COMPARATIVE STUDY OF CRACK GROWTH DUE TO MECHANICAL AND THERMAL LOADS ON A CURVED SURFACE

Mahantesh. Matur[1], V. Krishnan, P. Dinesh[2]

[1]M.S.Ramaiah Institute of Technology, Department of Mechanical Engineering, Bangaluru.
mahanmatur@gmail.com

Abstract

In the high temperature regime, components fail by thermal damage at the defects, also failure can happen under mechanical loading of the parts, as it induces substantial amount of stresses around the defects. From the literature it is learnt that, much of the work has been done on study of combined mechanical and thermal loading effect on the life of the component with defects, hence mechanical and thermal loading effects on Stress Intensity Factor were studied independently. Finite Element Method is used to determine Stress Intensity Factor at the crack tip of an AT specimen with initial notch under mechanical and thermal loads separately. In case of thermal loading, both the inner and outer surface of the AT specimen was subjected to different temperature. Results so obtained were expressed in terms of the crack tip Stress Intensity factor, as defined by the theory of linear elasticity. Comparison of the results of mechanical and thermal loading are made and found in good agreement with the similar work done by the other authors.

Keywords: *Stress intensity factor, Arc shaped Tension specimen, Temperature, Mechanical load, Finite Element Analysis.*

--***--

1. INTRODUCTION

High temperature operating requirements for components and equipments have drastically increased over the past 30 years, as industries such as chemical, aircraft and thermal plants are greatly dependent on the safe operation of such equipments. In this regard, the power generation industry components were strictly directed to operate for extended periods of time at temperature between 0.3 to 0.5 T_m, where T_m is melting point of material. In fossil fired power generation plants and petrochemical industries, carbon steels and low alloy steels were extensively used at elevated temperatures as their properties matches with application. For carbon steel materials, temperature range recommended by ASME Boiler and Pressure Vessel Code- Section VIII is 350^0C to 540^0C [ASME. 2007]. Some of the important issues with outcomes, after the thorough literature survey are highlighted in the present study and it follows as below.

Failure of parts as a result of creep crack propagation rather than stress rupture occurs most commonly in large components that are subjected to non-uniform stress and temperature distribution. Components operating at high temperatures experience changes in conditions from beginning to end of each operating cycle, resulting in transient temperature gradients [P. Chellapandi & Ng Heong Wah. 1997]. The primary cause of crack initiation and propagation in steam turbines is creep-fatigue and occasionally brittle fracture due to high transient thermal stresses. Creep contributes to crack growth in regions where temperature exceeds 427^0C [A. Saxena.1996]. While, failure by creep rupture of thin section of steam pipes was examined by the author [Boot. P. et.al.1997].

In case of high temperature resistant ductile materials, crack growth is associated with significant amount of creep deformation at the crack tip. Examples of such materials include Cr-Mo Steels [Akio Fuji . 1993& Kamran Nikbin.2000], Stainless Steels [Boot P.1997, Edward L.1991] and Cr-Mo-V Steels [Boot P.1997 & Akio Fuji.1993]. Where in brittle materials, crack growth is accompanied by small scale creep deformation with different rate of creep deformation in a cracked body. For cases where the temperature is non uniform such as with convection furnace heating with cold water sprays [J W H. Price.2004], temperature gradients are developed along the axis of the specimen. Thermal gradients in turn may result in thermal stresses that produce thermal K-values that alter the Isothermal –K solution for a given specimen and thus makes the problem a complicated one. [A. Ohta. Et.al.1988] found that crack growth rate at 300^0C in a Middle tension specimen matches RT data in a low alloy ferritic Steel-SB46 material only. The Finite Element Analysis (FEA) results were compared with experimental outcomes and was found to be in good agreement.

