DETERMINATION OF BEREMIN'S PARAMETERS FOR 20MnMoNi55 FERRITIC STEEL

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ABSTRACT

Ferritic steels are widely used in reactor pressure vessel constructions. In the transition region, fracture toughness of the material drops drastically as the temperature drops. Local approach has been used to compute 'σ_u' and 'm', Beremin's parameters (material properties) at different temperatures considered. The material under study is the reactor pressure vessel Steel 22MnMoNi55 low alloy ferritic steel. Brittle fracture has been analyzed and probability of cleavage failure is calculated using Beremin's model. Numerical simulation (2D FEA) of tensile test was carried out on 30 round notched tensile specimens (RTNS) at -50°C, -100°C and -150°C each to determine material properties 'σ_u'(scaling parameter) and 'm' (shape parameter).

INTRODUCTION

Irradiation embrittlement is one of the major problems faced by structural materials in nuclear reactors. Irradiation embrittlement is manifested by an increase in ductile brittle transition temperature (DBTT) of ferritic steel. Components like reactor pressure vessels (RPV) which use low alloy ferritic steel [4, 5] operate under high neutron flux over considerable period of time. According to USNRC regulatory guide 1.99 Rev. 2, [1] the shift in DBTT (in °F) as a function of the neutron fluence is given by:

$$\Delta \text{ DBTT} = [CF] * f^{(0.28 - 0.1*\log f)} \quad (1)$$

Here [CF] is a function of the weight percentages of copper and nickel in the material and *f* is the neutron fluence in the unit of 10^{19} n/cm^2 (E>1MeV).

It is essential to assess the structural integrity of the irradiated RPV subjected to different degree of fluence under accidental scenarios. One such analysis scenario involves occurrence of 'loss of coolant accident' (LOCA), followed by a delayed appearance of emergency-core-cooling system . The rapid cooling of the vessel material can bring down the temperature to below ductile-brittle transition temperature under the presence of large scale tensile stresses. Under such condition, the micro-cracks in the component subjected may lead to unstable cleavage fracture. Knowledge on such fracture behavior of the RPV material at transition temperature is mandatory to quantify the inherent safety margin available under these undesirable events.

MODELING BRITTLE FRACTURE

The mechanism of cleavage fracture in reactor pressure retaining material is significantly different from ductile fracture. The cleavage fracture in a material usually originates from micro-cracks, which are formed by different mechanisms. The micro-cracks are formed due to a non-homogeneous distribution of plastic deformation within the grains, called slip-initiated cleavage. The cracked grain boundary carbides also are the sources to originate the micro-cracks. This occurs when the stress normal to the planes of the carbide particles is sufficiently high. The fracture takes place by the formation of micro-cracks and their subsequent extension with little global plastic deformation. The cleavage process is stress controlled and consumes little deformation energy and hence, the crack grows unstably fast. In such case the local fracture criterion is generally based on a critical cleavage stress. Based on the weakest link assumption [2] and Weibull statistics, Beremin developed a model for the analysis of cleavage fracture process [3]. Present work is based on two-parameter Weibull statistics. These parameters termed as

Beremin's parameters are determined using experimental fracture data and finite element (FE) analysis, which are essential to predict probability of cleavage fracture in a reactor component. Experiments are done to obtain load-deformation data at failure and FE analyses are done to get the stress distribution in the test specimen at failure. The failure probability is given by:

$$P_f = 1 - \left[-\left(\frac{\sigma_w}{\sigma_u} \right)^m \right] \tag{2}$$

Here, σ_u is the scaling parameter describing the mean value of σ_w for a failure probability value of 63.2% and 'm' is the Weibull exponent or shape parameter quantifying the slope of P_f.

The Weibull stress σ_w is defined as:

$$\sigma_w = \left[\sum_{j=1}^{n} \left(\sigma_I^j \right)^m \left(\frac{V_j}{V_0} \right) \right]^{1/m} \tag{3}$$

Here, σ_I is the maximum principal stress, n_{pl} is the total number of elements undergone plastic deformation, V_j is the volume of the j^{th} yielded element and V_0 is the reference volume.

