

## 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<sup>1</sup>. Master curve methodology developed by Wallin<sup>2</sup> 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  $100 \text{ MPa}\sqrt{\text{m}}^{3-4}$ . 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 20MnMoNi55 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<sup>5</sup>. 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<sup>6</sup> 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<sup>7</sup> tried to capture the constraint effect near the crack tip for a centrally cracked specimen for various elastic-plastic materials. Gao<sup>8</sup>, *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<sup>9</sup> 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<sup>10</sup>, *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.

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).

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

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).

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

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

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

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  $K_{JC(\text{median})}$  value is determined for the data set at test temperature and has been used to calculate  $T_0$  at  $K_{JC(\text{median})}$  of 100 MPa√m by applying Eqn. (4).

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

**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.

**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

**4. EXPERIMENTAL ANALYSIS**

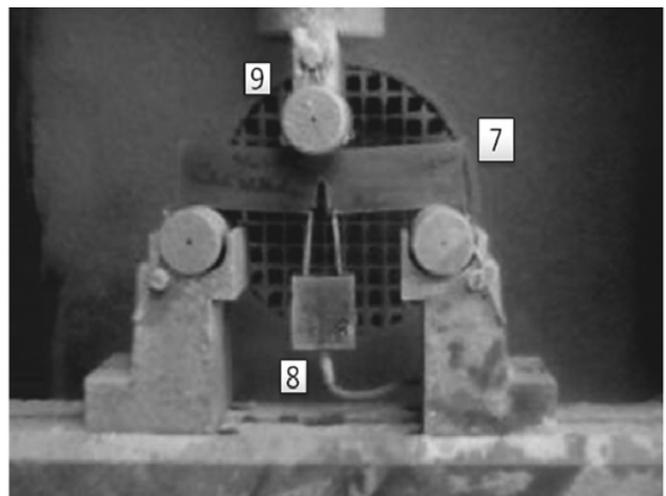
**4.1 Experimental details of Fracture Toughness Test**

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.



**1 Cryo-chamber                      2 Controller                      3 Operator panel  
4 Support computer                      5 Liquid nitrogen cylinder  
6 Temperature indicator.**

**Figure 1. Experimental arrangement for low temperature  $J_c$  test.**



**7.TPB Specimen                      8. COD Gauge                      9.Rigid Roller**

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

**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	77.44	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	88.174	99.974	71.94
					254.54			

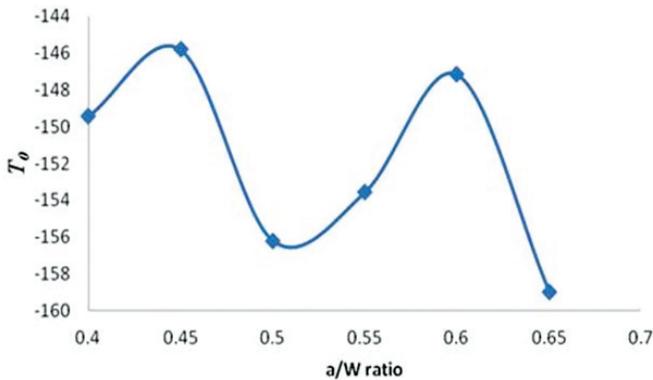
by T.L. Anderson while studying the Effect of Thickness on Apparent Fracture Toughness. It is seen from Wallin's<sup>9</sup> that for the material which he used in case of TPB specimen fracture toughness remains practically constant for crack size above  $a/w=0.3$ , and for  $a/W$  less than 0.3 fracture 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.

