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Modelling the Constraint Effect on Reference Temperature with Finite Element Parameters for Reactor Pressure Vessel Material 20MnMoNi55 Steel

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ABSTRACT

A series of experiments were performed in the ductile to brittle transition region on three-point bending specimens of different thicknesses and a/W ratio of 20MnMoNi55 steel. Master curve and reference temperature (T_0) are obtained as per ASTM E1921-02 with different thickness and a/W ratio of the specimen and a variation of T_0 is obtained, which indicates constant dependent on T_0. Mathematic models are formulated to correlate T_0 with Q-stress, T-stress and Triaxiality ratio to count for the constraint loss. Both the average value and also the maximum value of the finite element parameters are considered to predict T_0 at different constraint label and compared with the experimental results.

Keywords: Reference temperature; T-stress; Q-stress; Triaxiality ratio

1. INTRODUCTION

Reactor pressure vessel materials, such as 20MnMoNi55 low carbon steel, used in this work show a ductile nature in the upper-temperature domain and a brittle nature in the lower temperature domain. Within the transition region, fracture toughness is scattered and depends on temperature[1]. Master curve methodology developed by Wallin[2] is able to capture both scatter and temperature dependence of fracture toughness in the transition zone using the weakest link theory to the random distribution of potential nucleation sites in ferrite steels for modelling cleavage fracture in the transition region using 3 parameters Weibull distribution. Reference temperature (T_0) is the vital parameter of master curve which is defined as that temperature at which the median fracture toughness of the material is 100 MPa√m[3-4]. The major achievement of this parameter lies in the fact that it could be determined by at least 6 numbers of tests.

For RPV material 20MnNMoNi55 steel, master curve and reference temperature (T_0) is determined as per ASTM E1921-02 for TPB specimen of different thickness and a/W ratio. Reference temperature obtained shows a variation with thickness and a/W ratio which indicates clear dependence on the constraint level[5]. The reference temperature, is a measure of the degree of embrittlement and useful for comparison of materials. But the T_0 obtained from E1921 is questionable when applied for assessments of structural defects. Structures most often have shallow, surface-breaking or embedded defects and are loaded predominantly in tension not bending, and the local *J* values vary strongly along the crack fronts. The "applicability" of T_0 values obtained from high-constraint, straight through-cracks to real applications requires additional models that accommodate the effect of differences in constraint level (such as dimensions, geometry, etc.) and variations in local J values. Micromechanical models for brittle fracture offer the most promising approach at present to understand toughness transferability issues and to develop quantitative frameworks. In order to relate the variation in T_0 with thickness and a/W ratio in terms of constraint, it is required to investigate the stress scenario at failure near the crack tip. Many researchers used different finite element parameters like *Q-Stress, Triaxiality ratio, T-stress*, to study the effect of constraints on T_0.

Moattari & Sattari-Far[6] studied the constraint loss in fracture specimen with the help of the *Q-Stress* parameter for the material A516 Gr 70 steel. They established a relationship between Q-Stress and T_0 and verified with the experimental results. Graba[7] tried to capture the constraint effect near the crack tip for a centrally cracked specimen for various elastic-plastic materials. Gao[8], *et al.* tried to capture the constraint loss effect in terms of *T-stress* to predict T_0 shift between single edge notch bend specimens (SEN(B)) with deep cracks and compact tension specimens (CT) specimens, and also between SEN(B) specimens with deep and shallow cracks.

Wallin[9] relates the loss of constraint effect on the specimen with T_0 by *T-stress*. He showed nearly a linear relation between T_0 and *T-stress* and verified experimentally for various crack depths of SEN(B) specimens. Bhowmik[10], *et al.* tried to capture the effect of constraint loss on T_0 for CT specimen of 20MnMoNi55 steel with the help of the Triaxiality ratio.

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In the present work, the constraint loss effect is studied vividly for the TPB specimen of 20MnMoNi55 steel in light of *Q-stress, Triaxiality ratio*, and *T-stress*. A separate mathematical model is established for each of the parameters relating to reference temperature T_0 and compared with the experimental results.

Both maximum value and the average value of the parameters are calculated but in some cases, average values give better-predicted values and in other cases, maximum values give more compatible results which are discussed in this work.

