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Studying the Effect of Thermal Shock on Stress Intensity Factor Using FEM

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Abstract

This research concerns with studying the effect of sudden increment in temperature or thermal shock effect on Stress Intensity Factor generated at crack region. The Mechanical Stress Intensity Factor (MSIF) was computed using Finite Element Method technique with the aid of ANSYS software as well as a theoretical methods. The percent of error as a comparison between these results was about (3.18%). Elements used for thermal analysis were plane77, then by using switch element technique from thermal to structural so, elements would be plane82 for structural analysis. A comparison between this value and the values of Thermal Stress Intensity Factor (TSIF) which is generated due to thermal stresses in case of applying a thermal load (thermal shock) had been adopted to know the importance of this effect. So, a coupled field method with the same program, had been used to calculate these values with estimation effect of heat transfer method. The results proved that for an instant temperature difference the effect of steady-state heat transfer method was more than the transient method. Also TSIF for low temperature difference, may exceed the value of MSIF in case of (100 MPa) statical structural applied load without considering the temperature effects.

Keywords: Stress Intensity Factor, Thermal Shock, Heat Transfer Method.

دراسة تأثير الصدمة الحرارية على معامل شدة الإجهاد باستعمال طريقة العناصر المحددة

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الخلاصة

يتناول هذا البحث دراسة التأثير المفاجئ لدرجات الحرارة أو تأثير الصدمة الحرارية على معامل شدة الإجهاد المتولد في منطقة التشقق. لقد تم حساب معامل شدة الإجهاد الميكانيكي (MSIF) بطريقة العناصر المحددة باستخدام برنامج ANSYS ومقارنتها مع الطرق النظرية. بينت النتائج إن نسبة الخطأ عند المقارنة بلغت مايقارب (3.18%). حيث تم استخدام عنصر (plane77) للتحليلات الحرارية، بعد ذلك تم تحويل العناصر الى (plane82) عند التحول الى التحليلات التركيبية بطريقة تحويل العناصر. تم بعد ذلك اعتماد مقارنة بين هذه القيمة وقيم معامل شدة الاجهاد الحراري (TSIF) الناتجة من الاجهادات الحرارية المتولدة نتيجة لتسليط حمل حراري (حرارة مفاجئة) وذلك لمعرفة مدى خطورة هذا التأثير. حيث وبالاعتماد على طريقة المجالات المقترنة

في البرنامج المستخدم تمت دراسة الإجهادات الحرارية المتولدة عند منطقة التشققات وتأثير طريقة انتقال الحرارة على معامل شدة الإجهاد الحراري (TSIF). لقد بينت النتائج إن لفرق معين في درجات الحرارة فان طريقة انتقال الحرارة الثابتة مع الزمن تكون أكثر تأثيرا من تلك الطريقة المتغيرة مع الزمن. كما إن معامل شدة الإجهاد الحراري المتولد نتيجة لفرق بسيط في درجات الحرارة قد يتجاوز معامل شدة الإجهاد الميكانيكي عند تسليط حمل ميكانيكي ساكن مقداره (100 MPa) بدون اعتبار تأثير الحرارة.

1. INTRODUCTION

Repeated thermal shock loading is common in the operation of pressure equipment particularly in thermal power stations. Thermal shock can produce a very high stress level near the exposed surface that eventually may lead to crack nucleation and crack growth as shown in **Fig.1** (Price, et al 2004; Wasiluk, et al 2008). The intensity factor generated due to thermal effect called Thermal Stress Intensity Factor (TSIF) (Neethi, et al 2009). Cladding may be used to reduce this high thermal stresses (Choi, et al 2000). The isotropic thermoelastic crack problems for semi-infinite and finite plate had been investigated by many researches (Nied 1983; 1987), Many other studies assumed cracks in an orthotropic plate with thermal shock (Liu, et al 2005 ; Abd El-Fattah 2004). Xuejun, et al (2006) indicated that the number of axial cracks in a coated hollow cylinder may be increased due to the thermal shock.

