# A study of Cleavage Fracture of A508 Steel using Round Notched Bar Specimens

**A. Mirzaee-Sisan[1], S. Hadidi-moud[2], C. E. Truman and D. J. Smith**
Department of Mechanical Engineering, University of Bristol, UK, BS8 1TR
A.Mirzaee-Sisan@Bristol.ac.uk

## ABSTRACT

This paper presents the results of an experimental and numerical study carried out to investigate the scatter in cleavage fracture in A508, a reactor pressure vessel steel, using a local fracture criterion based on Weibull's analysis. It aims to measure the discrepancy in the fracture stress at low temperatures. The difficulty of transferability of Weibull parameters in Round Notched Bar (RNB) specimens with different notch geometry is discussed.

Keywords: ***cleavage fracture, local approach, failure probability***

**NOMENCLATURE**

| | |
|---|---|
| $a$ | Crack length, mm |
| $i$ | order number of specific specimen ($i$=1, .., $N$) |
| $m$ | Weibull exponent, - |
| $N$ | total number of specimens (sample size) |
| $P_f$ | Probability of failure, % |
| $P_r$ | Fracture load, N |
| $V_0$ | Reference volume, mm$^3$ |
| $\sigma_f$ | Fracture Stress, MPa |
| $\sigma_{min}$ | Threshold stress, GPa |
| $\sigma_I$ | Maximum principal stress, GPa |
| $\sigma_{1,2,3}$ | Three principal stresses, GPa |
| $\sigma_u$ | Weibull reference stress, GPa |
| $\sigma_w$ | Weibull stress, GPa |
| $\phi$ | Initial Diameter of RNB, mm |
| $\phi_F$ | Diameter of RNB after fracture, mm |
| $T_f$ | Triaxiality factor, - |
| $\varepsilon_F$ | Fracture strains, - |

**Introduction and Background**

There is extensive experimental evidence to show that low alloy steels, fractured by cleavage at lower shelf temperatures, exhibit highly scattered fracture toughness. To predict failure conditions at lower shelf temperature "local" approaches have been developed.

For example, based on Weibull's concept of probability distribution, Beremin [1] developed a model used to predict cleavage fracture in ferritic steels.

Following Beremin attempts have been made to use this model to predict the fracture response of ferritic steels in transition temperature regime. For instance, Schmitt et al [2] combined Gurson-Tvergaard-Needleman model and the Beremin local approach [1] to investigate the material failure in brittle to ductile transition region.

In this paper, attention is focused on using a local stress based approach. This based on the Beremin model recently modified by Hadidi-Moud et al [3].

In Beremin model, it has been assumed that micro-cracks might be found at the onset of plastic deformation and that unstable fracture will occur should the maximum principal stress reach sufficiently high levels. In other words, the plastic deformation is referred to as a primary event prior to failure. Global failure is predicted by invoking the weakest link theory. This assumes that a body of material can be fragmented into many independent volumes, linked together like a chain, and the failure of a body commences when its weakest element link fails.

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[1] PhD student, Department of Mechanical Engineering, University of Bristol, UK.
[2] Research associate, Department of Mechanical Engineering, University of Bristol, UK.

A schematic diagram of a cracked body under mode I loading is shown in Fig 1. Increasing the applied load results in development of a plastically deformed zone ahead of the crack tip. The extent of the plastic region, shown in grey in Figure 1, increases by increasing the applied load.

The local approach modified by Hadid-Moud et al [3] is a Beremin type model with the inclusion of a minimum threshold stress, $\sigma_{min}$. It is a four-parameter Beremin-type distribution function, given by:

$$P_f\left[\sigma_f\right] = 1 - exp\left[-\left(\frac{\sigma_w - \sigma_{min}}{\sigma_u - \sigma_{min}}\right)^m\right] \qquad (1)$$

where $\sigma_w$, the Weibull stress, is given by:

$$\sigma_w = \left[\sum_{i=1}^{n_{pl}} \left(\sigma_1^i\right)^m \frac{\Delta V_i}{V_0}\right]^{1/m} \qquad (2)$$

The Weibull stress, $\sigma_w$, is a characteristic stress obtained by integration of the maximum principal stresses over the plastic zone and scaled by a reference volume, $V_0$. This approach is used in the present work in conjunction with finite element analyses.