2. EVALUATION OF T_0 FROM SINGLE TEMPERATURE TEST DATA

The temperature dependence of the median fracture toughness in the transition region is described by in Eqn. (1).

$$K_{JC(median)} = 30 + 70\exp\left[0.019\left(T - T_0\right)\right] \quad (1)$$

The master curve along with reference temperature value completely defines the transition toughness curve in a manner appropriate for use in both probabilistic and deterministic analysis which is adopted in ASTM-E1920-06. In this work Reference temperature (T_0) has been determined for 20MnMoNi55 steel using TPB specimens of different thicknesses and different a/W ratio and a variation of T_0 is observed For single temperature evaluation, the estimation of the scale parameter K_0 is performed according to the Eqn. (2).

$$K_0 = \left[\sum_{i=1}^{N} \frac{\left(K_{JC(i)} - K_{\min}\right)^4}{N}\right]^{1/4} + K_{\min} \quad (2)$$

The fracture toughness for a median (50 %) cumulative probability of fracture is determined using Eqn. (3),

$$K_{JC(median)} = K_{\min} + \left(K_0 - K_{\min}\right)\left(\ln 2\right)^{1/4} \quad (3)$$

Here $K_{JC(i)}$ is the individual $K_{JC(1T)}$ value and N is the number of K_{JC} values. The term N is replaced by the number of valid K_{JC} values (if censored K_{JC} values are included) in the calculation. The $K_{JC(median)}$ value is determined for the data set at test temperature and has been used to calculate T_0 at $K_{JC(median)}$ of 100 MPa√m by applying Eqn. (4).

$$T_0 = T_{test} - \frac{1}{0.019}\ln\left[\frac{K_{JC(median)} - 30}{70}\right] \quad (4)$$

3. MATERIAL DETAILS

The material used in the present study is 20MnMoNi55 low carbon steel which is an RPV application steel. 20MnMoNi55 is basically a German designated material. A test block of this material is received from the Bhaba Atomic Research Centre (BARC), India. The chemical composition of the material is furnished in Table 1.

4. EXPERIMENTAL ANALYSIS

4.1 Experimental details of Fracture Toughness Test

Figures (1) and (2) show the experimental set up for fracture toughness test under cryogenic condition. On Instron 8801 testing machine the experiments are performed and the cryogenic conditions are maintained by the flow of liquid nitrogen. Fracture toughness at failure (J_C) is obtained from the J-Δa results for different thicknesses and a/W ratio. Fracture toughness tests are done in accordance with ASTM E1820 and the method is applied especially to specimens having notch or flaws that are sharpened with fatigue cracks on Standard TPB specimens which are machined according to ASTM E399-90 standard.

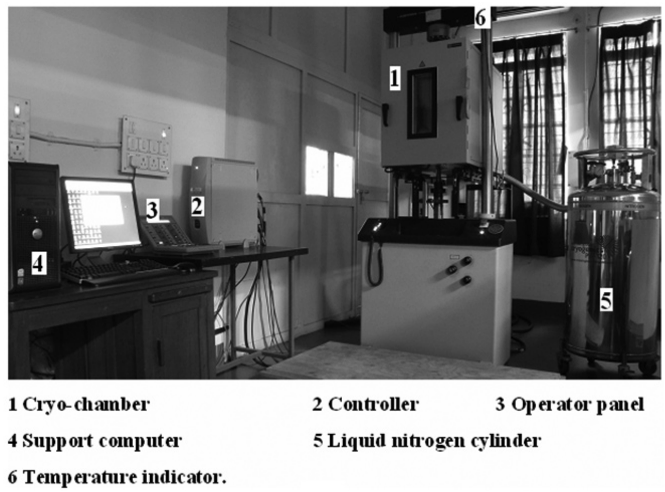

Figure 1. Experimental arrangement for low temperature *Jc* test.

