# LOCAL PARAMETERS SUSCEPTIBILITY CHECKUP USING FRACTURE TOUGHNESS DATA

V. Kozák and A. Novák

Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Žižkova 22, 616 62 Brno, Czech Republic

## ABSTRACT

Fracture toughness transition behavior of C-Mn cast steel intended for fabrication of large transport and storage container for spent nuclear fuel (ŠKODA 440/84) has been carried out. The fracture resistance has been assessed using data from static tests of the bend CVN and pre-cracked (PCVN) specimens and from the axisymmetric notched tensile specimens. Local material parameters have been calculated arising from Beremin approach. Transferability of the crack resistance data received on the small pre-cracked CVN specimens has been tested using toughness scaling models for correction. The small PCVN specimens have been thus used for the prediction of the fracture toughness. As the reference data the fracture toughness values from the 1T specimens with various crack lengths have been used.

## INTRODUCTION

Transport and storage containers have to ensure the storage of radioactive material safely for the environment for the supposed container lifetime, in case of most severe accident loading and earthquake. For the safe enclosure of radioactive material during transportation there has to be shown that crack initiation will not occur at the tip of this postulated crack like reference flaw. For an acceptable design the applied stress intensity factor even in case of most severe accident loading (earth quake etc.) has to be smaller than the material fracture toughness at the design temperature (divided by a safety factor).

For the safe storage of spent nuclear fuel an additional embrittling effects (age hardening due to service temperatures and irradiation) should be taken into account. Irradiation of steel (although comparably smaller than that in nuclear pressure vessels) decreases the fracture toughness and increases the risk of brittle fracture. The container lifetime (supposed at minimum about 60 years) is controlled by shift of transition region and due to this by lower shelf region occurrence at service temperature

Several approaches might be applied or developed in order to solve the problem of the container integrity from the point of view of material fracture resistance and its prediction. Its capability to predict the fracture behavior for any configuration of defect and component could be accepted as a very hard criterion of the assessment procedure.

*The statistical local approach* (Beremin conception) using procedure recently suggested by TC 1 within ESIS. As the local material parameters (Weibull stress and location parameter) are transferable to any component including test specimen, the shift of brittle to ductile transition curve for pre-cracked specimen (due to any embrittlement) could be directly predicted from notched ones.

*The methodology of master curve (MC)* is currently widely used for transition behavior evaluation of fracture toughness. The verification of this concept has been performed for steel of pressure vessel and weldments. For determining the reference transition temperature, $T_o$, which is taken as a basic material characteristic localizing the MC on the temperature axis, the large (1T) specimens are required. There are components (container cask as one of typical example) for which the transition behavior of fracture toughness is of great interest. However for these components only small specimens can be used for assessment of degradation. The effort is now concentrated on application of small specimens (PCVN) for these purposes.

*Toughness scaling model* for cleavage quantifies constraint effects by coupling the global parameter $J_c$ with a near–tip failure criterion applicable to transgranular cleavage. The model adopts material volume ahead of the crack front over which the normalized (maximum tensile) principal stress $\sigma_1/\sigma_0$ exceeds a critical value $\sigma_c$, as the local fracture criterion. For the same material/temperature combination, attainment of the equivalent stress volumes ahead of the crack front in different crack bodies implies the same probability for triggering cleavage fracture. This model leads immediately to a weakest-link interpretation but enables a more general interpretation of stress controlled failure mechanism of crack bodies and components with defects [1].

The aim of the paper can be seen in using the Beremin conception [2] of local approach to fracture resistance assessment. The main effort is concentrated on (i) the use of notched tensile bars and (ii) small test specimen (Charpy V notch or pre-cracked CVN) for fracture toughness temperature diagram determination including scatter characteristics.

## MATERIAL CHARACTERISTICS AND EXPERIMENTS

Manganese cast steel has been utilized for experiments having a chemical composition in wt %: 0.09C, 1.18Mn, 0.37Si, 0.01P, 0.025S, 0.12Cr, 0.29Ni, 0.29Cu, 0.03Mo, 0.028Al. Škoda Company has supplied the material as a component part produced for attest of the container of nuclear spent fuel.

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 5.8 was used to model elastoplastic behavior for tensile notched specimens. In all cases the multilinear model for true stress – true strain curve was used.

