Penerbit Akademia Baru

CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

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Finite Element Analysis of Thermal Stress Intensity Factors for Cracked Bimaterial System Under Convective Cooling

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ARTICLE INFO

Article history:
Received 29 September 2018
Received in revised form 16 December 2018
Accepted 24 December 2018
Available online 28 December 2018

Keywords:
Bi-material systems, crack tip, finite element analysis, stress intensity factor, thermal stress

ABSTRACT

Edge-crack bi material systems subjected to convective cooling is considered. The medium is assumed to be insulated on one surface and exposed to sudden convective cooling on another surface containing the edge crack. Superposition and uncoupled quasi-static thermo elasticity principles are adopted to find temperature and thermal stress distribution. The ANSYS results for the stress intensity factors of an edge crack are calculated and presented as a function of time, crack length, and thickness ratio for two different bimaterial systems, namely a stainless steel layer welded on ferritic steel and a ceramic layer coating on ferric steel.

1. Introduction

Bimaterial systems possessing a variety of thermal and mechanical properties are common to many engineering applications where a base metal must be protected from thermal damage. Some examples of this include stainless steel cladding for nuclear pressure vessels, the thermal barrier coating of super alloys by ceramics used in jet engines, and any number of diffusion bonded materials for use in microelectronic components [1]. Service life assessments of devices and materials often depend on the stress intensity factor (SIF) as well as fracture characterization and subcritical crack growth data.

There has been much investigation of crack problems in multi-layered materials under thermal loading where the crack length is parallel to the interface [2-4] but little work had been done where the crack face is perpendicular to the interface by using finite element method [5-7]. Edge cracking caused by transient thermal loading for homogeneous plates or hollow homogeneous cylinders was the focus of research in [8] and [9], respectively. Both multiple edge cracks of differing density and single cracks were analyzed for thermal shock resistance in their coating–substrate systems [10].

With the use of Ansys, truly three dimensional fracture mechanics analyses are performed wither as the J-integral method, crack tip opening displacement method for elastic plastic fracture

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mechanics (EPFM), and crack opening displacement method for linear elastic fracture mechanics (LEFM) [11]. Ansys is one of the best softwares to use inorder to validate the numerical results involved with heat transfer analysis [12]. Fracture mechanics is a subset of solid mechanics that considers how cracked bodies mechanically behave [13]. Some results suggest that the variation of the stress intensity factor is greatly influenced by the crack spacing parameter. As the crack spacing decreases, the stress intensity factor also decreases. Over very short lapses of time, not only does the stress intensity factor increase, but the occurrence of the peak stress intensity factor will be recorded earlier. It should be noted that the reduction in the crack's depth, coefficient of thermal expansion for the coating and coating's modulus [14] are among the other factors that contribute to a reduction in the stress intensity factor for any given substrate. It appears from the aforementioned researches that finite element analysis which utilized in structural engineering, estimates the overall behavior of a structure through dividing it into a number of simple elements, each one of them has well-defined mechanical and physical characteristics [15]. This paper is focused on the interface problem's effects and the stress intensity factor at the crack tip. In particular, the finite element method is used to solve problems with bi-material systems containing a crack that is normal to the interface, undergoing cooling on the cracked surface.

2. Methodology

Figure 1 shows a system composed of a thermoelastic bimaterial. There are two different material layers, with system A containing different thermal properties but equal mechanical properties, and system B containing different thermal and mechanical properties. Layer 1 has a thickness of h_1, contains a crack of length b that is normal to the interface. This is bonded to layer 2, with a thickness of h_2. This system is begins assumed at a uniform temperature of T_0. At $t \geq 0$, the plane $x = 0$ is undergoes sudden convective cooling at an ambient temperature of T_a but the boundary $x = h_1 + h_2$ remains insulated from this cooling.

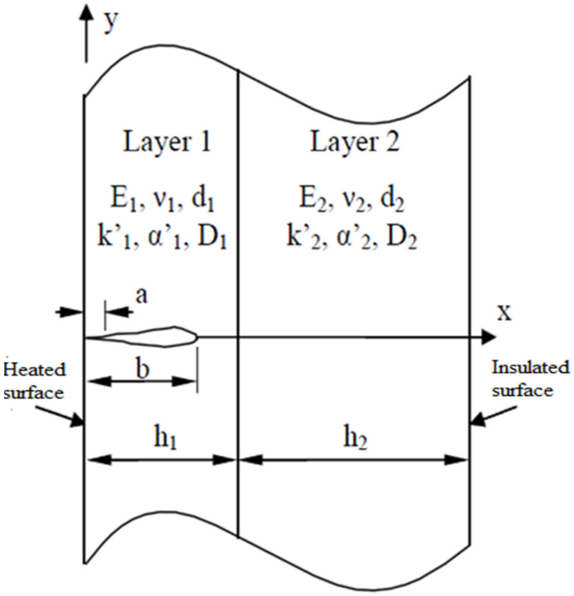


Fig. 1. Crack geometry in the surface-cooled bimaterial system

A finite element method (FEM) is used to solve the edge crack problem with different crack lengths $b/h1 < 1$ through ANSYS [16]. Symmetry in the model allows for only half of the section of the bi-material system to be considered with a plane strain condition.