An arbitrary region, which is illustrated, as the “fracture process zone” in Figure 1 is modelled with a fine mesh in the finite element analysis. This zone is large enough to include all the elements that undergo the plastic deformation by incremental loading to calculate the Weibull stress.

The Weibull parameter, $\sigma_u$, is known as a reference Weibull stress corresponding to a failure probability of 63.2% and is referred to as the mean stress. The exponent “m” is the shape parameter describing the scatter in the fracture test data. As can be seen in equation (2) the Weibull stress is a function of “*m”*, the reference volume, $V_0$, and $\sigma_1$ , the maximum principal stress. The threshold stress, $\sigma_{min,}$, is included to the original Beremin model to address the structure will not fail at loads lower than a certain level.

The Weibull parameters are determined from experimental results. In the Beremin approach, the exponent “m” and the reference stress $\sigma_u$ were first determined by calibrating the parameters using the test results from round notched bars (RNB) specimen. It was suggested that these parameters are only material dependent. It should be noted that the Weibull parameters suggested by Beremin were obtained by calibrating the parameters using a database of experimental data collected from a wide range of RNB specimens having various notch tip geometry and tested at different temperatures. It was suggested that the same parameters were appropriate to use in predicting scatter in fracture data for other configurations including specimens with different geometry and / or containing sharp cracks.

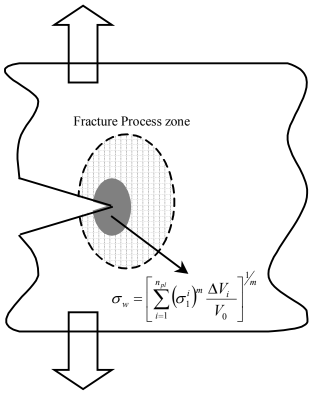

Fig1: Schematic of fracture process zone ahead of crack tip.

Beremin also suggested that the reference volume, $V_0$, was a volume equivalent to about ten grain size of the material, typically $V_0$=0.001 mm$^3$. However, Hadidi-Moud et al [3] argued that a good fit to the experimental results may be obtained by assuming $V_0$ as a free scaling parameter and that the Weibull exponent, m, is equal to 4.0 for sharp cracks (as suggested by Wallin [4]. It is also suggested by that “m” increases by decreasing the stress triaxiality. The pertinent details are discussed in Ref [3]. Here the intention is to investigate the dependency of these parameters for round notched bars containing different sized notches.

The extensive fracture test programme using A508 steel RNB test specimens is described in next section. Details of finite element simulations of RNB specimens are then presented and the results are used in conjunction with the local approach to examine the transferability of distribution parameters for different shaped notches.

## Experiments and Results

Round notched bars were used in this study to re-examine the Beremin approach. The RNB test specimen is convenient for achieving a variety of stress states by simply altering the severity of notch root raduis.

A total of 30 RNB specimens were extracted from a plate of A508 Class3 C-Mn steel. This material is used widely in manufacturing reactor pressure vessels in the nuclear industry.