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 procedures. The diameter of the specimen was 16 mm and notch depth 4 mm. Three geometry of circumferetial U - notch have been tested having notch tip radius 0.2, 0.7 and 1.0 mm respectively, one circumferetial V – notch (radius 0.25 mm) and Charpy V – notch.

Fracture toughness data were measured using standard 25 mm thick specimen loaded in the 3-point bending with a/W ratio of 0.5. Small pre-cracked Charpy type specimens have been also tested in the same temperature range. Charpy type specimens were tested under the two types of loading: (i) CVN impact energies were measured using instrumented impact tester over a temperature range of –90°C to 25°C; (ii) CVN specimen were tested in static 3-point bending over temperature range –180°C to –50°C.

## LOCAL PARAMETERS

### *Theoretical background of Beremin approach*

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

$$P_f(\sigma_W) = 1 - \exp\left[-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right], \qquad (1)$$

the stress integral over the fracture process zone is denoted $\sigma_w$ and is termed the Weibull stress. This stress is defined by

$$\sigma_w = \left[\frac{1}{V_0}\int \sigma_1^m dV\right]^{1/m},$$

(2)

where m is so-called Weibull slope, $V_0$ is a reference volume, the integral is computed over the plastic zone, and $\sigma_1$ is the first principal stress. The parameters $\sigma_u$ and m of the Weibull stress $\sigma_w$ at fracture are material parameters, i.e. independent of the stress state of materials, but may depend on the temperature. The first principal stress values are obtained from ABAQUS stress analysis and the Weibull stress is integrated element by element.

The determination of two parameters m and $\sigma_u$ has to be performed iteratively as $\sigma_w$ depends on the parameter m. This can be done by the least square method or preferably by the maximum likelihood procedure, e.g. [3,4], $\sigma_u$ can be determined by the following equation

$$\sigma_u = \left( \frac{1}{N} \sum_{j=1}^{N} \left( \sigma_w^{(j)} \right)^m \right)^{1/m} . \qquad (3)$$

***Local approach procedures***

Accepting the Beremin approach and ESIS methodology [5] to the analysis of local criteria for cleavage fracture the location $\sigma_u$ and shape parameters m were calculated using FEM for notched tensile bars having various type of notch geometry (Table 1). 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 and quality of mesh for FEM is presented in the Table 2 ($V_0 = (100e\text{-}6)^3\ m^3$ , $\sigma_{th}/\sigma_0 = 1$).

The intrinsic model for notched bars is proposed with respect to symmetry as a half of bar. The axisymmetric elements CAX6 from Abaqus FEM [6] package are being used. In case of Charpy body the C3D8I elements were applied and due to symmetry the fourth part of body was solved. Approximately the same element size ahead the crack tip in the region 1 mm is being used because the data from this region are mainly exerted for determination of Weibull stress. The radii of notch was divided at least into 20 parts. The principal stress distribution at the maximum fracture force can be seen in Figure 1.

TABLE 1

FEM mesh for various geometry

| Geometry | No. of elements | No. of nodes | No. of plastic elements | No. of plastic nodes. | Steps | CPU time [min] |
|---|---|---|---|---|---|---|
| V notch | 8243 | 16784 | 7625 | 12234 | 17 | 48 |
| U 1 mm | 10279 | 20784 | 8747 | 16234 | 20 | 56 |
| U 0.7 mm | 8755 | 17836 | 7765 | 15788 | 14 | 39 |
| U 0.2 mm | 11303 | 22966 | 9645 | 18496 | 15 | 54 |

For the following step of modeling the right setting of determined material characteristics of the cast steel is necessary. As can be seen in [7], at tests temperatures the stress – strain curve has the region where the Lüders deformation is dominating. Therefore the standard relations seems to be not appropriate for the modeling. Incorrectness of standard Ramberg-Osgood or exponential description and then necessity to use piecewise linear description expressed in case of modeling the body with a crack. The dependence measurement 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 in Tab. 2 were applied.