[D. Coker. et. al.1993], conducted a FEA of single edge crack specimen with thermal gradients between the plane of the crack and RT grips . For their specific geometry and temperature profile, Stress Intensity Factor (SIF) denoted by KI due to thermal stresses were below 2Mpa√m for $\frac{a}{w} \leq$ 0.8. While these values are small, but near to the threshold stress intensity range (ΔK) of the material. It is important to have estimates of thermal stress induced values that have non-uniform temperature profiles. Thermal gradients and effective values of K resulting from Direct Resistance heating are discussed by [Cunningham.1990 and Griffin.1991].The results indicates that stress intensities resulting from thermal gradients alone are generally small except when thermal cycling frequencies are high. In application such as pressure vessels [Ng Heong Wah.1997], steam turbines and boiler tubes selection of steel material involves compromise between thermal efficiency and cost of the equipment. Hence the present study is undertaken to encounter the different loading effects on damage severity of Arc shaped Tension (AT) specimen made up of steel. The study , begin with an AT specimen with initial notch with it under the tensile load. SIF at the crack tip is determined using the Finite Element Method and process is repeated for different crack lengths under same tensile load. SIF data were generated for every crack advancement and recorded for further investigation. Later effect of thermal loading on the SIF at the crack tip were studied. In case of thermal loading, both the inner and outer surface of the AT specimen was subjected to different temperatures and SIF values were recorded independently. The details of the work have been explained in the further section to follow.

2. METHODOLOGY

Finite Element Analysis of AT specimen under Mechanical loading

ANSYS software is used as, it can be a powerful tool to perform variety of analysis on cracked geometries of an AT specimen. En8 steel material is considered for the analysis the properties of which is as shown in table 1. The specimen geometry considered for both mechanical and thermal loading is as shown in fig. 1.
A systematic procedure of numerical simulation as described by the author [Mahantesh.Matur.2015], is followed to get the solution of the current problem.

Table 1 : Property of En 8 Steel material

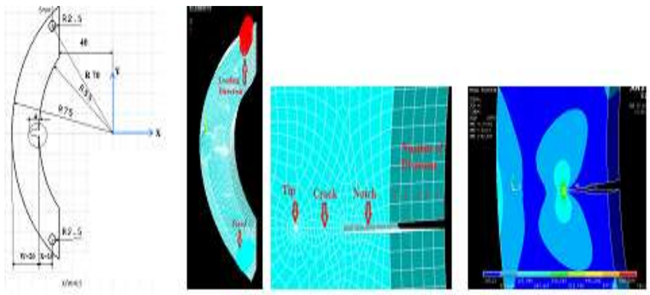
Material properties	Steel		
	Temperature (^{0} C)		
	250	375	500
E (GPa)	183	165.1	136.6
v	0.29	0.30	0.31
α (m/m^{0}c)	12.25e-6	13.2e-6	13.9e-6

Meshing operation is carried out using two types of mesh elements, namely, 2D -PLANE 183 and 3D solid 186. To obtain crack tip stress fields, a fine mesh around the notch or crack tip compared to the surrounding is maintained [Raju. I.S.1979]. Whole meshed area is extruded in the thickness direction, that is in z- axis direction with respect to the origin. Note that in the element extrusion option, element type selected must be the Brick 20 node 186 and number of element division to be 5. The final 3-D mesh, after the sequence of operations so explained is as shown in fig 2b. Maximum tensile load of 6500N is applied with other constraints as shown in fig 2a. Von Mises Stress distribution in the cracked specimen is as shown in the fig 3.

Finite Element Analysis of AT specimen; Thermal loading

An attempt has been made to assess the influence of the temperature on the stress distribution from the notch in a steel specimen of sufficient thickness using FEA. Consequently, three different temperature units 250^0 C, 375^0 C and 500^0 C were selected and applied to the same specimen geometry. Initially, crack size of 1 mm from the notch was considered, but extended up to the critical size of 11 mm, in steps of 1mm under the three temperaratutre conditions separately. Ends of the specimen are fixed and outer and inner surface of the specimen are constrained in Z-axis, respectively for internal and external surface loading. It was learnt from the mechanical loading of the Aluminum specimen through the experiment [Mahantesh. Matur.2014] that, crack can extend from the notch more than 5 mm before reaching the critical-size.