In maximum likelihood method [4, 5], the values of the two parameters m and σ_u are adjusted to have maximum probability of occurrence of experimental results. This is equal to the probability that all σ_w values occur simultaneously. The likelihood function is given by the product of all the individual fracture probabilities. The expressions for σ_u and m are then obtained by maximizing this likelihood function. The principle of maximization gives the following two nonlinear equations,

Where N is the total number of specimens.

$$\frac{N}{m} + \sum_{i=1}^{N} \ln(\sigma_{w_i}) - N . \frac{\sum_{i=1}^{N} (\sigma_{w_i})^m . \ln(\sigma_{w_i})}{\sum_{i=1}^{N} (\sigma_{w_i})^m} = 0 \tag{4}$$

$$\sigma_u = \sqrt[m]{\frac{1}{N} \sum_{i=1}^{N} (\sigma_{w_i})^m} \tag{5}$$

These two nonlinear equations are solved iteratively to arrive at the values of m and σ_u.

GENERATION OF TRUE STRESS VS PLASTIC STRAIN CURVE

Material under study is 20MnMoNi55 low alloy ferritic steel. Tensile tests on smooth and notched tensile specimens were conducted at room temperature, -50°C, -100°C & -150°C to determine the material properties and engineering stress strain curve. Material properties are tabulated below.

Table 1. Material properties of 20MnMoNi55 low alloy ferritic steel

Young's modulus of elasticity (GPa)		200
Poisson's ratio		0.3
Temperature (°C)	**Yield strength (MPa)**	**Ultimate tensile strength (MPa)**
Room temperature	490	620
-50	537	699
-100	600	785
-150	685	841

True stress-plastic strain data was derived from the experimentally obtained engineering stress-strain data. From the engineering stress-strain data, true stresses and strains have been found out up to the ultimate stress, using standard correlations. True stress-plastic strain curves for input to numerical analysis were generated at room temperature, -50°C, -100°C and -150°C and the plot of the same is shown in Fig.1.

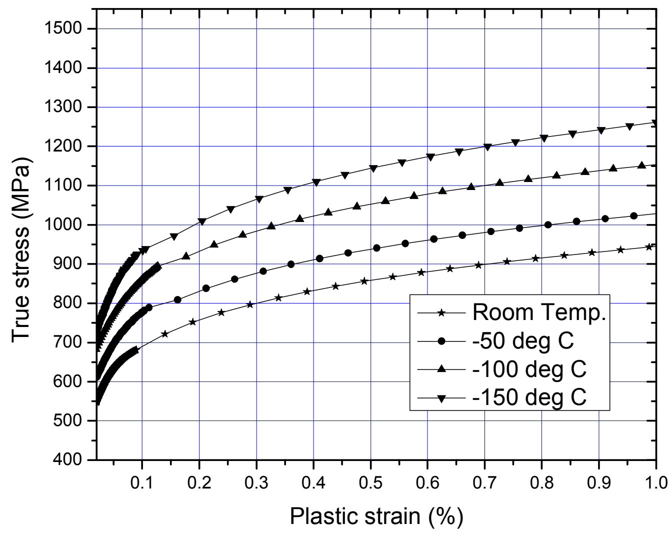

Fig.1. True stress- plastic strain curves (Input to MADAM CODE)

Input true stress-strain data is used and the simulation is carried out. Numerically generated load vs diametral contraction curve is compared with the existing experimental load displacement curve. As discussed in previous paragraph, slight mismatch is observed. To find the beremin's parameters it is required to match the curves especially at breaking load region. Breaking load is considered as ranking parameter to determine beremin's parameters. Percentage difference between the experimental breaking load and load on numerical curve corresponding to the diametral contraction of experimental breaking load is found. Based on this percentage difference value at breaking load, input stress-strain curve is varied.

FE MODELING AND ANALYSIS OF ROUND NOTCHED TENSILE SPECIMENS (RNTS)

Dimensions of RTNS are shown in Fig. 2. The meshes for 90 notched tensile specimens (30 specimens each at -50°C, -100°C & -150°C) were generated using in house code FEMSHAPE. In case of RNTS as the specimen has two axis of symmetry, only one fourth of the specimen was modeled. The geometric models were made such a way that the mesh size near the crack tip was equal to two times the critical length. Meshes away from the crack path were intentionally made large to reduce computational time. All the elements were 2D 8-node iso-parametric elements. The output file of FEMSHAPE was used to make input file for MADAM code. 2D mesh generated for RNTS is shown in Fig. 2. The total number of elements and nodes formed by meshing the finite element model of notched tensile specimen are 2380 and 7389 respectively. The element size at the notch root is 0.05mm X 0.05mm. This size relates to reference volume 'V_0' which is taken as 0.001 mm^3 in this analysis which is of the same order as the dimensions of micro structural features such assize of ferrite grains in the material. Loading is applied as homogeneously prescribed displacements in axial direction at the top edge of the model.