TABLE 2

Material properties

| | | | |
|---|---|---|---|
| Yield stress | ε <0,002434 – 0,03981> | $\sigma = 695{,}6\varepsilon + 496{,}3$ | at –160°C |
| hardening | ε <0,03981 – 0,9> | $\sigma = 1151 * \varepsilon^{0{,}2436}$ | E = 205 000 MPa |
| | | | |
| Yield stress | ε <0,0017512 – 0,02429> | $\sigma = 562{,}2\varepsilon + 361$ | at –100°C |
| hardening | ε <0,02429 – 0,9> | $\sigma = 1110 * \varepsilon^{0{,}2921}$ | E = 205 000 MPa |

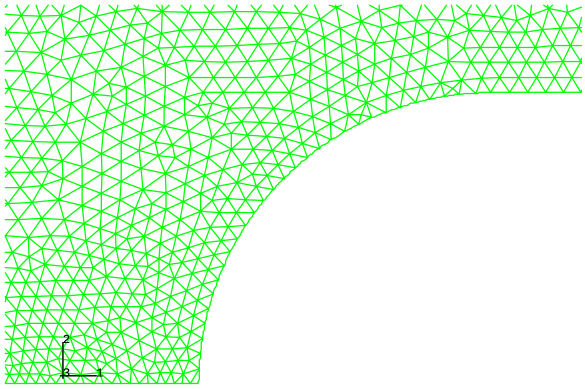

**Figure 1**: Example of a FE mesh-detail for the notched specimen U= 0.7. mm

The presented results for two geometry which can be seen in Fig. 2 show the plastic size difference as to region where the maximal principal stress is dominant. For the sharp notch the localization is close to notch tip, but for the notch with big radius is distributed in bigger profile. To verify each experiment and its numerical results the checkup of the elongation and the contraction was done. The example of this procedure can be seen in Fig. 3.