The temperature distribution calculation relies on 2-D 4-Node structural solid elements. To do structural analysis, element has to be switched from thermal to struct in order to find the stress intensity facctor and the thermal stress distribution. It is important to carefully place the element meshing, particularly near the crack tip where element refinements are necessary.

Singular elements and quarter points were placed in the vicinity of the crack tip in order to pick up the square root singularity nature of the crack-tip strain field with greater accuracy. Figure 2 is the model used in Ansys where $y = 0$ is the axis of symmetry with areas. Figure 3 is the model of meshing around the crack tip in Ansys. It was not easy to mesh due to interface. So meshing is done very carefully.

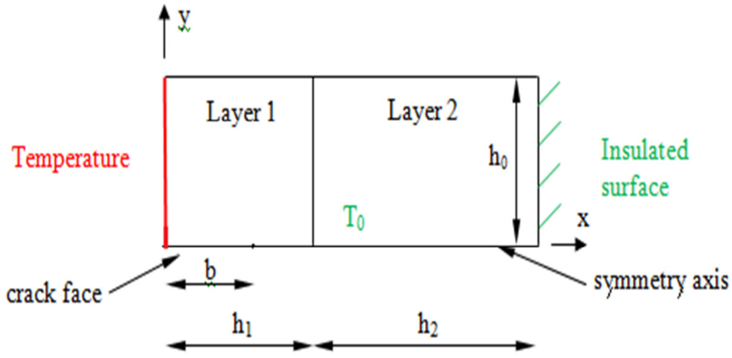


Fig. 2. Geometry in ANSYS

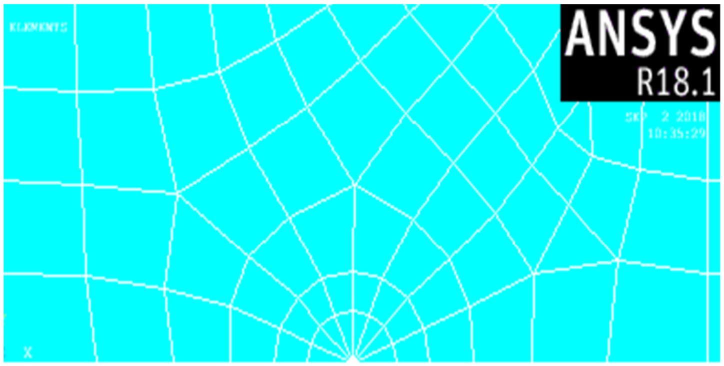


Fig. 3. Finite Element Meshing around crack tip

The following formula is used to obtain the resulting uncracked medium's transient thermal stresses, as a plane strain problem in the *z*-direction [6]

$$\sigma_{iyy}^{T}(x,t)=\sigma_{izz}^{T}(x,t)=\frac{E_i}{1-\upsilon_i}[\varepsilon_o(t)+\frac{x}{\rho(t)}-\alpha_i^{'}\theta_i(x,t)] \tag{1}$$

where the Young's modulus is designated with constant *E*, the Poisson's ratio by ν, and the thermal expansion coefficient by α. The following formula is used to extract the stress intensity factor from the finite element solution [17]

$$K_I = \frac{E_i u_y^q}{(1+\nu_i)(1+\kappa_i)}\sqrt{\frac{2\pi}{r_q}} \quad (i=1,2) \tag{2}$$

where u_y^q is the y-directional displacement at the quarter point of the singular element on the free face of the crack, r_q is the distance from quarter point to the crack tip, $i=1$ when the crack tip is within the coating and $k_i = 4 - 3v_i$ in the plane strain problem case. The substrate and coating were endowed with material constants, so a series of runs were necessary to duplicate all of the results previously published by Rizk and Hrairi [7]. The results from Ansys and the numerical results calculated by using equations 1 and 2 are compared below.

3. Results

There are two different bimaterial systems (A and B) modelled in this study, with typical results for the layered medium presented for each model. The ratio of both material pair's thermoelastic properties for A and B are presented in Table 1, since normalized quantities are used to formulate the problem. System A is a stainless steel layer (layer 1) welded onto a ferritic steel layer (layer 2) whereas system B is a ceramic layer (layer 1) bonded to a ferric steel layer (layer 2).