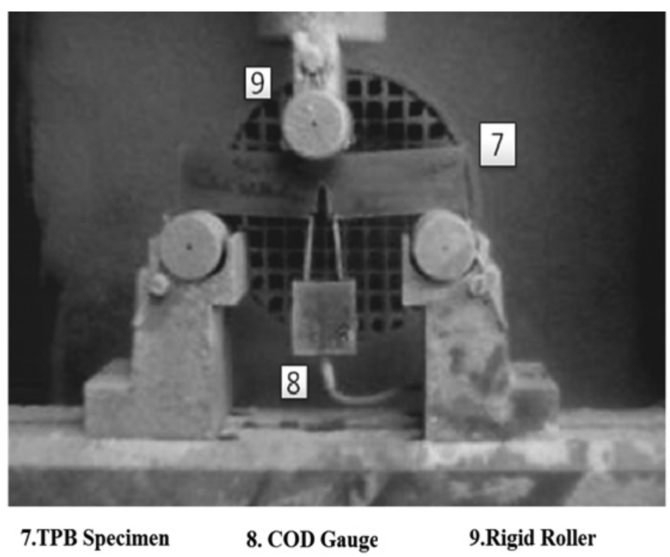

Figure 2. Experimental set up of TPB specimen for low temperature *Jc* test.

Table 1. The different chemical compositions of the material

Elements	C	Si	Mn	P	S	Al	Ni	Mo	Cr	Nb
Percentage Composition (in weight)	0.20	0.24	1.38	0.011	0.005	0.068	0.52	0.30	0.06	0.032

Table 2. J_{1c} values collected from the experiment at a fixed temperature of -110 °C

a/W / Thickness	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7
8 mm		151.33	617.24				187.69	
10 mm		290.56 75.84	77.44 146.35	336.82	44.28			
12mm		449.283	153.257	199.90		65.55 105.08	92.7	
15 mm	314.1	114.39	182.48	210	353.413	191.553	138.92	
20 mm		78.39	282.12	224.58	206.71	170.28	518.69 153.7 121.38 429.52	118.33
25 mm		171.9148	150.7126	167.9186	127.662	281.699	140.12	
30 mm				288.51	103.083 254.54	88.174	99.974	71.94

4.2 Constraint Effect on T_0

The variation of T_0 with a/W ratio is shown in the Fig. 3 and with thickness in Fig. 4

It is seen that from Fig. 4 as expected fracture toughness increases with decreasing thickness as it is moving from plain strain to plain stress condition, but this phenomenon continues up to 20 mm. After that, it is seen that the fracture toughness falls with decreasing thickness this trend is also described by T.L. Anderson while studying the Effect of Thickness on Apparent Fracture Toughness. It is seen from Wallin's[9] that for the material which he used in case of TPB specimen fracture toughness remains practically constant for crack size above a/w=0.3, and for a/W less than 0.3 fracture toughness increases with decreasing crack depth.

For 20MNMONI55 steel (the material which was used in our work) was observed that in case of TPB specimen fracture toughness remains practically constant for crack size above a/w=0.4 and for a/w less than 0.4 fracture toughness increases with decreasing crack depth. as shown in Fig. 3.

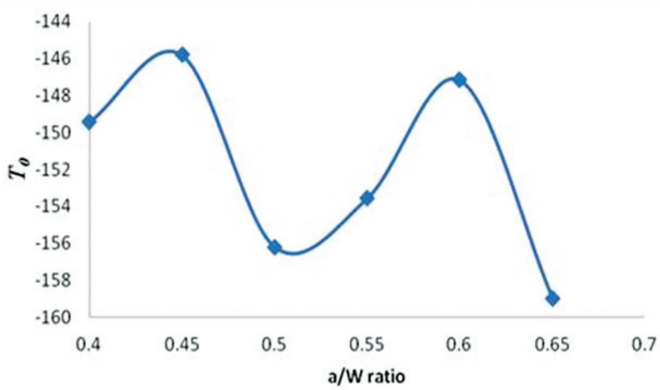

Figure 3. The variation of T_0 with a/W at a fixed test temperature of -110 °C.

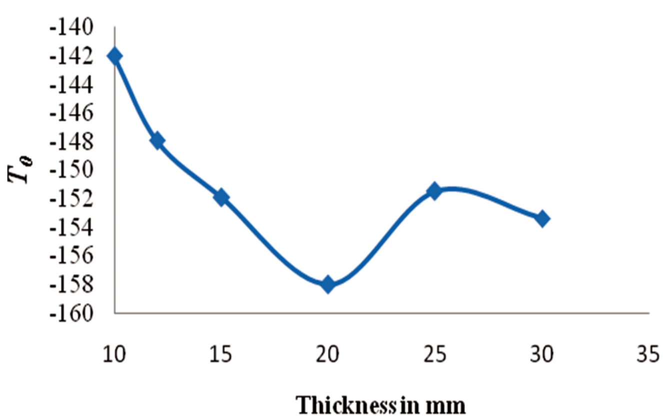

Figure 4. T_0 variation with thickness.