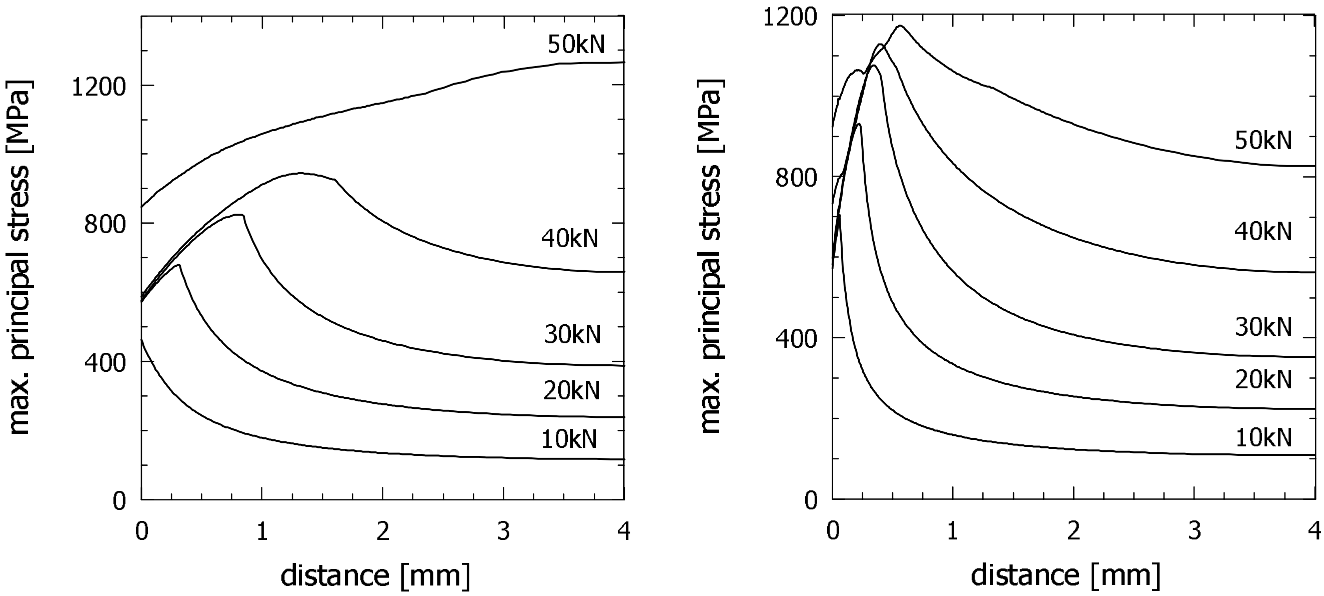


**Figure 2:** Stress distribution ahead of tip, U notch = 1 and 0.2mm

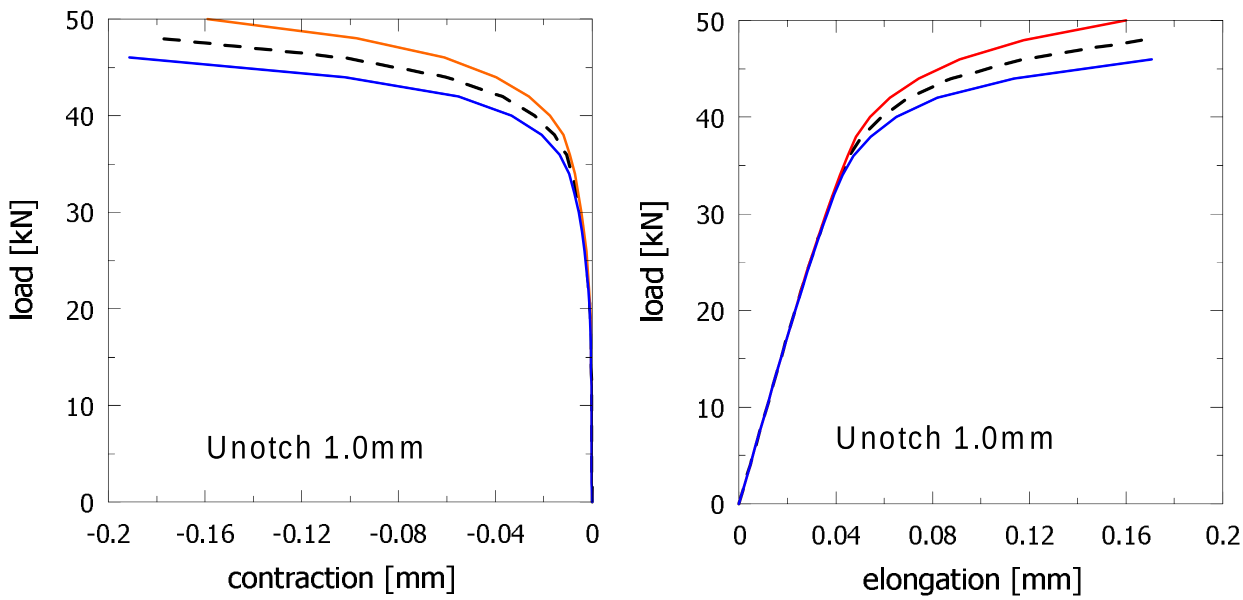


**Figure 3**: Elongation and contraction for U notch 1mm, the mean value is received from FEM, outer values correspond to the maximum and minimum of the fracture force

In case when the measured and computed values are compared the quality is different for various geometry. This discrepancy can be explained by two factors. The first one is caused by the variability of yield stress and length of Lüders deformation, the second one by the different level of plastic deformation size. The both factors put forth at the same time by the comparison of data record force – elongation for various tested body geometry. This discrepancy is due to own measurement of elongation where the Lüders deformation plays the dominant role. This phenomenon was observed at experiments for which the dependence force – contraction was measured. In case U notch 0.7 mm the accordance was nearly perfect and we can raise a presumption that the computation in place of local deformation is less sensitive with respect to variability of material characteristics given by static tensile test, especially for the material in inhomogeneities such as can be found in cast steel.

***Local parameters determination***

To determine the local parameters it is very important how to modify the base statistical data set. After the surface fracture inspection it is needful to omit these experiments whose character is unmatched to the weakest link theory. A selection is based on the usage of scanning digital camera and the following processing on a personal computer. The investigation showed that the right criterion for selection can come from the following relation $\sigma_w = f(\varepsilon_p)$, kde $\varepsilon_p = -2\ln(d/d_o)$. Example of a such dependence is on the Fig. 4. The reference volume $V_0$ is prescribed in [4] to be 0.001 $mm^3$ , but in this Fig. 4 the influence of various values with respect to real microstructure is tested. This value relates to microstructural dimensions as well to the element size of the FE mesh. The acceptable choice is this where the curve is linear. It means that in our test set in case U notch with radius 1 mm and 0.7 mm the valid data are for the deformation greater then 4 %, but for the specimen with U notch 0.2 mm from 0.3 %.