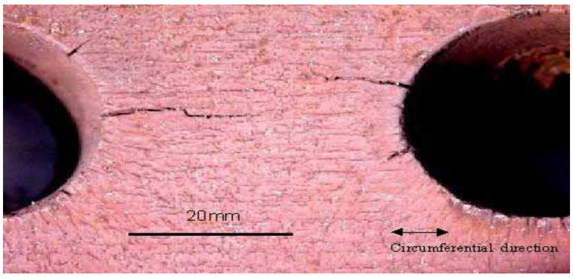


Fig.1 crack due to high thermal stresses (Price, et al 2004)

Development of computer technique gives new opportunities for engineers in exploration of different technological processes. Modern computer technique allows carrying out complicated calculations of installation work under various stresses in a relatively short time. Processes, which take place in complicated conditions, such as high temperature or a very short time, attract a special interest for modeling, because of difficulties in direct supervision (Andrew 2011). A coupled field method with ANSYS software had been regulated to compute the magnitude of SIF.

The basic practical problem facing a designer is to make a decision as to the method for determining stress intensities. It is not easy to strike a balance between the accuracy of the method, time required to get a solution, and cost. Numerous equations

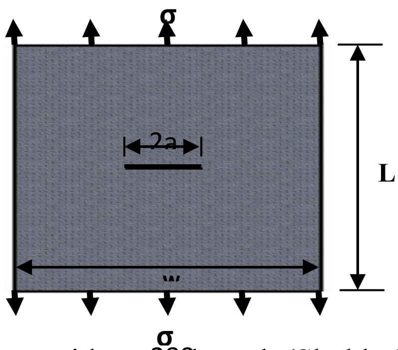


Fig.2 Plate with central crack (Shukla 2005)

These factors represent various geometries and loading conditions of fundamental importance in the prediction of structural failure of cracked bodies. In all there are probably more than 600 formulas for calculating SIF (KI) values for different crack configurations, body geometries, and loading situations (Shukla 2005). However, it appears that the bulk of fracture mechanics work to date has been largely limited to a single-mode loading because little is known about mixed-mode phenomena. For this and other practical reasons, this research is restricted to pure Mode "I" (tensile) loading and plane-strain behavior to plate with central crack as shown in **Fig. 2**.
The expression of calculation the Mechanical Stress Intensity Factor (MSIF) for this case with a through-thickness crack is given by eq. (1) (Shukla 2005):-

$$K_I = \sigma\,(\pi a)^{0.5}\, f(a/w) \qquad (1)$$

Where K_I; MSIF for mode "I" (MPa. $m^{0.5}$), a; half length of crack (m), σ; applied mechanical stress (MPa), w; width of the plate (m), L; length of the plate (m) and $f(a/w)$;correction factor.

There are several expression for the term $f(a/w)$, Brown (Janssen, et al 2004) found a four terms approximation in a form of power series:

$$f(a/w) = 1 + 0.256\,(a/w) - 1.152\,(a/w)^2 + 12.200\,(a/w)^3 \qquad (2)$$

Another expressions were applied by Irwin, Feddersen, Isida. The comparison between them are shown in **Fig. 3** (Janssen, et al 2004).

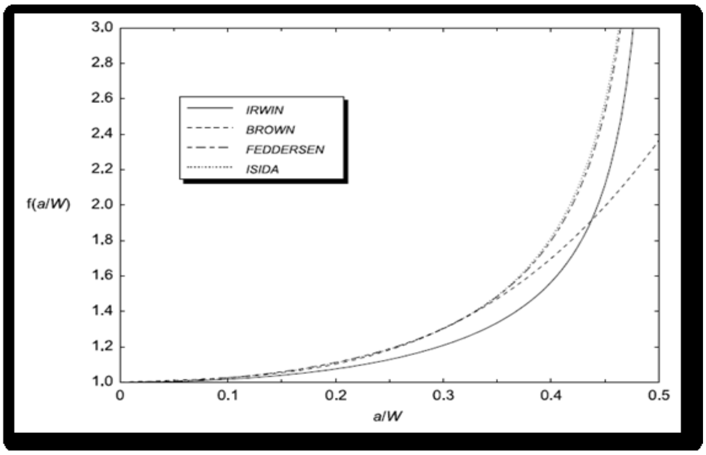


Fig.3 Comparison of correction factor for the center crack (Janssen, et al 2004)