Steady state operating condition are assumed for the thermal stresses under consideration. FE model is used to compute the stresses statically, considering every crack under the steady state temperature condition. Calculation based on LEFM principles were carried out by using two finite element types in order to determine SIF at the notch tip. Eight node quadrilateral and twenty node brick elements were used and mesh was focused more near the notch tip. Mid side nodes were moved to ¼ - point position next to the notch tip and coincident nodes were constrained to have the same displacement to maintain strain singularity.



(a) (b)

Figure 1:Arc shaped tension Specimen geometry
Figure 2 : Finite Element mesh with
Figure 3: von Mises stress distribution

a) Boundary conditions b) Crack and notch

After loading the specimen under specific surface temperatures and body constraint, the solution in terms of Von Mises stresses are obtained. The solution for all the crack size of the specimen are generated and tabulated.

3. RESULTS AND DISCUSSION

As pointed from the literature survey, the SIF , is a measure for the stress-strain distribution of the crack tip. Hence K is used to characterize the material under mechanical and thermal loading conditions separately.

AT specimen under mechanical Loading

The finite element results of AT specimen made up of steel under 6500 N tensile force are discussed as follows;

SIF values so tabulated shows the dependency of crack and subsequent growth on the stress intensity factor. As the intensity of stress is more at the notch nose-tip, crack nucleates from the tip overcoming the resistance of the material. Independent studies of subsequent increase in crack sizes, had clearly shown a common feature. i.e , Mode-I loading prevails, thus opening of the notch takes place. Hence on every increment in crack size, SIF increases and finally reaches the critical value, wherein an unstable growth of crack takes place and the same is shown in fig 4. That is crack growth takes place at faster rate with less or same SIF value.