The next problem solved in this paper is if the quality of the FE mesh size has some influence on the generated local parameters. As can be seen e.g. in Tab. 3, the influence of this is nearly insignificant. Establishing $\sigma_{th}/\sigma_0$ the influence of process zone was tested. But this aspect is insignificant for the same geometry too. Another problem is the difference in obtained local parameters for different notch diameter. The quality of generated local parameters can be seen in Fig. 5.

TABLE 3
Influence of the mesh and of the used process zone

| U notch 0,2 mm | | | | | | |
|---|---|---|---|---|---|---|
| | ~11300 | | ~6500 | | ~3500 | |
| $\sigma_{th}/\sigma_0$ | m | $\sigma_u$ | m | $\sigma_u$ | m | $\sigma_u$ |
| 0 | 65,6 | 1340 | 64,6 | 1343 | 63,3 | 1350 |
| 1 | 65,6 | 1340 | 64,6 | 1343 | 63,3 | 1350 |
| 1,5 | 65,6 | 1340 | 64,6 | 1342 | 63,3 | 1350 |
| For extreme coarse mesh ~ 800 elements m=62,6 | | | | | | |
| **U notch 0,7 mm** | | | | | | |
| 0 | 17 | 2485 | 16,9 | 2491 | 16,8 | 2506 |
| 1 | 17 | 2484 | 16,9 | 2491 | 16,8 | 2506 |
| 1,5 | 16,9 | 2489 | 16,9 | 2494 | 16,8 | 2508 |
| For extreme coarse mesh ~ 500 elements m=17,5 | | | | | | |
| **U notch 1 mm** | | | | | | |
| 0 | 18,2 | 2117 | 17,8 | 2145 | 17,8 | 2146 |
| 1 | 18,2 | 2117 | 17,8 | 2146 | 17,8 | 2146 |
| 1,5 | 18,2 | 2120 | 17,7 | 2148 | 17,7 | 2149 |