It must be known that high pressure associated with high fluid temperature that may emissive from the hole crack (if the crack penetrate the wall) of a thermal power station (as an example) will increase the value of Mechanical Stress Intensity Factor (MSIF) at the crack tips because the mechanical component will be taken into a count.

The aim of this work is to study the effect of thermal shock on the stress intensity factor by using Finite Element Method (FEM) with the aid of ANSYS software.

2. FINITE ELEMENT MODELING

Finite Element Analysis FEA with ANSYS software using coupled – field technique was carried out for two cases, transient and steady- state thermal analysis. For each one of these two cases, thermal analysis was conducted first to obtain the global temperature distribution due to thermal shock at the crack region, then stress analysis was developed with the nodal temperature obtained from the thermal analysis, which are applied as a force. But in the first, the stress intensity factor must be computed without heating effect to compare its value with the theoretical results value. The accuracy of the Finite Element Method (FEM) depends on the density of the mesh used in the analysis, mesh density is extremely important, if mesh is too coarse, results can contain serious errors, on the other hand If mesh is too fine time will lost and program may not run progressively, as well as at sharp edge and sudden cutout, mesh must be refine because like this region form a very complicated region. A concentrated keypoint mesh with (1/4) skewed point (skew midside nodes of the first row of element to 1\4 point of crack tip singularity) option had been used at the crack tip, while the region away from this crack tip a more coarse mesh was used as shown in **Fig. 4-a**. And element shape shown in **Fig. 4-b**.

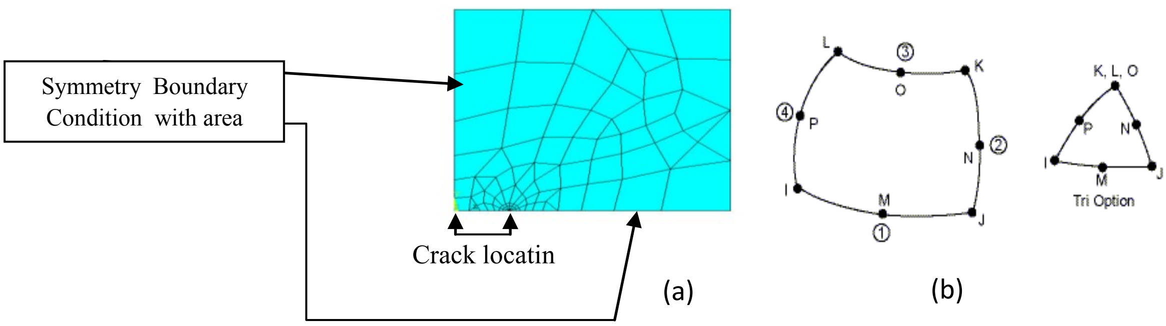


Fig.4 Finite element mesh and element shape

3. MATERIAL AND GEOMETRY

Material employed in this investigation was low carbon steel (AISI 1010). Thermal and mechanical properties are tabulated in **Table 1**, the values of thermal conductivity and specific heat are appropriate for T < 400*K*, where T is temperature. If T ≥ 400*K* **Table 2** listed new properties (Çengel 2007).