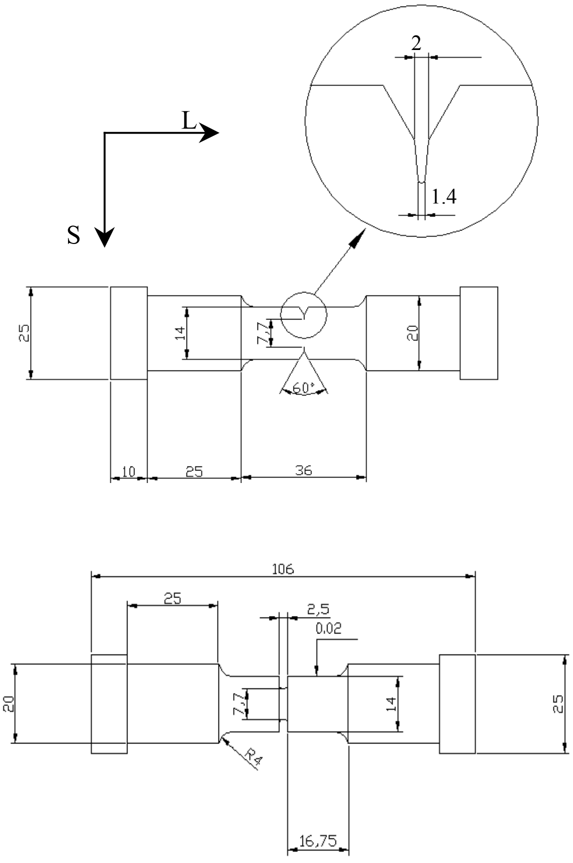

Fig2: Specimen geometry of Round Notched Bars (RNB). Dimensions in mm

The composition of material in weight percent is: C=0.15, Mn=1.3, Ni=0.72, Mo=0.52, Si=0.23, Cr=0.18, S=0.003 and P=0.004. The specimens were manufactured in the S-L orientation from the steel plate. Sharp and shallow circumferential notches were introduced into the mid section of the bars. The geometry of the specimens and details of the notch-tip are shown in Figure2.

Two series of tests were carried out using shallow 'U' shape notches with a tip radius of 1.25mm.

One set tested at -120°C and the other set tested at -150°C. RNB specimens with similar geometry but containing sharp 'V' notches with an average tip radius of 0.07mm were also tested at -150°C.

All specimens were subjected to a quasi-static displacement controlled loading in the axial direction at a constant rate of 0.18 mm/min at the desired temperatures.

The fracture stresses were calculated using $\sigma_F=4P_f/\pi\phi^2_F$.The fracture diameter ($\phi_F$) was measured on the fractured specimens using a shadow-graph. The range of fracture stresses of shallow notches at –120 °C was 1371 MPa and 1648 MPa with the average value of 1544 MPa. The mean value of fracture stresses at -150 °C was 1380MPa, while the maximum and minimum measured fracture stresses were 1466 and 1231 MPa respectively.

The RNB with sharp notches exhibited a the range of fracture stresses between 620 MPa and 1059 MPa .

Table 1 summarises the measured fracture strains. It can be seen that a plastic deformation of round bars with sharp notches was small. The fracture strains at -120°C however varied from 18.7% and 44.1% with the average value of 30.3%. This amount of fracture strain indicates that for tests at –120°C necking occurred before fracture

Table1: The fracture strains: $\varepsilon_F=2\ln(\phi/\phi_F)$

| Geometry | Temp(°C) | Mean(%) | Max(%) | Min(%) |
|---|---|---|---|---|
| r =1.25 | -120 | 30.3 | 44.1 | 18.7 |
| r =1.25 | -150 | 8.1 | 11.8 | 2.9 |
| r =0.07 | -150 | 1.6 | 3.0 | 0.4 |

The scanning electron microscopy (SEM) technique was used to observe the details of the fracture surfaces. It revealed that specimens fractured at -150°C have failed entirely by cleavage.

Typical features of the fracture surfaces are shown in Figure 3a for a shallow notch specimen tested at -120°C. This is evidence of shear lips on the outer edge of the specimens. In Fig3b for tests at -150°C there was strong evidence of cleavage failure for both shallow and sharp notch specimens across the whole section.