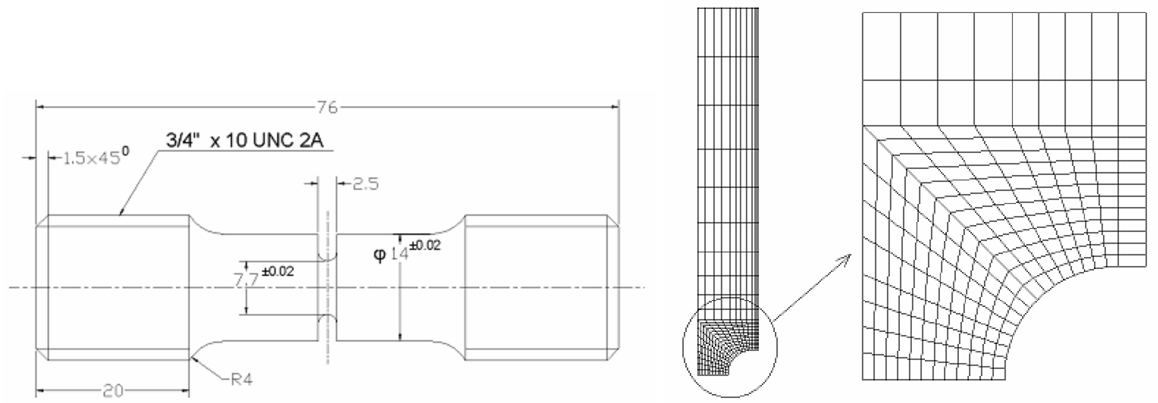

Fig. 2. Dimensions of notched tensile specimen and FE model of grooved tensile specimen showing enlarged view of grooved region.

FEM analysis was carried out by using in house developed MADAM code. 30 RTNS specimens in each test temperature (-50°C, -100°C & -150°C) showed a nearly identical load deformation behavior up to the respective failure point are used for the application of beremin's model.