Table 1 Mechanical and thermal properties of carbon steel (AISI 1010)

Property	**Value in metric unit**	
Density (ρ)	$7.872 * 10^3$	kg/m^3
Modulus of elasticity (E)	200	GPa
Thermal expansion (α)	$12*10^{-6}$	K^{-1}
Tensile strength (σ_u)	325	MPa
Yield strength (σ_y)	180	MPa
Specific heat capacity (C_p)	434	J/(kg**K*)
Thermal conductivity (κ)	63.9	W/(m**K*)
Poisson's ratio (ν)	0.3	

Table 2 properties at different temperature

Properties	Temperature (T)			
	400*K*	600*K*	800*K*	1000*K*
κ(W/m.*K*)	58.7	48.8	39.2	31.3
C_p(J/kg)	487	559	685	1168

A quarter of the plate shown in **Fig. 2** with whole dimensions, width (w) = 0.2 m, half length of crack (a) = 0.02 m and length (L) = 0.2 m were considered in this study, and the mechanical applied stress was 100 MPa in tension.

4. RESULTS AND DISCUSSION

4-1. Mechanical Stress Intensity Factor (MSIF)

The MSIF without thermal effect had been conducted to show the accuracy of the FEM results that shown in **Fig.5** with the theoretical method eq.(1&2). The percent of error which is tabulated in **Table 3** is an accepted value.

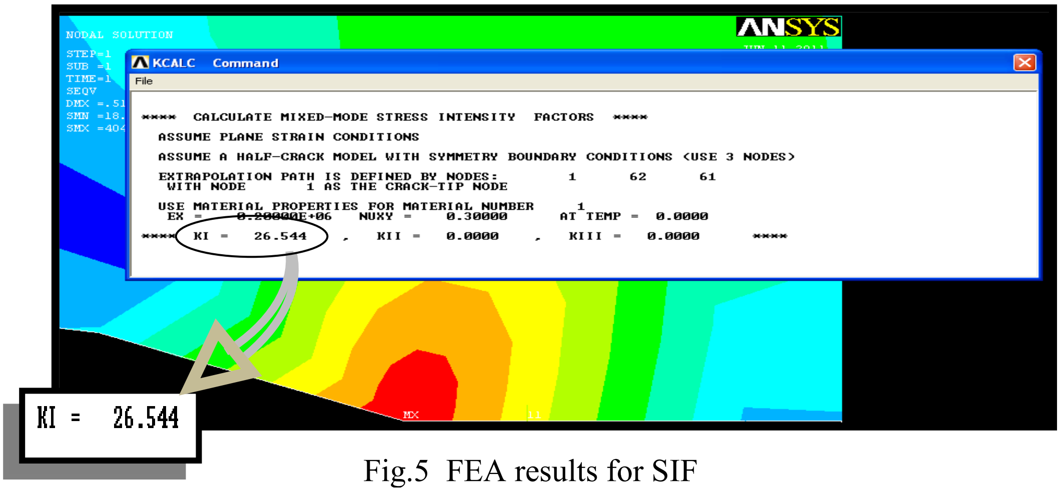


Fig.5 FEA results for SIF

In fact the maximum mechanical stresses are generated at the tip of the crack, then it decreased gradually as far away from this position. Mechanical stress intensity factor (MSIF) value as computed by ANSYS software was shown in **Fig. 5**.

Table 3 Percent of error for MSIF results

Theoretical MSIF (MPa. $m^{0.5}$)	FEA MSIF (MPa. $m^{0.5}$)	Percent of error %
25.725	26.544	3.18

4-2. Thermal Effect

The safety assessment of structures in harsh thermal environments is of increasing design engineers. It is known that components work under high temperature variation usually given rise to defects or cracks (Chih, et al 2001). If a crack penetrate surface, and heat emissive from this region, then high thermal stresses will be generated. Three main effects had been studied, which are heat transfer type (time dependent), boundary condition consideration as shown in **Fig. 6**, and temperature difference. The temperature at the crack will denoted (T_c) and reference temperature of the plate (T_a).