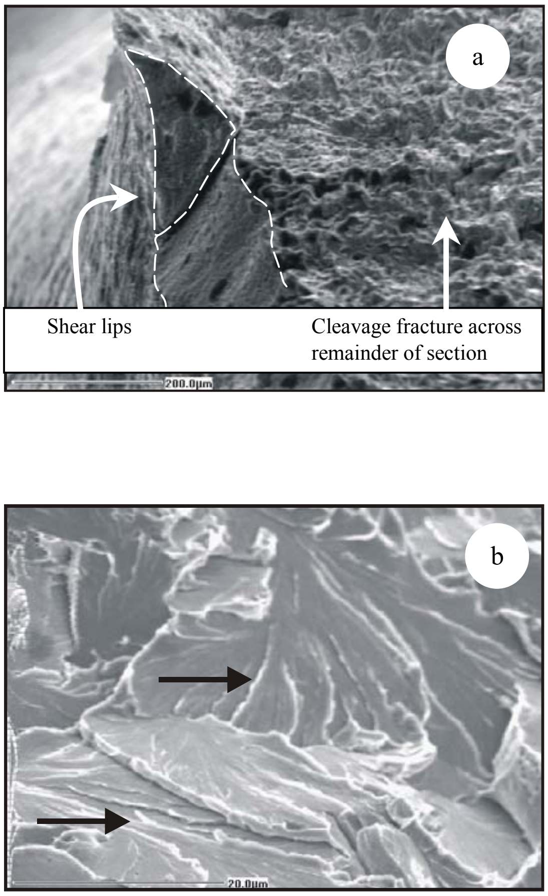

Fig3. SEM observation of fracture surface of RNB specimen
(a )Evidence of shear slips at $-120^{o}$C
(b)Indications of cleavage fracture at $-150^{o}$C

### Finite Element Studies

Finite element analyses were performed to provide information required as input to an analysis using the local approach to predict failure conditions.

The commercial code ABAQUS CAE (V 6.2) was used to generate finite element models of RNB specimens with sharp and shallow notches having adequate mesh refinement at notch tip. To take advantage of symmetry only, one quarter of specimens were modelled using axi-symmetric (CAX8R), iso-parametric quadratic eight noded elements with reduced integration. Details of mesh refinement at the notch tip are shown in Figure 4. The smallest element size are about 0.12 x 0.12 mm and 0.03 x 0.01 mm for the shallow and sharp notched round bars respectively. Isotropic hardening material properties was used with yield strengths of 430MPa at 20°C, 632MPa at -120°C and 695MPa at -150°C.

Due to large plasticity that occurred at $-120^{o}$C, the stress strain data at this temperature were extrapolated, according to the relation mentioned by Carassou [7], to obtain the hardening data of A508 steel.

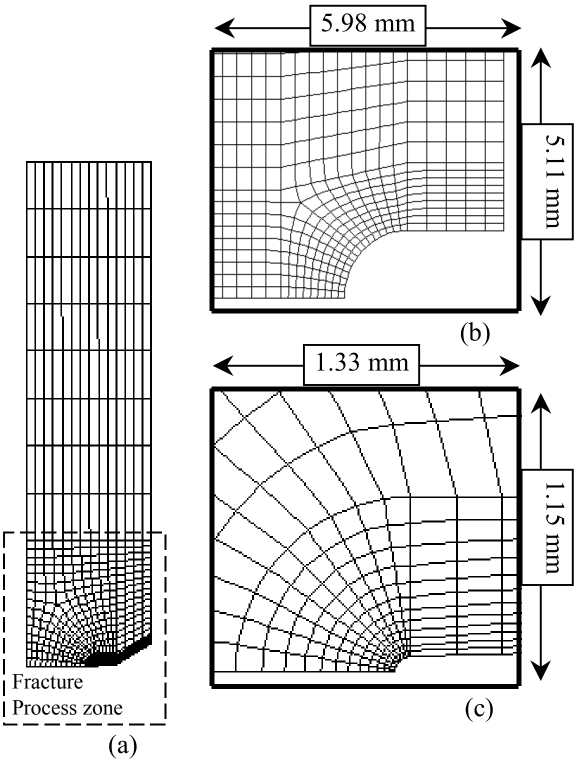

Fig4: Model of RNB specimen: (a) Total FE mesh; (b) details of FE mesh at tip of shallow notch; (c) details of FE mesh at tip of sharp notch