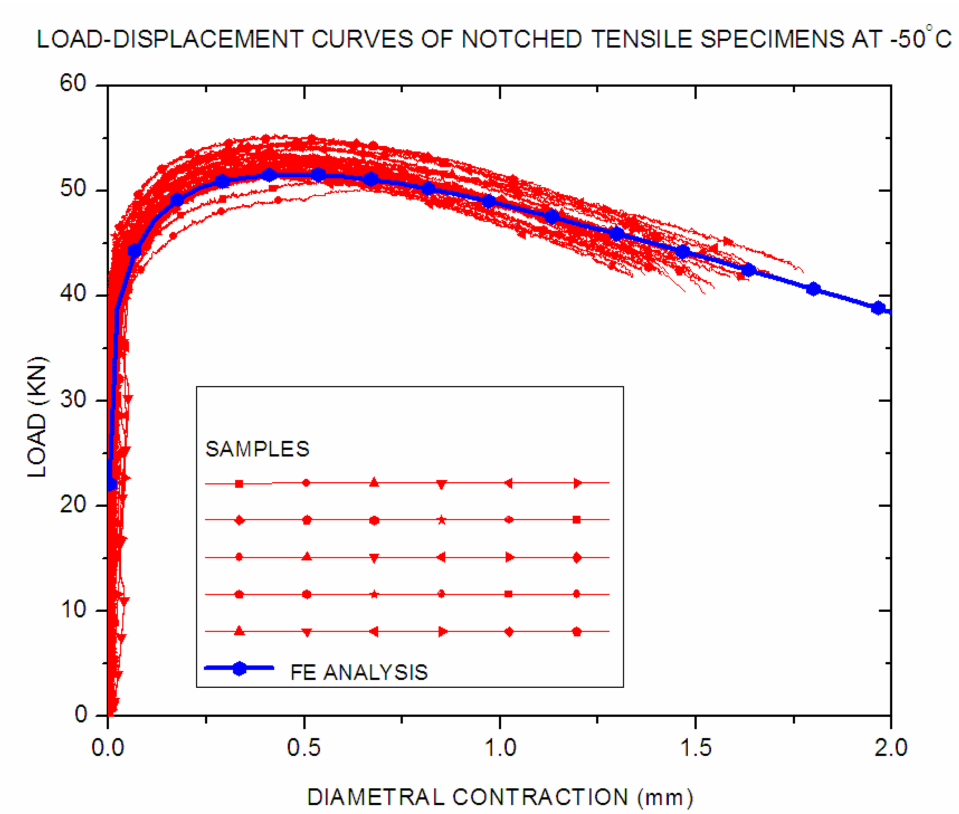

Fig.3. Comparison of experimental & numerical load-diametral contraction plots at -50°C

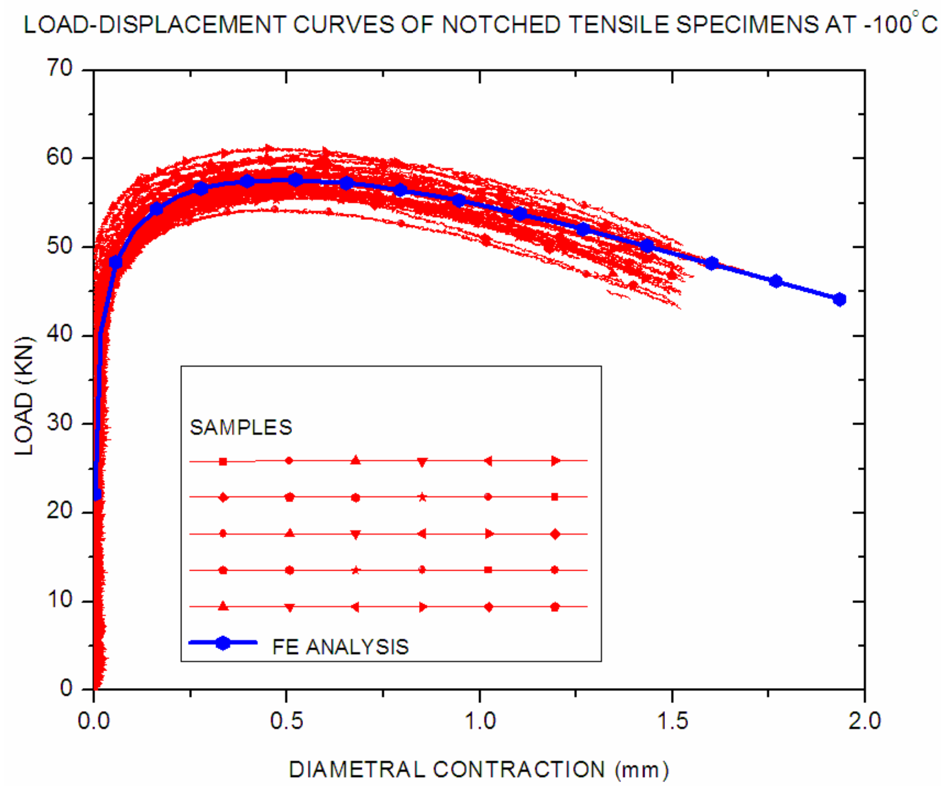

Fig.4. Comparison of experimental & numerical load-diametral contraction plots at -100°C