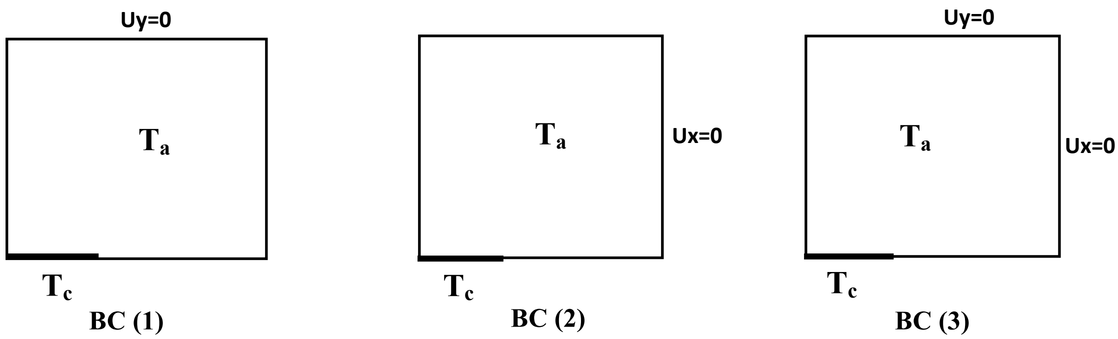


Fig.6 Boundary condition sets

It had been suggested that when an increment in the temperature will happen, heat transfer may proceed one of the two following methods:-

4-2-1. Steady-State Thermal Effect

Evidently, in this case the time dependent is not consider. So stresses will be generated due to boundary condition type and amount of temperature difference only. **Fig. 7** shows the effect of three boundary conditions sets with effect of temperature difference on TSIF.

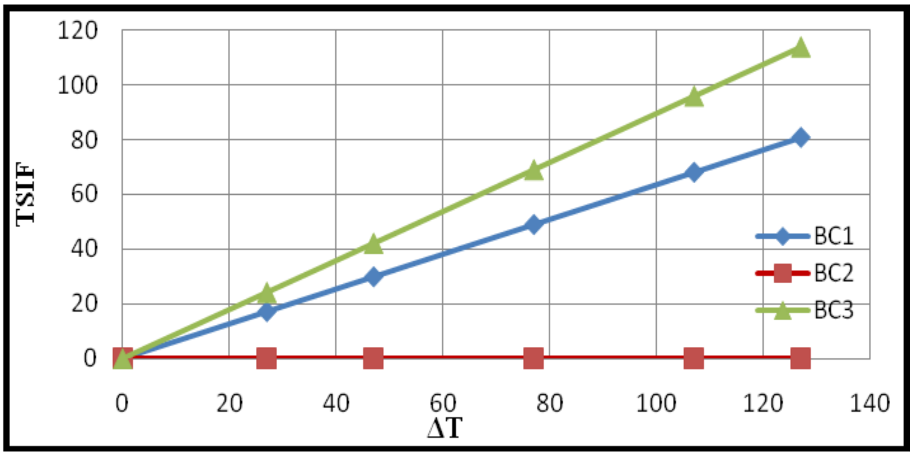


Fig.7 Steady-state thermal effect on TSIF

From this figure, it was clear that in case of BC set (3), a high values of TSIFs had been obtained. At the same time, this obtained results shows a linear relations between the temperature differences and TSEF. This related to the fact of thermal stresses generation in case of steady-state, which is subjected to a linear relation (equation of thermal stresses). In case of BC set (2) there is no TSIFs, because the plate is free in the y-direction, and generally thermal stresses comes from temperature gradient or fixed ends at boundaries of the plate.

Reference temperature of the plate assumed to be constant T_a = 273K, the results were tabulated in **Table 4**.