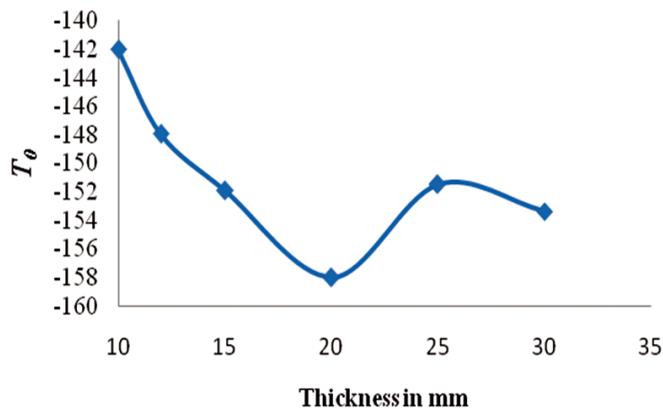
**4.2 Constraint Effect on  $T_0$**

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



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

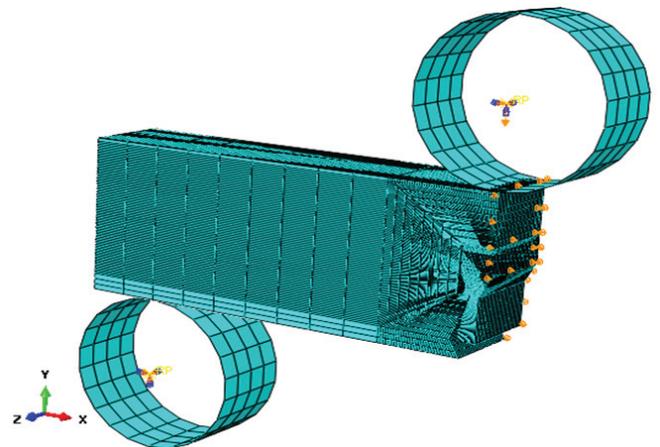


**Figure 4.  $T_0$  variation with thickness.**

**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 v Machine (Instron 8801)<sup>11-12</sup>. 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<sup>13</sup>. 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  $0.05 \times 0.05 \times 0.05 \text{ mm}^3$  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.

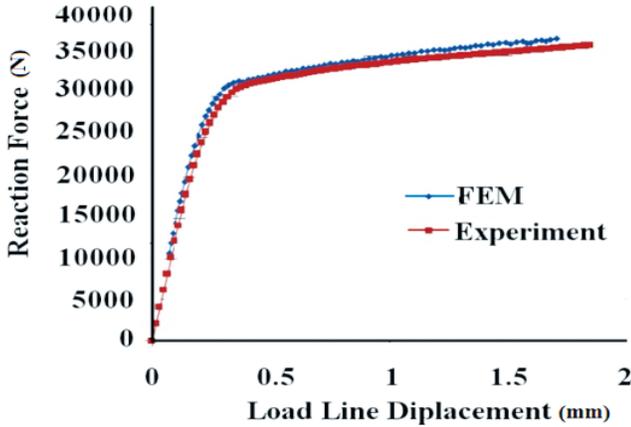


Figure 6. Comparison of load vs load line displacement -110°C.

**7. RESULT AND DISCUSSION**

**7.1 Finite Element Analysis for TPB Specimen**

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

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

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

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

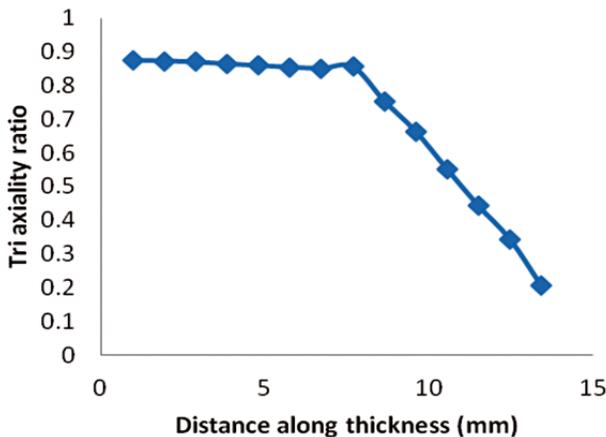


Figure 7. Tri axiality ratios vs thickness (mm).

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). Matching 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).

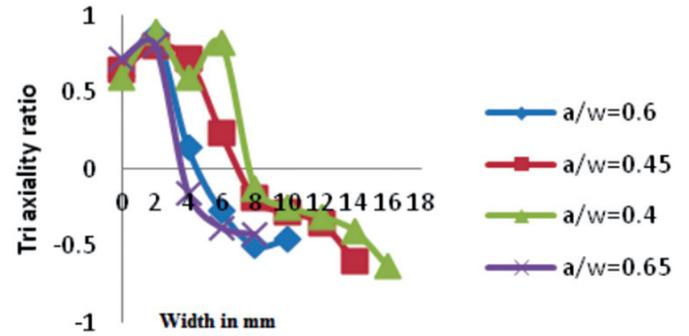


Figure 8. Showing Triaxiality variation for different a/W ratio along width of specimen.