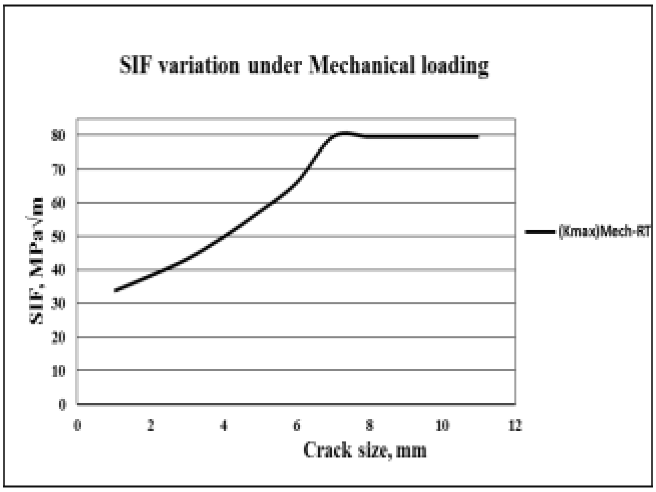


Fig.4 SIF variation under Mechanical Loading

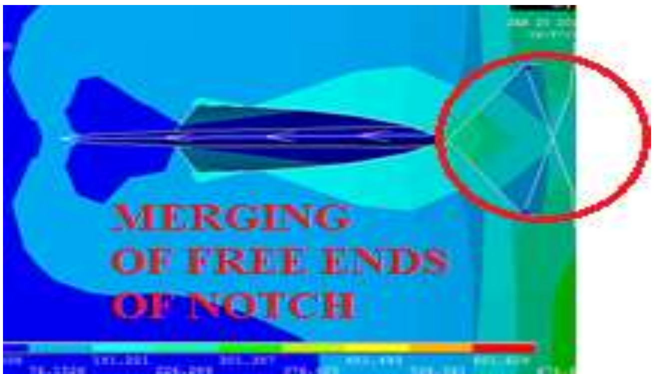


Fig.5. Stress distribution due to 250^0 C Internal Temperature loading

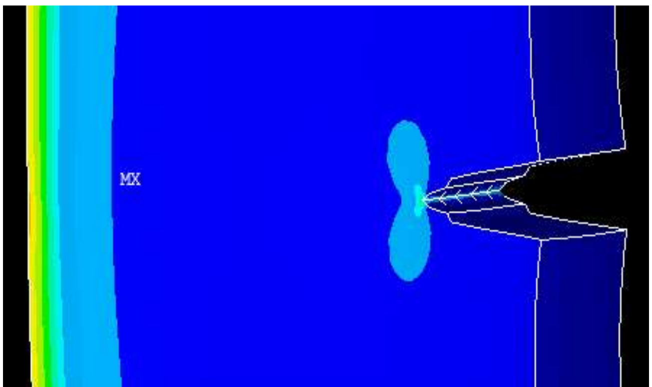


Fig.6. Stress distribution due to 250^0 C External Temperature loading

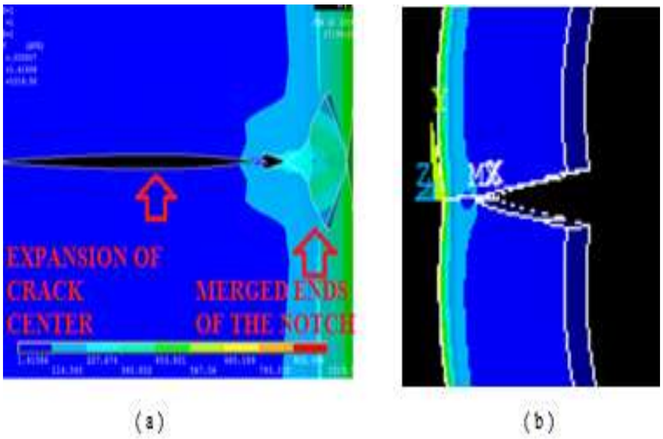


Fig.7 Stress distribution due to 375^0C for the crack size of 11 mm when loaded on the (a) Internal surface (b) External surface.

AT specimen under Thermal loading

From fig.5 , it is observed that due to 250^0 C temperature on internal surface of the specimen, stress gradually decreases from inner surface to outer surface . Due to more concentrated heat over small area of the face of the notch with 1 mm crack, the two edges of the notch were merged together (as if welded), where thermal expansion property of material plays a key role. Also stress intensity at the tip of the notch is less, hence growth of the crack is not possible. In case of specimen with 11 mm crack size, as the free surface to receive heat has increased, expansion of the material is reduced and hence edges of the notch are merged to comparatively to less extent. For the larger crack size also, stress intensity at the tip of crack is far below the critical stress. From fig.6, it is observed that due to 250^0 C temperature on external surface of the specimen, stress gradually decreases from outer surface to inner surface. A three point bending resembling effects are observed, as ends of the specimen are constrained and the specimen is thermally loaded. But by virtue of its strength, materials resist this initial deformation, due to which more SIF is observed along the crack front. This magnitude of the stress is far below the critical stress intensity, hence growth of the crack is not possible. Same consequence are observed for 375^0 C temperature on internal and external surface of specimen with 1 mm crack. But degree of merging varied, due to expansion variation of the material. Furthermore, as crack size increases up to 11 mm, bulging of. the free ends of the notch reduces and crack widens in hoop direction rather than extension in radiation direction as shown in fig 7 a &b. Material expansion process continues on further increase in temperature to 500^0 C. Bulging of free end are observed as shown in fig. 8 a &b.

Table 2. SIF comparison between Mechanical and Thermal loading of the
specimen

Crack size	Mechanical Loading	TEMPERATURE 250°C		TEMPERATURE 375°C		TEMPERATURE 500°C	
		On Internal surface	On External surface	On Internal surface	On External surface	On Internal surface	On External surface
	SIF(MPa√m)	SIF(MPa√m)		SIF(MPa√m)		SIF(MPa√m)	
	KI	KI	KI	KI	KI	KI	KI
1	33.68	2.169	8.936	0.359	9.235	2.484	8.533
2	38.26	3.011	9.131	0.667	9.488	1.886	8.781
3	43.21	3.721	9.328	1.057	9.764	0.922	9.113
4	49.79	3.921	9.411	1.081	9.927	0.886	9.345
5	57.47	3.234	9.502	1.124	10.136	0.802	9.628
6	66	3.161	9.511	1.119	10.281	0.749	9.88
7	79.6	3.069	9.523	1.115	10.429	0.673	10.122
8	79.6	3.017	9.413	1.225	10.447	0.518	10.242
9	79.6	2.973	9.305	1.325	10.478	0.233	10.397
10	79.6	2.896	9.235	1.409	10.646	0.226	10.693
11	79.6	2.812	9.168	1.506	10.733	0.22	10.969