5. FINITE ELEMENT ANALYSIS FOR COMPUTING T-STRESS, TRIAXIALITY RATIO AND Q-STRESS AT FAILURE POINT FOR TPB SPECIMEN

Elastic-plastic finite element analyses for all the fracture tests are performed using ABAQUS 6.13. The material constitutive properties are defined by Young's modulus E and Poisson's ratio, and Yield stress versus plastic strain obtained from tensile test data performed at -110 °C in Universal Testing ν Machine (Instron 8801)[11-12]. Isotropic elastic and isotropic hardening plastic material behaviour are considered for the material used.

3-D finite element modelling is done for quarter TPB specimens of respective *a/W* ratio and thickness to calculate the stress at the crack tip. The FE model has meshed with 8-node isoparametric hexahedral elements with 8 Gauss points taken for all calculations as referred by IAEA-TECDOC-1631[13]. Reduced integration with full Newtonian non-linear analysis computation is carried out for all the specimens. In the region ahead of crack tip the mesh was refined with element volume of 0.05 x 0.05 x 0.05 mm^3 as shown in Fig. 5.

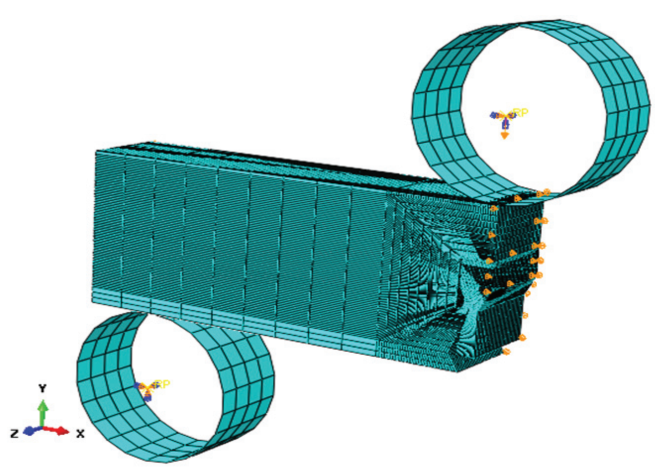

Figure 5. Showing boundary condition and mesh distribution on TPB specimen of a/W = 0.5.

6. VALIDATION OF THE FE MODEL AND MATERIAL PROPERTIES

Figure 6 gives a comparison between experimental load versus load line displacement (LLD) of TPB specimen with FE simulated results from Abaqus 6.13 at the referred test temperature. The FEA results show a close match with experimental results that validate the FE model, material parameters used. Now for each analysis, Weibull stress at failure point can be computed from FE simulated results.

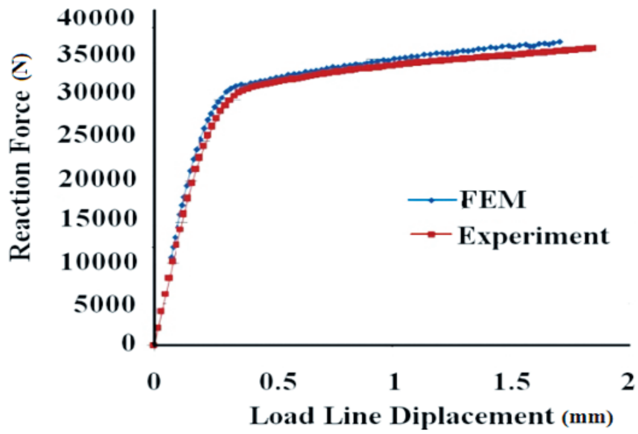

Figure 6. Comparison of load *vs* load line displacement -110°C.