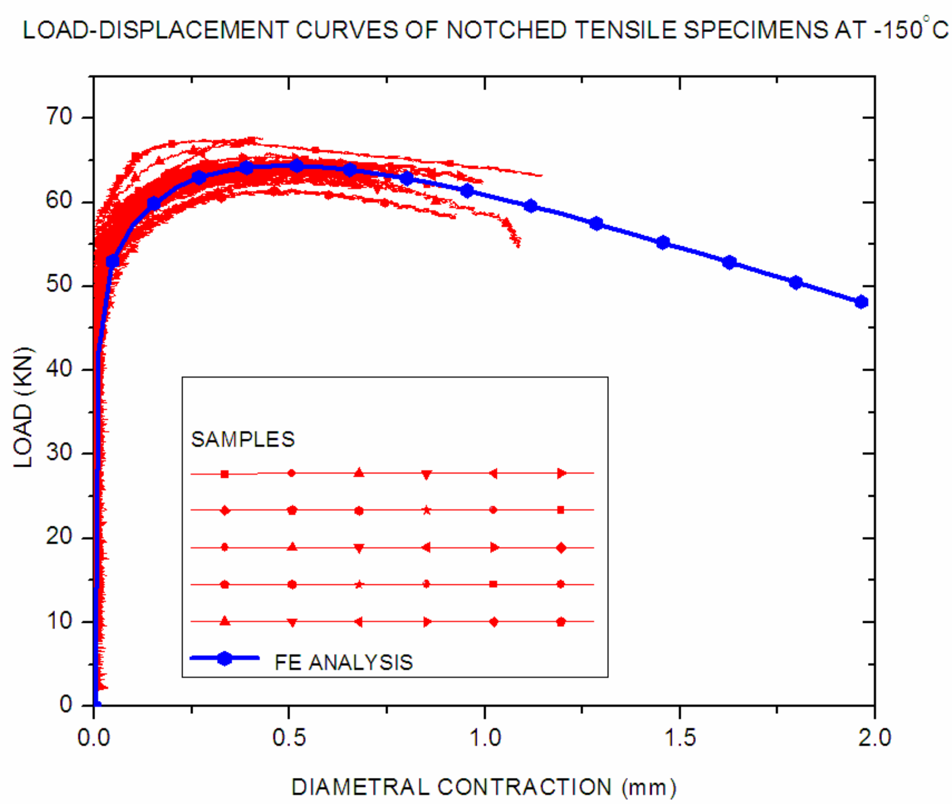

Fig.5. Comparison of experimental & numerical load-diametral contraction plots at -150°C

CALCULATION OF BEREMIN'S PARAMETERS

Beremin parameters are material properties which are found by employing local approach to cleavage fracture analysis. Weibull statistics is considered as a well-established characterization tool in the field of fracture strength of brittle materials [4]. Weibull equation describes the relationship between the probabilities of failure P_f of a perfectly elastic body under a uniaxial tensile stress. It thus predicts the inherent dispersion in fracture strength of brittle materials. Once a set of N experimentally measured fracture stresses are obtained, it is desirable to fit the weibull equation (Eq. 2) to these observations, i.e. to estimate the two parameters m and σ_u, knowledge of which leads to complete characterization of the material for the given volume. Maximum likelihood estimator is used in estimation of weibull parameters, as this estimator leads to the least dispersion, i.e. best reproducibility, for all sample sizes [4].