Table 4 Steady-state thermal results for TSIF

			BC1	BC2	BC3
Tc(*K*)	Ta(*K*)	ΔT(*K*)	TSIF (MPa.m$^{0.5}$)	TSIF (MPa. m$^{0.5}$)	TSIF (MPa. m$^{0.5}$)
400	273	127	80.746	0.000	113.830
380	273	107	68.030	0.000	95.901
350	273	77	48.956	0.000	69.013
320	273	47	29.882	0.000	42.125
300	273	27	17.167	0.000	24.199
273	273	0	0.000	0.000	0.000

It was clear that in case of BC set (2) TSIF equal to zero because no temperature gradient and no fixed end y-direction. But in both other BC sets (1&3) TSIF will be generated and it may exceed the MSIF introduced from applied mechanical stress of 100 MPa in tension even for relatively low temperature difference.

4-2-2. Transient Thermal Effect

Transient thermal heat transfer method is more actually than the previous one. In this case time of heat transfer is adopted so TSIFs will be generated for all BC sets as shown in **Fig. 8**. Generally in cases of BC sets (1&3) TSIF is greater than the BC set (2) as tabulated in **Table 5**, which is not equal to zero as in case of steady-state method, this happen due to temperature changing with time in case of transient thermal heat transfer, and stresses may generated even in case of free-free boundary condition (in x and y directions) which is not considered in this study.

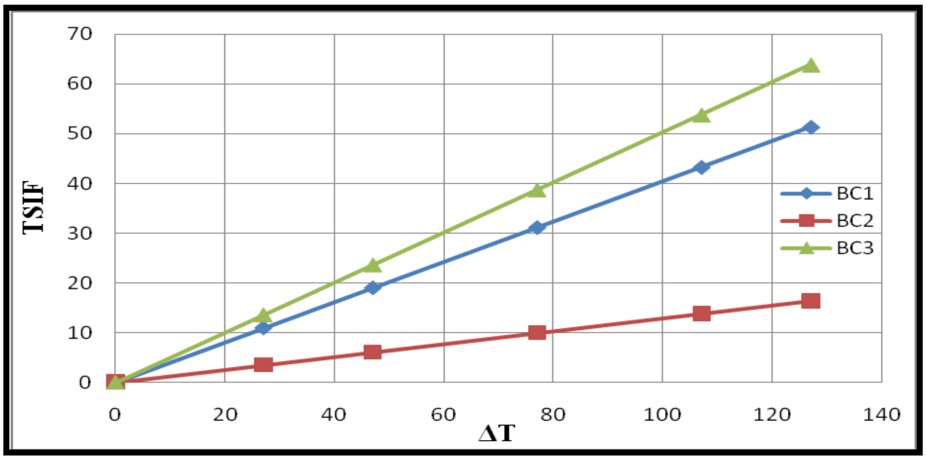


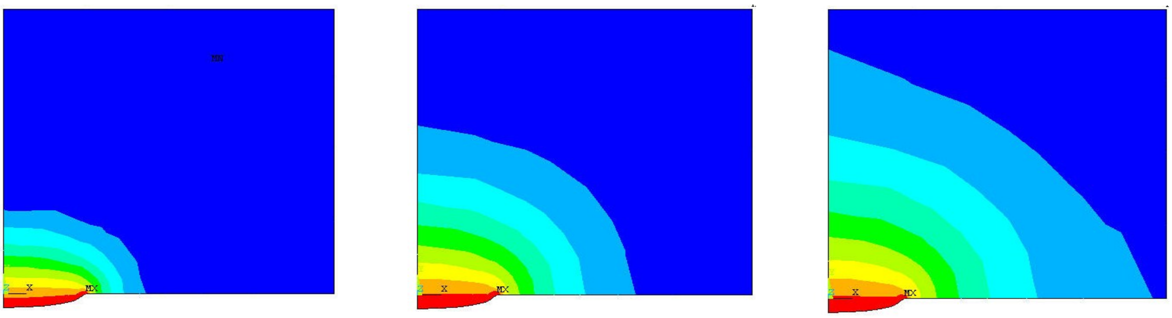
Fig.8 Transient thermal effect on TSIF

In this figure the results also showed a linear relations between TSIFs and temperature difference, because the time adopted in this case was constant at (300s) at each value of temperature difference and the results were taken at this particular time. The BC set (3) represent the high values of TSIFs. It was noted that in case of BC set (2) the thermal stresses were generated due to temperature difference with time, but generally it was less than the other two BCs sets because of the free end in the y-direction, so plate will expand more and more with no retardation and the generated thermal stresses will be lower as compared to the other BC sets.