**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  $\sigma_0 = \text{Yield stress}$ .

**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  $\sigma_{yy}$  is stress in the Y-direction at the crack tip,  $\sigma'_{yy}$

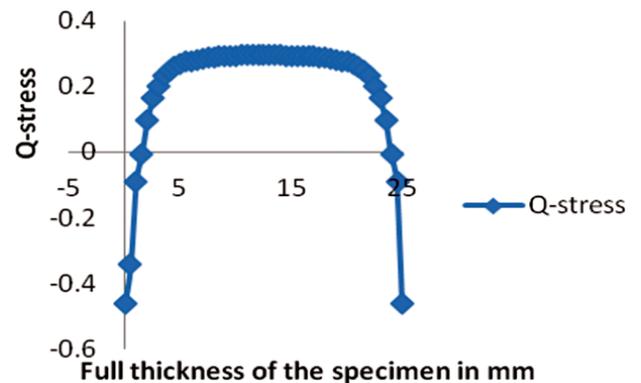


Figure 9. Q-Stress variation with thickness of the specimen.

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  $\pm 10^\circ\text{C}$ . This is well within experimental error

$$T_{0(xx)} = \left[ \left\{ \left( \text{TriaxialityRatio}_{(xx)} - \text{TriaxialityRatio}_{(0.5)} \right) * (-100) \right\} - 0.1 \right] + T_{0(0.5)} \tag{10}$$

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

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

$T_{0(xx)}$  = 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

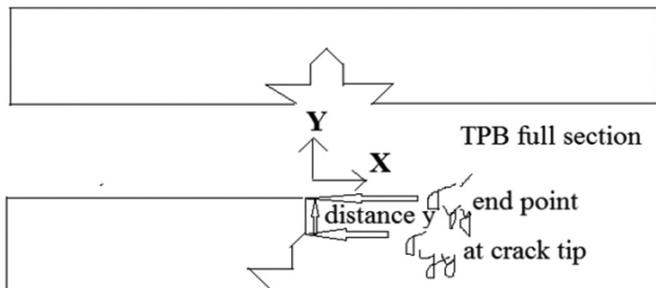


Figure 10. TBP half section.

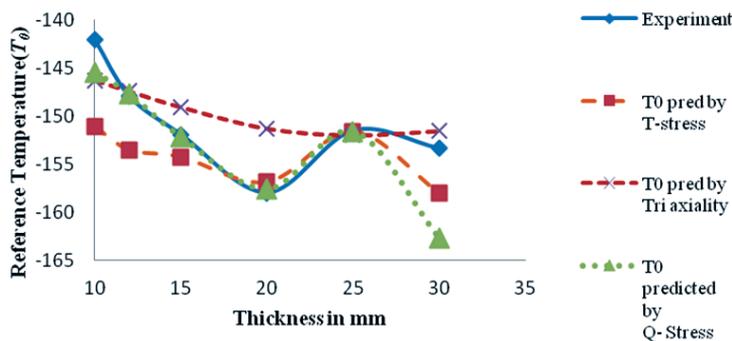


Figure 11. Predicted variation of  $T_0$  from Triaxiality ratio, T-Stress and Q-stress with *a/W* ratio of the specimen.

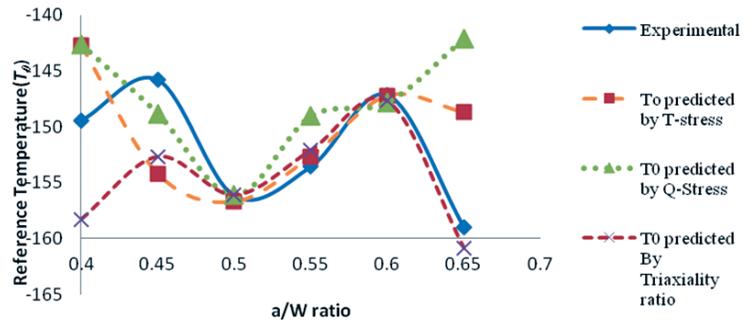


Figure 12. Predicted variation of  $T_0$  from Triaxiality ratio, T-Stress and Q-stress with a thickness of the specimen.

specimen with a thickness of 25 mm and *a/W* ratio 0.5 is taken as reference for calculation.

*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*<sub>(0.5)</sub>,  $Q\_Stress_{(0.5)}$ ,  $T\_stress_{(0.5)}$  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.

$$T_{0(xx)} = \left[ \left\{ \left( \text{TriaxialityRatio}_{(xx)} - \text{TriaxialityRatio}_{(25)} \right) * (-20) \right\} - 0.5 \right] + T_{0(25)} \tag{13}$$

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

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

$T_{0(xx)}$  = 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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