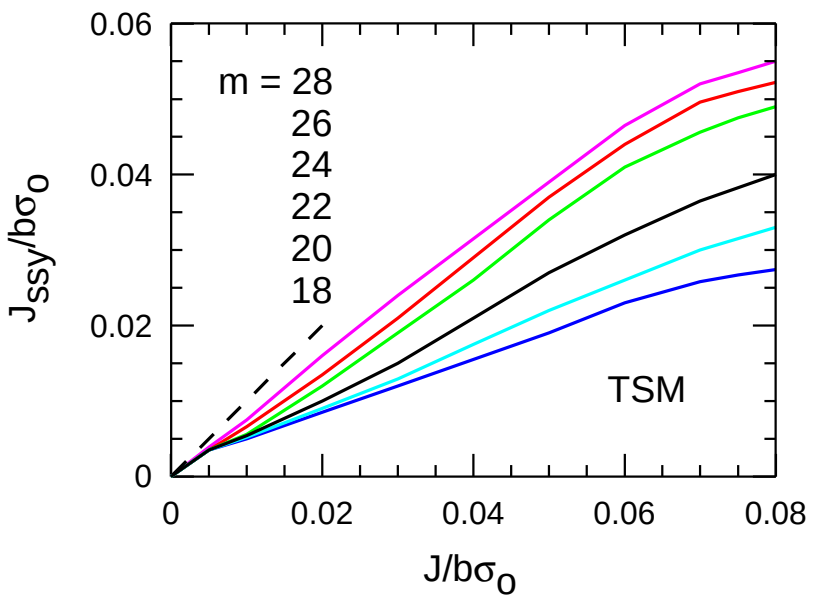

Figure 7. Toughness scaling diagram based upon the Weibull stress with varying Weibull moduli.

WEIBULL PARAMETERS CALIBRATION

From discussion presented in [3], macroscopic values of cleavage fracture toughness measured using high-constraint specimens follow a Weibull distribution with the failure given by

$$P_f(J) = 1 - \exp\left[-\left(\frac{J}{b}\right)^2\right]. \tag{6}$$

Where β defines toughness value at a 63.2 percent failure probability. Equating failure probabilities leads to

$$(\frac{J}{b})^2 = (\frac{s_W}{s_u})^m \tag{7}$$

The weakest link based thickness correction procedure of E-1921 can be used. Let t_{ssy} and t_A denote thickness for the SSY reference and configuration A, then J_{ssy} (i)=1.8+(t_A/ t_{ssy})^2(Jc(i)-1.8). Results of this transformation can be seen in Tab. 1 and in the Fig.8.

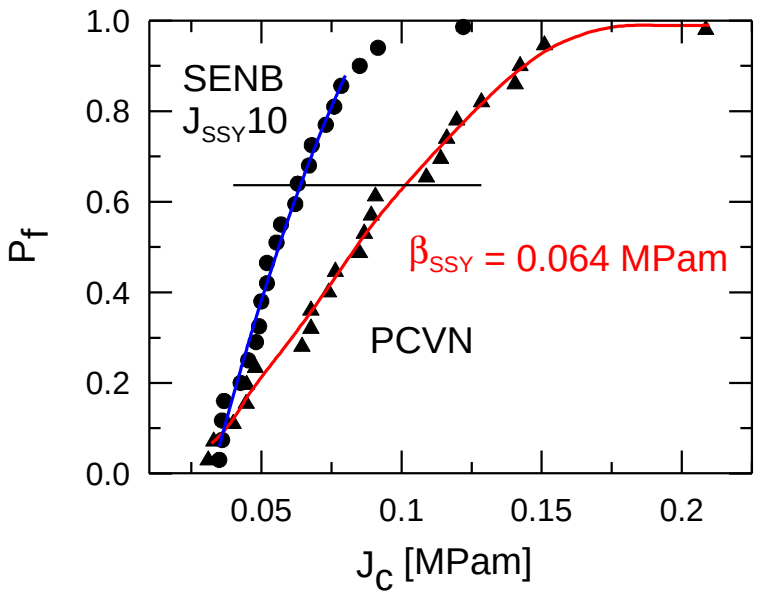

Figure 8. Rank probability diagram for J_c size corrected values (from J_c to J_{SSY} 10)

For the material considered in this paper β_{SSY} =0.064 MPam and calibrated m-value=24.1. The estimation of calibrated m-value is clear from plot given in Fig. 9.

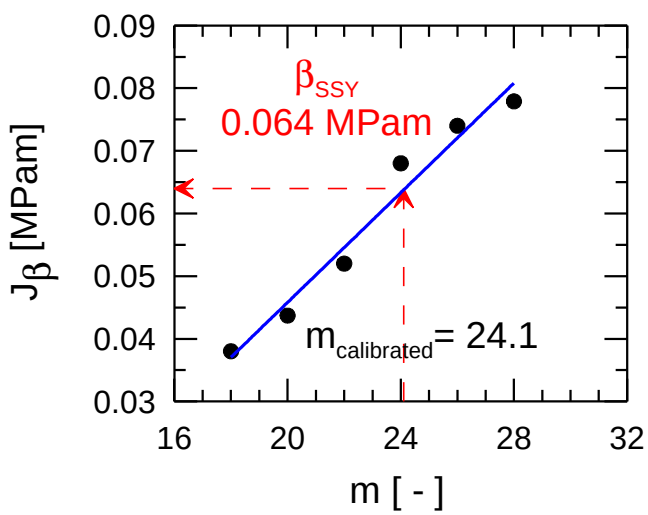

Figure 9. Calibration of Weibull stress parameters using fracture toughness data.

SUMMARY AND CONCLUSION

The main results obtained in this work can be summarized into the following items:

- The Beremin model with strain correction (slightly modified) was used for the calculation of σ_w, a reference volume V_o = 1 mm^3 was used for all computations.
- The valid local parameters are received on test specimens with notch radius 0.7 and 1 mm. The distribution of maximum principle stress has little influence on the microstructure inhomogenities that can be found in the separated specimens. For more detailed information see [10]. The Weibull parameters received are close to m=19.
- The fracture toughness-scaling diagram based on the local approach for SSY specimen was determined and used for the transformation of data received on small pre-cracked specimens. Other experiments are currently being carried out to test this approach.
- The calibration procedure based on the work Gao, Ruggieri and Dodds presented in [3] has been applied on the cast manganese steel and calibrated m-value was found to be m=24.1. The calibrated m-value makes the MBL estimate for the toughness of the constraint corrected fracture toughness data experimentally received on PCVN specimens.
- Constraint corrected data for PCVN are presented in Tab. 1.
- Calibrated m-value is a bit differing to m-value received on the notched axisymetric specimens. It shows that a direct application m-values generated on the notch specimens is controversial.

ACKNOWLEDGEMENTS

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