### Probabilistic modelling

To estimate probability of fracture a routine developed by Hadidi-Moud et al [3] was used in conjunction with the results from the FE analyses. The fracture process zone is the area around the tip where the material undergoes plastic deformation. In each element, the integration points where plasticity was reached were included in the computation. The routine also allows for the intersection of the boundary of the process zone with the elements by including only the plastic fraction of the elements on the boundary in the integration volume. This increases the accuracy of estimation of Weibull stresses, especially when the elements on the boundary are large.

Prior to using the model, it was necessary to first calibrate the distribution parameters, m, $V_0$, $\sigma_u$ and $\sigma_{min}$.

The calibration process has also been used by Gao and co-workers [8]. Their results reveal that the parameters could not be uniquely defined. Milella and Bonora [9] suggest that the shape parameter *m* is a function of the notch tip geometry (or alternatively local triaxial stress-state). They suggest that for blunt notches in ferritic steels *m* has values of 20 or higher while for sharp cracks is 4.0.

In this study, the reference volume is fixed for 0.001mm$^3$ and the remaining parameters (m,$\sigma_u$ and $\sigma_{min}$) were determined by obtaining failure probabilities from the FE analysis that best matched the experimental fracture data at each temperature and or geometry.

For experimental results failure probability , $P_f$, is determined by Bergman [10]:

$$P_f = \frac{i - 0.5}{N} \tag{3}$$

where *N* is the total number of specimens, and *i* the rank or order number. Experimental results as shown in Fig 5 were directly interpreted in terms of fracture stress. The parameter values that provided a close fit to the experimental results for the shallow notch tests at –150°C were $m$=24, $\sigma_u$ =2.36GPa and $\sigma_{min}$ =0.8GPa.

In the case of RNB specimens tested at -120°C the calibrated parameters were m=23, $\sigma_u$ =2.7GPa and $\sigma_{min}$ =0.0GPa.

Similar procedures were followed to determine the parameters that best matched for sharp-notched RNB specimens' tests at that temperature. The values obtained for sharp notch were $m$=8, $\sigma_u$ =4.57GPa and $\sigma_{min}$ =0.0GPa.

The shape factor "*m*" for sharp RNB specimen was much less than the values obtained from the shallow notches. Generally, lower values of *m* correspond to wider scatter in the fracture data.

As shown in Fig 5b and 5c the scatter in sharp and shallow notch RNB specimens tested at –150°C was significantly higher than those tested at –120°C. Furthermore, it seems that there are two clusters of results. This is very similar to observations of Yahya [11] who referred to as "bi-modality" in fracture mechanism. Based on this observation in the distribution of fracture data at lower temperatures, where cleavage brittle fracture is more likely to occur, Yahya [11] suggests there is possibility of different mechanisms in triggering final failure. Our results illustrate similar features and bi-modality at -150°C is higher than at -120°C, where fractures is accompanied by considerable plastic deformation.

Milella and Bonora [9] suggested the Weibull exponent "*m*" is independent of temperature if the triaxiality factor through the softening of the material remains constant. They argued that a change in triaxiality would have an impact on the value of *m* since localised triaxiality determines the extent of the process zone.

The triaxiality factor TF is given by :

$$T_f = \frac{\sqrt{2}}{3}\frac{\sigma_1 + \sigma_2 + \sigma_3}{[(\sigma_1 - \sigma_2) + (\sigma_2 - \sigma_3) + (\sigma_1 - \sigma_3)]^{\frac{1}{2}}} \tag{4}$$

In table 2, the calibrated values of *m* and values of $T_f$ determined from the FE analysis are compared with calculated values of m using of an expression developed by Bonora and Millela :

$$m = 55.4 - 22.4(T_f) \tag{5}$$

It can be seen in Table 2 that the calibrated Weibull parameters and their corresponding triaxiality in this study are close to values predicted by Millela and Bonora's .