7. RESULT AND DISCUSSION

7.1 Finite Element Analysis for TPB Specimen

$$\text{Triaxiality } Ratio = \frac{\sigma_{Hydrostatic}}{\sigma_{Equivalent}} \tag{5}$$

$$\sigma_{hydrostatic} = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3} \tag{6}$$

$$\sigma_{equivalent} = \frac{1}{\sqrt{2}} \sqrt{\left[\left(\sigma_{xx} - \sigma_{yy}\right)^2 + \left(\sigma_{yy} - \sigma_{zz}\right)^2 + \left(\sigma_{zz} - \sigma_{xx}\right)^2 \right]} \tag{7}$$

Figure 7 shows triaxiality variation with the thickness of the specimen. Average triaxiality is the average of Triaxiality ratio calculated from all nodal values along the width of the specimen in the middle plain and maximum triaxiality is the maximum value among all the nodes along the width of the specimen in the middle plain which occurs at a distance of 2 mm from the crack tip as shown in Fig. 8. T_0 predicted wrt a/W ratio 0.5 for both maximum and average value of triaxiality are calculated. The average value prediction of triaxiality provides better matching with experimental results as per Eqn. (10). Matiching result with experiments are also obtained while predicting T_0 wrt the thickness of 25 mm taking the maximum value of triaxiality are also obtained using Eqn. (13).

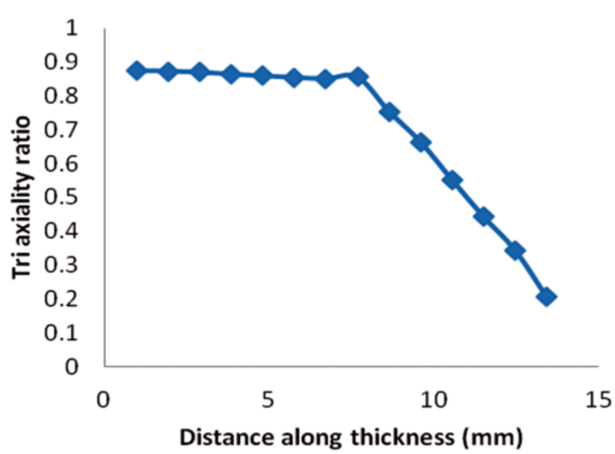

Figure 7. Tri axiality ratios *vs* thickness (mm).

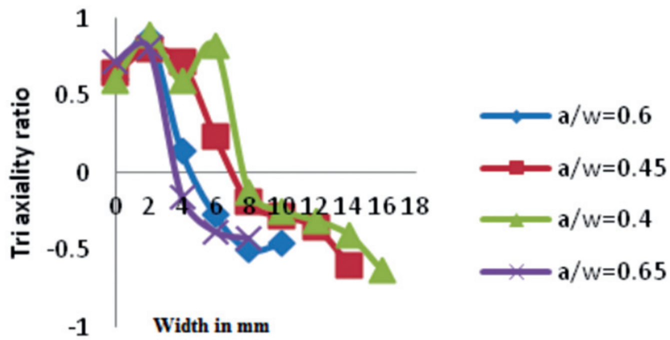

Figure 8. Showing Triaxiality variation for different a/W ratio along width of specimen.

7.2 Mode of Q-Stress Calculation

Q-stress is calculated along the crack face and its distribution with thickness is shown in Fig. 9. Prediction of T_0 wrt a/W ratio 0.5 and thickness 25 mm are done both for maximum and average value of Q-stress.

$$Q = \frac{(\sigma_{\theta\theta})_{Hydrostatic} - (\sigma_{\theta\theta})_{HRR}}{\sigma_0} \text{ at } \theta = 0,\ r = \frac{2J}{\sigma_0} \tag{8}$$

where $(\sigma_{\theta\theta})_{HRR} = \sqrt{\frac{J_c}{R}}$ and σ_0 = Yield stress.