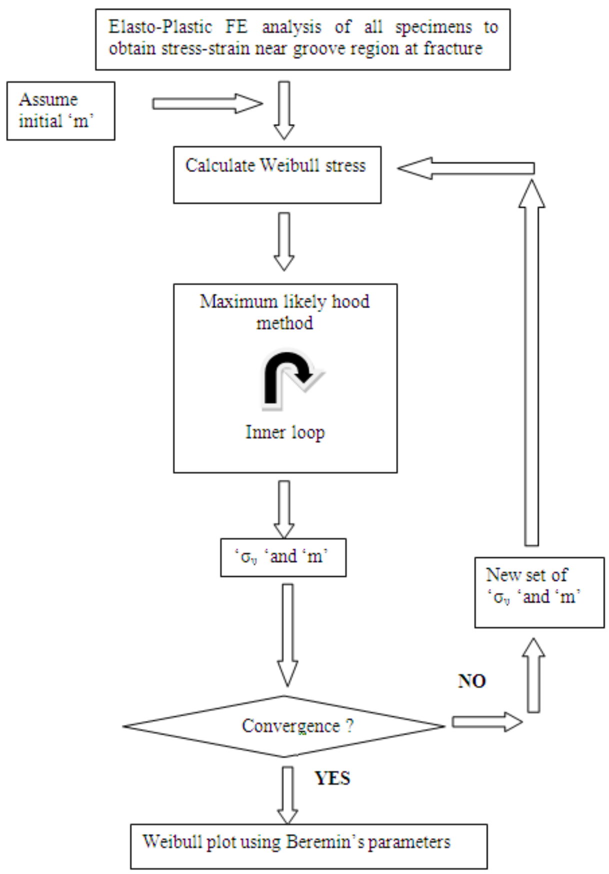

Fig.6. Algorithm to compute Beremin's parameters

Flow chart indicating the algorithm used to compute beremin's parameters is shown in Fig. 6. A conventional elasto-plastic analysis based on the theory of von mises with associated prandtl-reuss flow rule has been used. The failure probability is described by means of a weibull statistics as shown in Eq. 2. The weibull stress 'σ_w' has been calculated using a post-processor program according to Eq. 3. The summation in Eq. 3 has been performed over the gauss points of an element after putting the maximum principal stress to the power 'm' (initially assumed value, m=22). σ_w has been calculated for every specimen, i.e., up to the time step which corresponds to the fracture event and the time step in the finite element (FE) analysis has to be realized with a monotonically increasing ranking parameter. Both fracture load and ΔD at the point of fracture of each specimens has been taken as ranking parameter for ranking the fractured specimens. If N (=30) specimens have been tested, the relative fracture probability is given by h_j= (j-0.5)/N. This probability is assigned to the j^{th} rank in an ascending sequenced sample of N specimens. The parameters σ_u and m, they have been estimated using maximum likelihood method. An initial value of m deviates from that used in the previous iteration, the procedure is repeated until the difference of two iteration steps, Δm is less than 0.001. Calculated Beremin's parameters are listed in Table 2. Probability of failure (P_f) is calculated and the same is plotted against weibull stress (σ_w). The entire procedure is repeated for -50°C, -100°C and -150°C. Plot of P_f Vs σ_w is shown in Fig. 7.

Table 2. Beremin's parameters at -50°C, -100°C & -150°C

Temperature (ºC)	σ_u (Mpa)	m_{corr}
- 50	$2182.2 \leq 2200.9 \leq 2220.1$	$27.922 \leq 37.249 \leq 45.426$
- 100	$2438.8 \leq 2460.3 \leq 2482.3$	$27.587 \leq 37.050 \leq 45.293$
- 150	$3438.4 \leq 3509.0 \leq 3582.0$	$11.760 \leq 15.688 \leq 19.132$

Probability of failure (P_f) was found for each sample by employing σ_u and m. P_f and σ_w are plotted for -50ºC, -100ºC & -150ºC and the same is shown below.

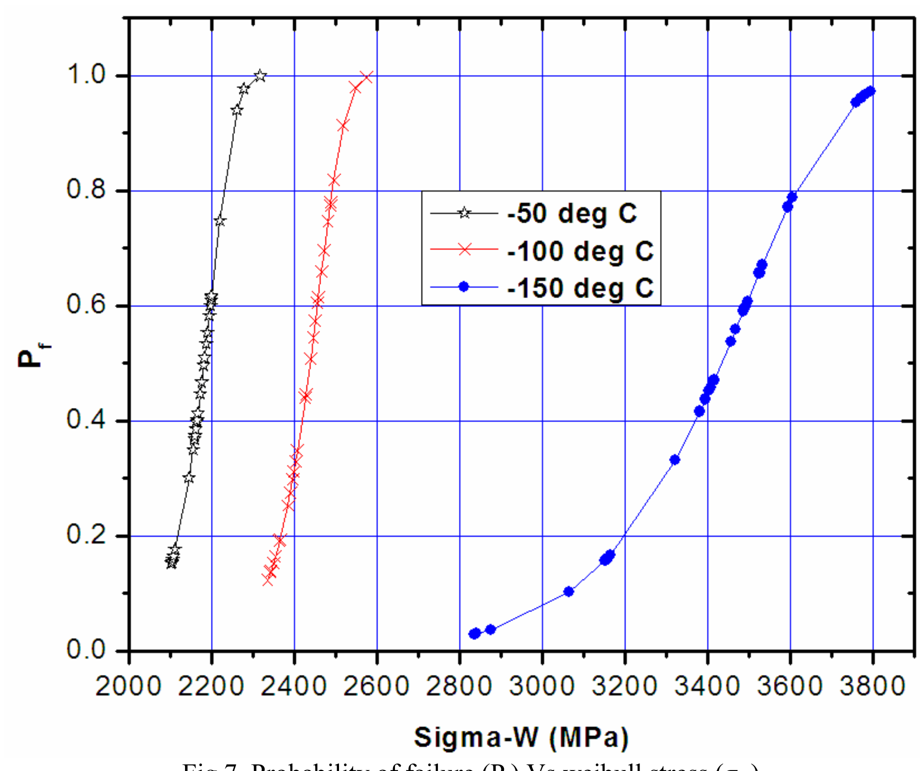

Fig.7. Probability of failure (P_f) Vs weibull stress (σ_w)