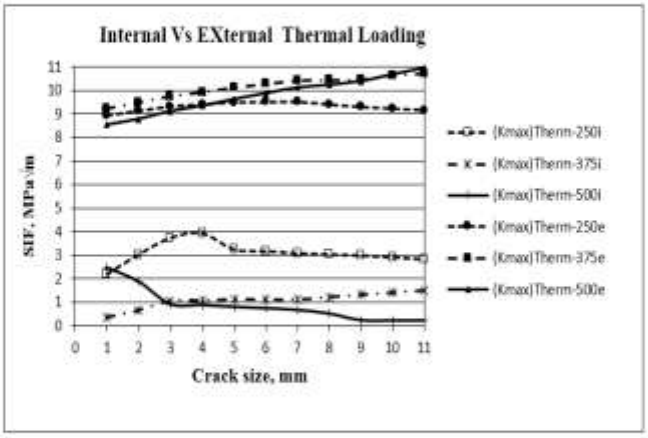
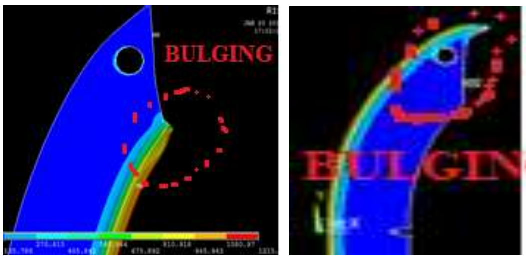


Fig.9. SIF variation for internal and external thermal Loading



(a) (b)

Fig.8 Stress distribution due to 500^0C temperature on the(a) Internal surface (b) External surface

From fig. 9, it is observed that , an AT specimen with external thermal loading, away from the crack, resists more amount of thermal stress than, the same by the internal thermal loading. Also trends of SIF against the increase in crack size are same for all the temperature units, except 500^0 C temperature, operating with the same material conditions. i.e., at 250^0 C loading, initially as crack size increases SIF increases, but further increment in crack length, SIF decreases continuously. The similar outcome was reported by the author[Akio Fuji, et.al.1993] , for a cylindrical shell. Wherein, at higher temperature regime i.e., 375^0 C and 500^0 C- external loading, increasing trend of SIF is observed , as was found in the other literature [J W H. Price.2004]. For the case of 500^0 C- internal loading, thermal expansion influence is clearly observed as the notch with crack surface was exposed first than the outer surface.

More influence of mechanical loading at room temperature than temperature loading on SIF at the crack tip, is observed, as thermal loading effect is far below the threshold, and hence their impact on the further crack growth could be neglected. The similar outcome was registered by the author [J. H.Griffin.1991], for steel material but under thermal-structural couple field.

CONCLUSIONS

Ominously, SIF so determined by FEA are far below the fatigue threshold for temperature loading than mechanical loading and thus the AT specimen is at safer side as per as thermal loading condition is concern. Furthermore, crack at the tip of the notch was loaded in compression than in tension when internal surface was thermally loaded. Hence the driving force for the growth of the crack becomes negative, thus growth of the crack is hampered. Whereas on thermal loading the external surface, an opposite phenomenon takes place. But influence of expansion of material on the SIF at the crack tip was undoubtedly smaller than the critical SIF, for the extension of the crack. Thus it is been concluded that, mechanical loading produce more stress distribution near the tip of the notch than does the thermal loading , under the identical conditions of the operating system.

REFERENCES

ASME 2007 Section VIII Division 1 Bilingue 2007 ASME Boiler and Pressure Vessel Code SNCT Publications 39/41 rue Louis Blanc – 92400 Courbevoie :1-42.