7.3 Mode of T-stress Calculation

T-stress is defined by

$$T = \left[\frac{\sigma_{yy} - \sigma'_{yy}}{y} \right] E \tag{9}$$

where σ_{yy} is stress in the Y-direction at the crack tip, σ'_{yy}

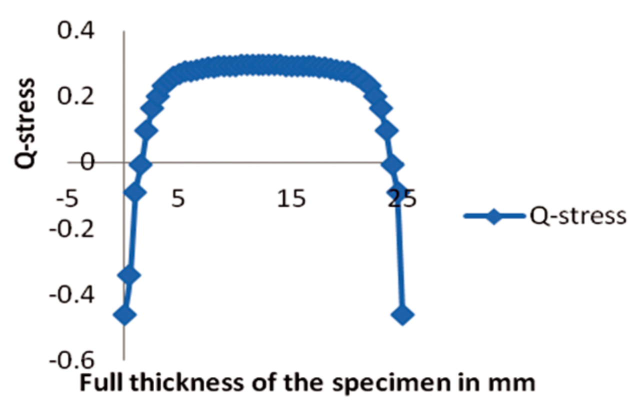

Figure 9. Q-Stress variation with thickness of the specimen.

is stress in the *Y*-direction at the end point, *Y* is distance between this two points, E is Young's Modulus of the material. As T-stress is calculated from the 2D analysis so the only maximum value of T-Stress is taken as shown in Fig. 10.

Prediction of T_0 wrt a/W ratio 0.5 is obtained with the help of Eqn. (12) and prediction of T_0 wrt the thickness of 25 mm are obtained with the help of Eqn. (15).

7.4 Prediction of T_0 from Triaxiality ratio, Q-stress, and T-Stress.

Prediction of T_0 wrt a/W ratio 0.5 with different parameters *Tri axiality ratio, Q-Stress, T-Stress* are shown and compared with experimental results together and shown in Figs. 11 and 12. In Figure 11 the matching is observed to be best for results obtained using Q-stress for both thickness and a/W ratio "is replaced with" the predicted T_0 by the constraint parameter T_0 correlation for all three parameters with a/W ratio and thickness agrees well with experimental values within ±10°C. This is well within experimental error

$$T_{0(xx)} = \left[\left\{ \left(TriaxialityRatio_{(xx)} - TriaxialityRatio_{(0.5)} \right) * (-100) \right\} - 0.1 \right] + T_{0(0.5)} \quad (10)$$

$$T_{0(xx)} = \left[\left\{ \left(Q\_Stress_{(xx)} - Q\_Stress_{(0.5)} \right) * (-100) \right\} + 0.1 \right] + T_{0(0.5)} \quad (11)$$

$$T_{0(xx)} = \left[\left\{ \left(T\_Stress_{(xx)} - T\_Stress_{(0.5)} \right) * (-50) \right\} - 0.5 \right] + T_{0(0.5)} \quad (12)$$

$T_{0(xx)} =$ reference temperature (T_0) of any a/W ratio.
$T_{0(0.5)} =$ reference temperature (T_0) of a/W ratio 0.5, as a specimen with a thickness of 25 mm and a/W ratio 0.5 is taken as reference for calculation.

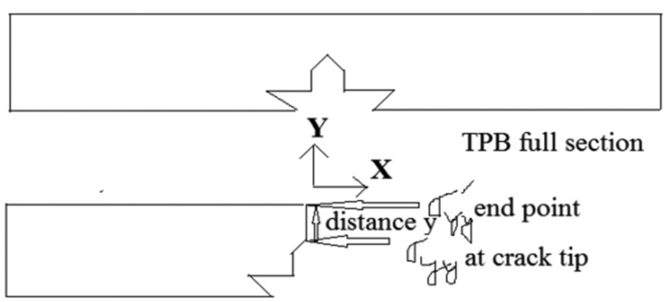

Figure 10. TBP half section.

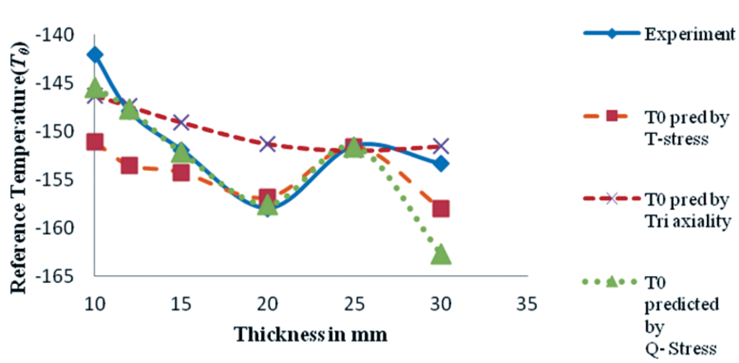

Figure 11. Predicted variation of T_0 from Triaxiality ratio, T-Stress and Q-stress with a/W ratio of the specimen.