From Fig. 7. we can say that there is a sharp rise in the σ_w value for -150°C when compared to -100°C and -50°C and high scatter in the σ_w value is also noticed at -150°C.

Table 2. shows that shape parameter at -150°C is very less compared to other two temperatures considered. As notched tensile test is a static problem, i.e., test involving very less strain rate, ductile to brittle transition temperature falls between -100°C and -150°C.

Since the estimation is only based on a sample of finite size N(=30), the parameters of the entire population of all possible specimens from the material cannot be determined exactly only confidence intervals can be evaluated.

Table indicating the values of t_u, t_l, l_u and l_l are referred for no. of samples (N) considered at 90 % confidence interval. Calculation of confidence intervals for σ_u and m are shown below.

CONCLUSION

Beremin's parameters are found by FEM analysis of finite no. of notched tensile samples. True stress-strain data under uniform loading conditions of smooth tensile samples were used for FEM analysis of RTNS samples. In order to find beremin's parameters, it is required to find the weibull stress at the breaking load. As it is practically not possible to measure weibull stress directly, numerical methods are used. Due to anisotropy in the material, numerical curve may not match exactly with experimental curve. Therefore variation in the input stress strain curve is made to match experimental curve particularly at breaking load region. It is found from the simulation that variation in input stress strain data is within acceptable limits i.e., 6% variation for -50°C and -100 °C and 2% variation for -150°C.

Beremin's parameters are scaling parameter (σ_u) and shape parameter (m). Scaling parameter serves as a limiting value of weibull stress at 63.2 % failure probability. We can say that when weibull stress for a given material exceeds this limiting value, then material fails. Table 2 shows σ_u at three temperatures and it is increasing as temperature decreasing. This behavior is due to dislocation pile-ups because of decrease in mobility of dislocations at low temperatures. Shape parameter represents the scatter in σ_u value for different specimens. If m value is high then scatter is low. It is found that with decrease in temperature, m value is decreasing represents more scatter. This shows that material is becoming more brittle with decreasing temperature. Confidence intervals (90%) are evaluated for beremin's parameters, so that 90% of the times beremin's parameters value lies in this interval for a given material.

REFERENCES

1. USNRC Regulatory Guide 1.99 Rev. 2, May 1988.
2. Landes, J.D., Shaffer, D.H., *Fracture mechanics, Twelfth conference,* ASTM STP 700, pp.368-382, Philadelphia, 1980.
3. F.M. Beremin, A local criterion for cleavage fracture of nuclear pressure vessel steel, Metall. Trans. A, 14A (1983) 2277-2287.7.
4. A. Khalili, K. Kromp, Statistical properties of Weibull estimators, Journal of Material Science, 26 (1991) 6741-6752.
5. Miami, F., Bruckner, F., Munz, D.,Trolldenier, B., International journal of fracture, Vol. 54, 1992, pp. 197-210.
6. G. Bernauer, W. Brocks, W. Schmitt, Modifications of the Beremin model for cleavage fracture in the transition region of ferritic steel, Engineering Fracture Mechanics 64 (1999) 305-325.
7. O. Cleizergues, T. Sturel, M. Difant and F. Mudry, Development and Use of Beremin Local Criterion for Cleavage Fracture in the Steel Industry, JOURNAL DE PHYSIQUE IV, Colloque C6, suppl6ment au Journal de Physique 111, Volume 6, October 1996.
8. BARC report on "Modeling of ductile and cleavage fracture by local approach" by M.K.Samal, B.K.Dutta and H.S.Kushwaha.
9. B. K. Dutta, S. Guin, M. K. Sahu and M. K. Samal, Temperature Dependency of Beremin's Parameters for 20MnMoNi55 Material, Transactions, SMiRT 19, Toronto, August 2007.

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