A. Saxena (January 1996) Life assessment Methods and Codes EPRI TR-103592 Electric Power Research Institute.

Boot P. et.al(1997) Validation of the shakedown route in R5 for the assessment of creep fatigue initiation. Transactions of the.

14th International conference of Structural mechanics in Reactor technology (SMiRT 14) Lyon France August : 17-22

A.Ohta, M. Kosuge et.al (1988) Significant effect of Thermal stresses on fatigue crack propagation properties. International Journal of Fracture (38): 207-216.

D.Coker, B.K. Parida , et.al (1993) Thermal stresses due to temperature gradient on a Single edge notch specimens. Report UDR-TM-93-07 University of Dayton Research Institute.

S.F. Cunningham and J. H.Griffin (1990) On the importance of Direct Resistance Heating in Thermo-Mechanical Fatigue International Journal of Fracture (46) : 257-270.

S.F.Cunningham and J. H.Griffin (1991) Estimating the importance of cyclic thermal loads in thermo-mechanical fatigue International Journal of Fracture (47) :161-180.

Edward L, Hoffman and Charles M. Stone(1991) Structural Analysis of a Reflux Pool-Boiler Solar Receiver Sandia Report SAND-91-0862 Sandia National Laboratories Unlimited Release Printed June .

Akio Fuji, et.al (1993) An experimental Study of Behavior of Low alloy steels in the initial growth stage of creep cracks. Engineering Fracture Mechanics Pergamon Press(45) No. 1: 39 -50.

P. Chellapandi, et.al. Thermal Hydraulics and Thermomechanical Analysis of thermal striping in a mixing Tee- junction of secondary Sodium circuit of Phenix Reactor Indira Gandhi Centre for Atomic Research (IGCAR) India: 63-88.

Ng Heong Wah and Lee Chuen Kum (1997) Fatigue crack growth calculations for a vessel internal corner crack under repeated thermal transients International Journal of Pressure vessels and Piping 71 : 239-251.

Kamran Nikbin,(2000) Comparison between crack growth in Fracture Mechanics Specimens and feature component tests carried out in a Low- Alloy Steel. Journal of Pressure Vessel Technology Transactions of the ASME (122): 40-44.

J W H. Price, M Chang and B Kerezsi (2004) Cracking of Carbon Steel components due to repeated thermal Shock SIF Structural Integrity & Fracture http://eprint.uq.edu.au/archive/00000836.

M. Rodig et.al. Creep and fatigue crack growth in tubes at High Temperatures, Institut Fiir Reaktorwerkstoffe, Kernforschungsanlage, Jiilich, P.O.B. 1913, D-5170, Jiilich, FRG, :1827-1834.

Srawley, JE [1976] Wide Range SIF Expressions for ASTM Standard E-399. Fracture Toughness Test Specimens Int. J. Fracture (12) : 475-486.

Bernard Gross and J.E.Srawley (1965) Stress intensity factors for three point bend specimens by boundary collocation Lewis Research Centre Cleveland Ohio NASA Technical note NASA TN D-3092:1-13.

Mahantesh. Matur, V.Krishnan and P.Dinesh (2015) Study On Fatigue Crack Growth Behavior Of Aluminum Alloy In The Presence Of Notch: An FEA Approach .IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684 p-ISSN: 2320-334X (12) Issue 5 Ver. II : 68-74.

S. Stoychev, D. Kujawski (2008) Crack tip stresses and their effect on Stress Intensity Factor for crack propagation Engineering Fracture Mechanics :752469- 752479 www.sceincedirect.com.

Mahantesh. Matur, V.Krishnan and P.Dinesh (2014) Influence of Inner Surface Notch on Fatigue Crack Growth Characteristics of Aluminum Alloy. International Journal of Engineering Research (3) Issue No.12: 749-752 .

Raju. I.S, and Newman. J.C. Jr (1979) Stress Intensity Factor for Wide Range of Semi-Elliptical Surface Cracks in Finite thickness Plates Engineering Fracture Mechanics (11) :817-829.