| Geometry | Temp(°C) | $T_f$(Max) | m(Bonora) | m(Calibrated) |
|---|---|---|---|---|
| r =1.25 | -120 | 1.5 | 22.2 | 23.0 |
| r =1.25 | -150 | 1.5 | 22.2 | 24.0 |
| r =0.07 | -150 | 2.0 | 9.5 | 8.0 |

Table 2: Relation between Triaxiality factor and Weibull parameter

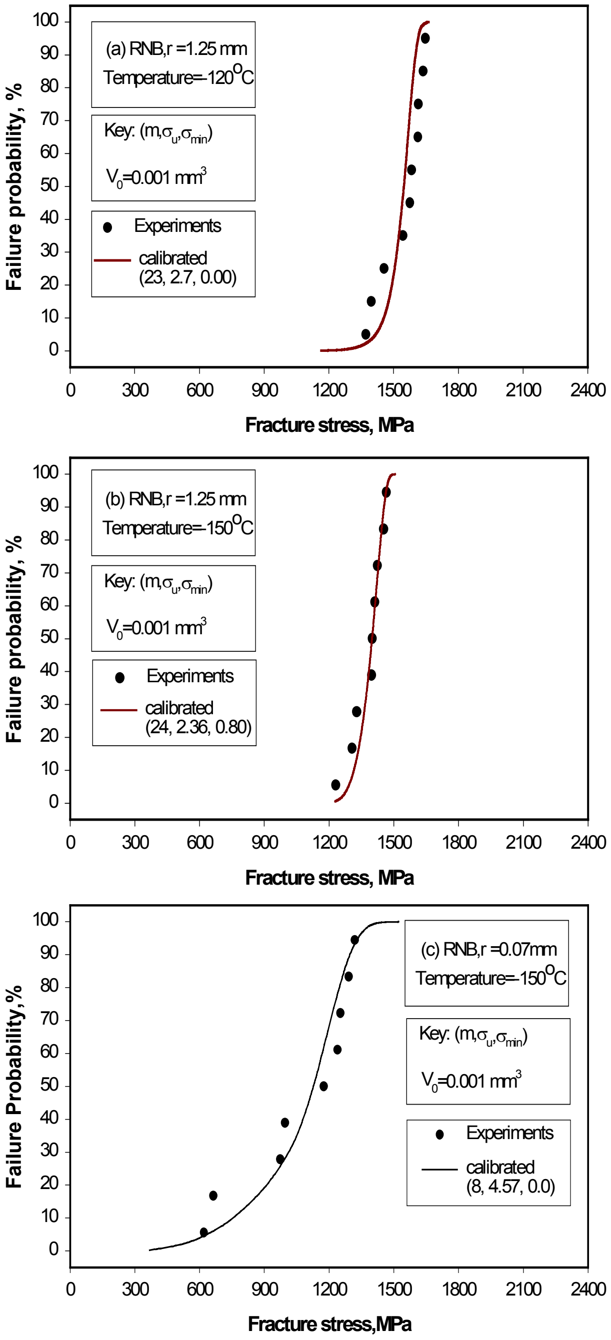

Figure5: Probability of failure for RNB specimens:
(a)Shallow notch at –120 ℃; (b) Shallow at –150 ℃;
(c) Sharp notch at -150 ℃

## Concluding remarks

Weibull parameters were obtained for different notched bars at different temperatures. The results revealed that increasing the sharpness of notches resulted in wider scatter in fracture stress.

It is apparent that there is difficulty in the transferability of Weibull parameters. One set of calibrated parameters can not be used for specimens with different shaped notches. This finding is in contrast to earlier work, by Hojo [12] who suggested that the Weibull parameters from CT specimens and notched tensile specimens have the same values.

This study, also, suggests that the Weibull exponent "*m*" does not change significantly with temperature when the same notch acuity is used.

Above all, further study is essential to provide a better understanding of dependency of the Weibull parameters on the degree of triaxiality.

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