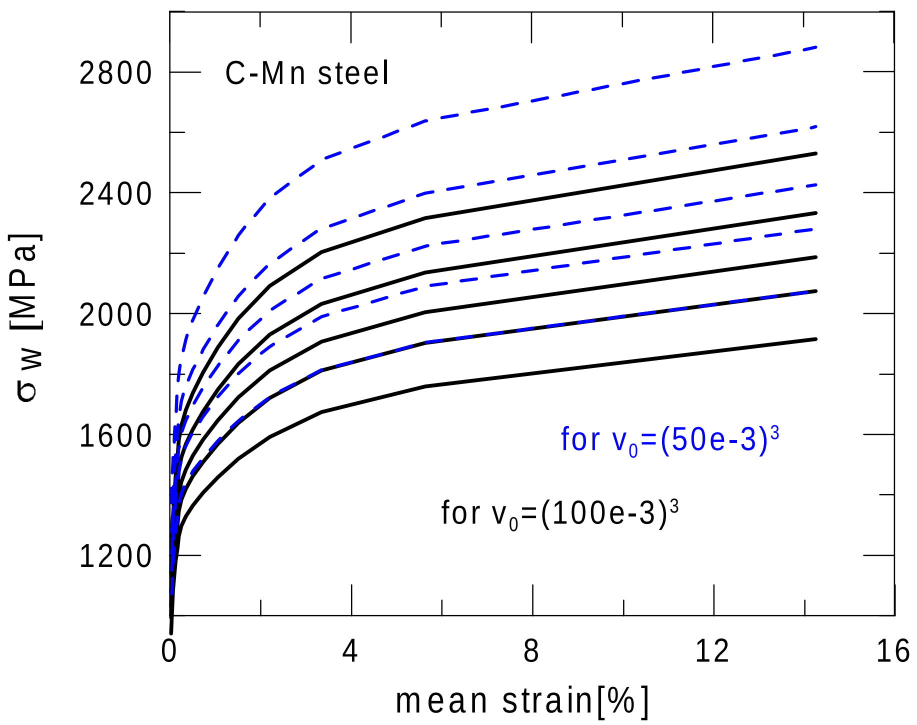


**Figure 4**: The valid data determination according to strain value for U notch 0.7 mm

### *Toughness scaling model based on the Local approach*

The studies [8,9] demonstrated the strong dependence of crack-tip field on the specimen geometry, mainly induced by shallow cracks and remote loading – the constraint phenomena is being studied. As can be seen in [10] the Weibull stress $\sigma_w$ seems to be as a suitable near-tip parameter to describe the coupling of the remote loading with a micromechanical model incorporating the statistics of microcracks (weakest link philosophy). Then one can use it in the prediction of critical parameters of the fracture initiation for the various cracks length and geometry of body. The material parameters received [11,12] 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 [9]. The result received can more precisely describe the behavior of bodies with cracks and better study the problems of transferability of some fracture parameter from one body geometry to another. The transformation diagram for three geometry was determined and is presented in Fig. 6. Detailed information can be found in [12, 13].

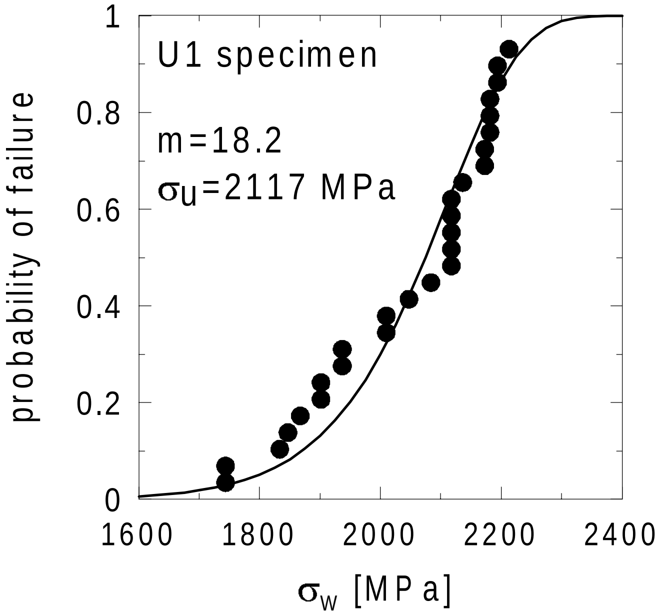


**Figure 5**: Probability of failure for m=17, $\sigma_u$=2845 MPa

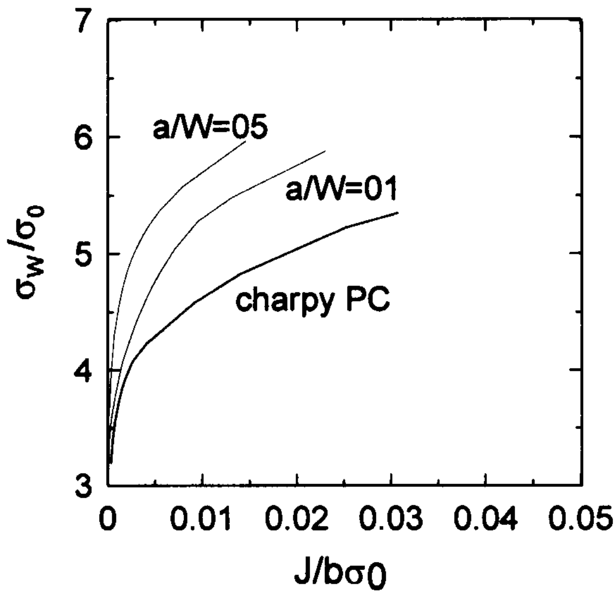


**Figure 6**: Transformation diagram

**CONCLUSION**

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

- The Beremin model with strain correction (slightly adapted) is used for the calculation of $\sigma_w$. The iterative procedure using the maximum likelihood theory was applied and the geometry effect for various notch radius of tensile bars is observed.

- The local parameters generated on the geometry with U notch 0.2 mm, V notch 0.25 mm and on the Charpy specimen give practically the same values.
- The valid local parameters are received on test specimens with notch radius 0.7 and 1 mm, where the character of maximum principle stress distribution has no influence on the microstructure inhomogenities which can be found in the cast steel.
- The transformation diagram based on the local parameters for three geometry 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.

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