Table 5 Transient thermal results for TSIF at time=300s

			BC1	BC2	BC3
Tc(*K*)	Ta(*K*)	ΔT(*K*)	TSIF (MPa. $m^{0.5}$)	TSIF(MPa. $m^{0.5}$)	TSIF(MPa. $m^{0.5}$)
400	273	127	51.346	16.381	63.861
380	273	107	43.260	13.801	53.804
350	273	77	31.131	9.932	38.719
320	273	47	19.002	6.062	23.633
300	273	27	10.916	3.483	13.577
273	273	0	0.000	0.000	0.000

The time effect of temperature transfer are shown for boundary condition set (3) as a contour plot in **Fig. 9**, to explain this effect individually, It was assumed that T_c = 400 *K* & T_a = 273 *K*, the time was varying within a range as tabulated in **Table 6**, then these results were plotted as shown in **Fig.10**.



Time=10 s Time=50 s Time=300 s

Fig.9 Contour plot of BC (3) for different heat transfer time.

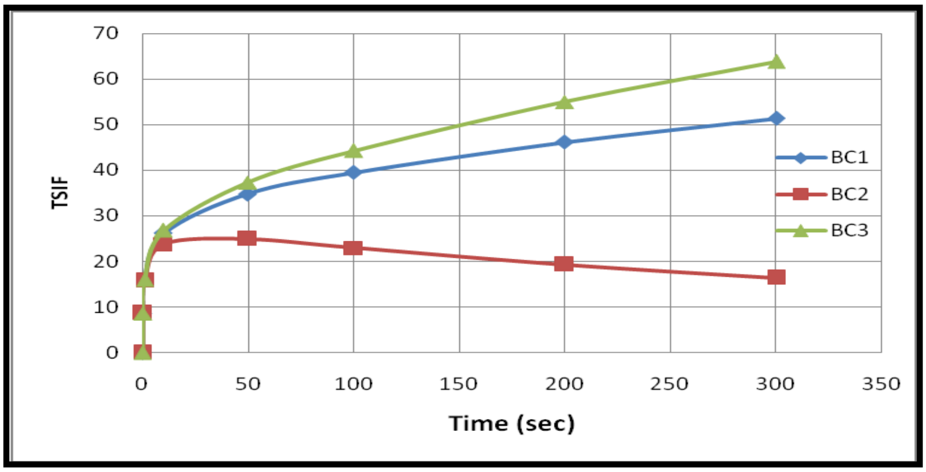


Fig.10 Heat transfer time effect on TSIF

This contour plot explain the fact of transient heat transfer, which bear in mind the time effect. As time was increasing heat will transfer to the vicinity area, and so on.

Table 6 TSIFs values for different times with $T_c = 400K$

	BC1	BC2	BC3
Time(sec)	K (MPa. $m^{0.5}$)	K (MPa. $m^{0.5}$)	K (MPa. $m^{0.5}$)
0.0	0.000	0.000	0.000
0.1	8.630	8.740	8.638
1.0	15.866	15.790	15.961
10.0	26.167	23.803	26.849
50.0	34.768	24.956	37.300
100.0	39.517	22.990	44.229
200.0	46.102	19.307	54.993
300.0	51.346	16.381	63.861

The affected area of temperature difference was increasing as time increased, at the same time thermal stresses and so, TSIFs will be increased too due to this difference. Heat transfer time effect declared that TSIFs were increasing as time period increased for cases of BC sets (1&3). At the other hand in case of BC set (2) the critical value of time was about 50s then TSIF will decreased, this related to how much the plates are fixing at the ends. Since the y-direction is free for this boundary condition set, and the plate is extend in this direction with no drawback the thermal stresses will be less than the other two.