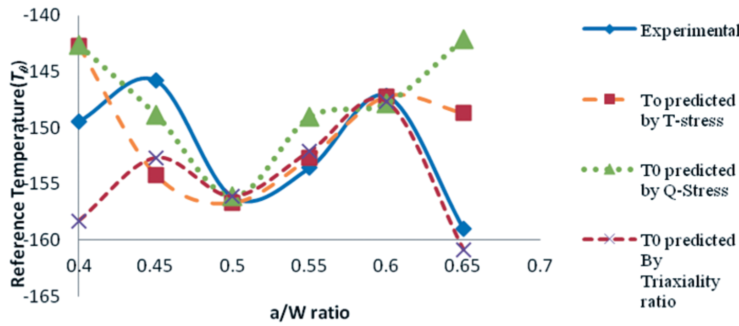

Figure 12. Predicted variation of T_0 from Triaxiality ratio, T-Stress and Q-stress with a thickness of the specimen.

Tri axiality ratio Q-Stress$_{(xx)}$, *T-stress*$_{(xx)}$ for any a/W ratio of the specimen which can be calculated from finite element analysis. *Tri axiality ratio*$_{(0.5)}$ *Q-Stress*$_{(0.5)}$, *T-stress*$_{(0.5}$ for a/W ratio 0.5 which is calculated from finite element analysis.

Prediction of T_0 wrt the thickness of 25 mm with different parameters *Tri axiality ratio, Q-Stress, T-Stress* are shown and compared with experimental results together and shown in Fig 12.

$$T_{0(xx)} = \left[\left\{ \left(TriaxialityRatio_{(xx)} - TriaxialityRatio_{(25)} \right) * (-20) \right\} - 0.5 \right] + T_{0(25)} \quad (13)$$

$$T_{0(xx)} = \left[\left\{ \left(Q\_Stress_{(xx)} - Q\_Stress_{(25)} \right) * (-20) \right\} - 0.1 \right] + T_{0(25)} \quad (14)$$

$$T_{0(xx)} = \left[\left\{ \left(T\_Stress_{(xx)} - T\_Stress_{(25)} \right) * (-5) \right\} - 0.1 \right] + T_{0(25)} \quad (15)$$

$T_{0(xx)} =$ reference temperature (T_0) of any thickness
$T_{0(0.5)} =$ reference temperature (T_0) of a/W ratio 0.5, as specimen with thickness 25 mm and a/W ratio 0.5 is taken as reference for calculation.

T-Stress$_{(xx)}$, *Q-Stress*$_{(xx)}$, *T-stress*$_{(xx)}$ for any thickness of the specimen which can be calculated from finite element analysis. *T-Stress*$_{(25)}$, *Q-Stress*$_{(25)}$, *T-stress*$_{(25)}$ for 25 mm thickness which is calculated from finite element

8. CONCLUSION

Variation of reference temperature (T_0) with a/W ratio and thickness of the specimen is observed from experimental results. In order to analyze this variation of T_0 some finite element parameters are put forward to account for this variation. The parameters which are nurtured in this work are Q-Stress, T-Stress and Triaxiality ratio. An attempt has been put forward to predict T_0 with the help of these parameters wrt a generally accepted a/W ratio 0.5 and thickness of 25 mm for TPB specimen. Predicted T_0 provides a qualitative and quantitative matching with the experimental results. From this study, it could be predicted that the effective study of constraint loss can be done with the help of these parameters.

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Contribution in the current study, he has guided with his vast experience in the Finite Element Analysis of the work.

Dr Jayanta Chattopadhyay done his PhD from University of Stuttgart, Germany. He is Outstanding Scientist & Head, Reactor Safety Division Hall-7, Bhabha Atomic Research Centre Trombay, Mumbai, India and Professor, Homi Bhabha National Institute, Anushaktinagar, Mumbai, India. His research area is Fracture mechanics the study of the influence of loading, crack size, and structural geometry on the fracture resistance of materials containing natural flaws and cracks.
Contribution to the current study, he shared his vast scientific experience to enrich the quality of the work.