The TSIFs were increasing so fast at less than 10 second, then it slow down, so, here it must be know that the thermal shock which is happen in very short time is more dangerous at the beginning of this shock effect.

5. CONCLUSION

According to the results obtained, it can be seen that;

1- Both theoretical and analytical results showed a good agreement for MSIF.
2- TSIF generated at the crack tip in the case of steady-state thermal heat transfer (if happened) is more effected as compared to transient heat transfer method, except in case of BC set (2).
3- TSIF increasing so fast in short time when a thermal shock are applied, especially for time less than (10 s), then it is slow down.
4- Thermal shock effect on TSIFs increases as time increased for BC sets (1&3). But its not be closed in case of BC set (2), because, TSIF increased till time 50s then it curved down.

6. REFERENCES

Abd El-Fattah A. R "Orthotropic Strip with a Crack under Thermal Shock" Department of Science in Engineering, Faculty of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia, e-mail: abdelfattah@iiu.edu.my, (2004).

Andrew V. Zabolotsky "Thermal Crack Growth Modeling in Refractory Linings of Metallurgical Installations", International Journal of Mathematical Model and Methods in Applied Sciences, Vol. 5, Issue. 3,pp.542-549,(2011).

Çengel. Y.A "Heat and Mass Transfer ", third edition, McGraw-Hill Pres. Inc, (2007).

Chih Yi Chang; Chien Ching Ma "Transient Thermal Conduction Analysis of a Rectangular Plate with Multiple Insulated Crack by the Alternating Method" International Journal of Heat and Mass Transfer, Vol.44, pp2423-2437.(2001).

Choi. S. N ; Jang. K. S; Kim. J. S; Choi. J. B & Kim. Y. J " Effect of Cladding on the Stress Intensity Factors in the Reactor Pressure Vessel". Nuclear Engineering and Design, V.199, pp.101–111, (2000).

Janssen. M; Zuidema. J & Wanhill. R. J. H " Fracture Mechanics" 2nd edition. Spon Press Taylor & Francis Group, London & New York, (2004).

Liu. L & Kardomateas. G.A "Thermal Stress Intensity Factors for a Crack in an Anisotropic Half Plane" International Journal of Solids and Structures. Vol.42 pp.5208–5223. (2005).

Neethi Simon. B; Prasath. R. G. R & Ramesh. K" Transient Thermal Stress Intensity Factors of Biomaterial Interface Cracks Using Refined Three-Fringe Photoelasticity", Journal of Strain Analysis, Vol.44, pp.427-438, (2009).

Nied. H. F "Thermal Shock Fracture in an Edge-Cracked Plate", Journal of Thermal Stresses, Vol. 6, pp.217-227. (1983).

Nied. H. F "Thermal Shock in an Edge-Cracked Plate Subjected to Uniform Surface Heating", Engineering Fracture Mechanics, Vol.26, pp.239-246. (1987).

Price.J. W; Chang. M & Kerezs. B "Cracking of Carbon Steel Components Due to Repeated Thermal Shock" Structural Integrity and Fracture. http://eprint.uq.edu.au/archive/00000836, Department of Mechanical Engineering, Monash University, (2004).

Shukla. A "Practical Fracture Mechanics in Design" Marcel Dekker Pres. (2005).

Wasiluk. B; Qian. X & Dodds. R.H "Nonlinear Analyses for Embedded Cracks Under Pressurized Thermal Shock: Comparisons with FAVOR and Weibull Stress Approaches" Office of Nuclear Regulatory Research, United State Nuclear Regulatory Commission, NUREG/CR-6956, (2008).

Xuejun Chen; Kun Zhang; Guangnan Chen & Gengxing Luo " Multiple Axial Cracks in a Coated Hollow Cylinder Due to Thermal Shock" International Journal of Solids and Structures, Vol.43, pp.6424–6435. (2006).