Table 1
Thermoelastic properties of the bimaterials systems used in the numerical results

Bimaterial System	K_2/K_1	D_2/D_1	α_2/α_1	E_2/E_1	ν_2/ν_1
A	3	3	0.75	1	1
B	3.385	4.07	2.294	0.611	1

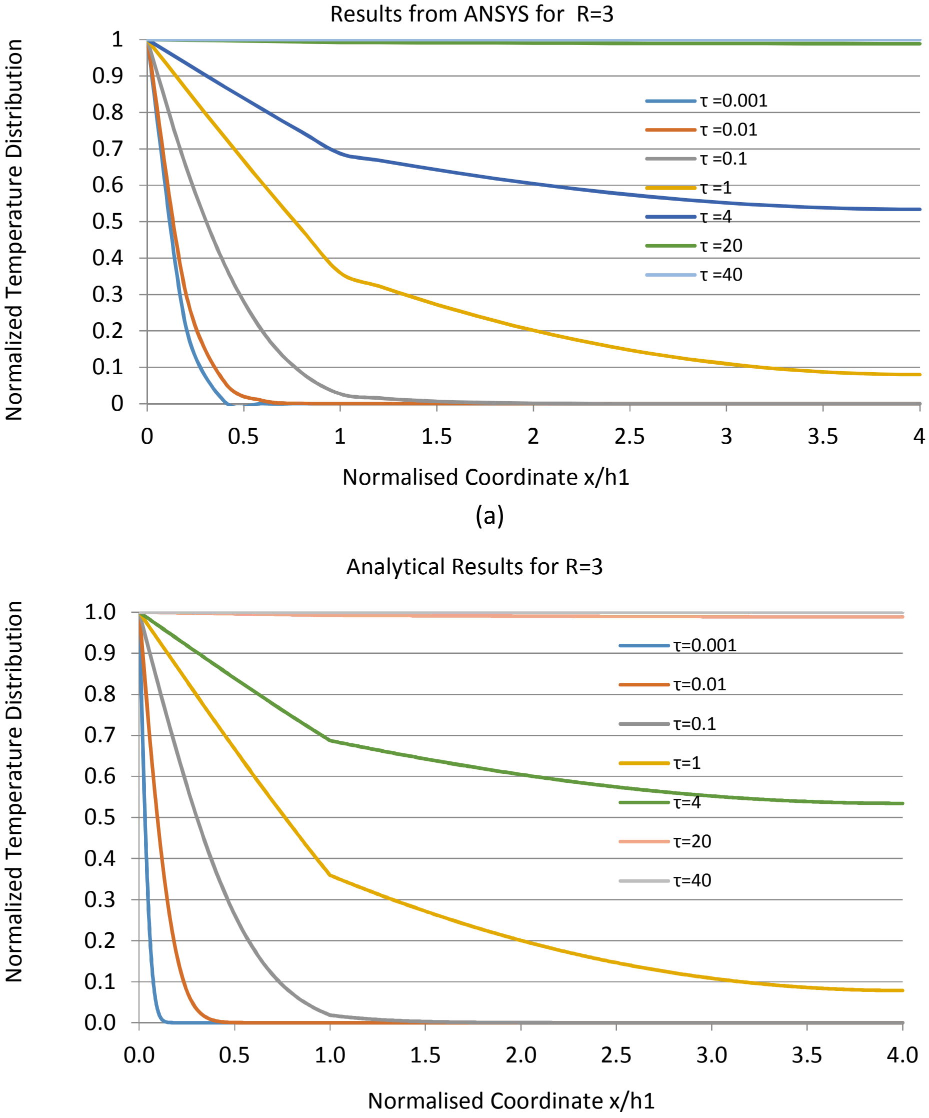
3.1 Temperature Distribution

Figure 4 presents the results for the normalized transient temperature distribution verses normalized coordinate $x/h1$ for various normalized time τ for system A and B. Normalised temperature θ/θ_0 is calculated by using a formula $\theta = T(x,t) - T_0$and $\theta_0 = T_a - T_0$. In Ansys, the uniform temperature $T_0 = 22°c$.

3.2 Thermal Stress Distribution

Figure 5 and Figure 6 show the results of normalized transient thermal stresses for two different systems and two thickness ratios where $R = h_2/h_1$. Each figure displays results against a normalized coordinate $x/h1$ for bi-material systems A and B. Some results for the normalized transient thermal stresses are calculated by σ_{yy}^T which is calculated from Ansys and divide by σ_0^T where $\sigma_0^T = -E_1\alpha_1\theta_0/(1-\vartheta_1)$.

For small Fourier number values $\tau = tD_1/h_1^2$, the initial normalized thermal stress is positive for bi-material systems A and B i.e., tensile stresses near the cooling surface (layer 1) and near the insulated surface (layer 2), whereas the stresses are positive (compressive stresses) within layers 1 and 2. As τ increases, different normalized thermal stress behaviour is observed between system A and system B. At the interface, a discontinuity in the thermal stresses is caused by different mechanical and thermal properties in different composite materials. The figures also highlight the thickness ratio's influence on the normalized thermal stresses. As the normalized thermal stresses increase, so too does h_2/h_1. The most dangerous area for a crack to propagate is in proximity to the cooled surface since the highest tensile stresses occur there.

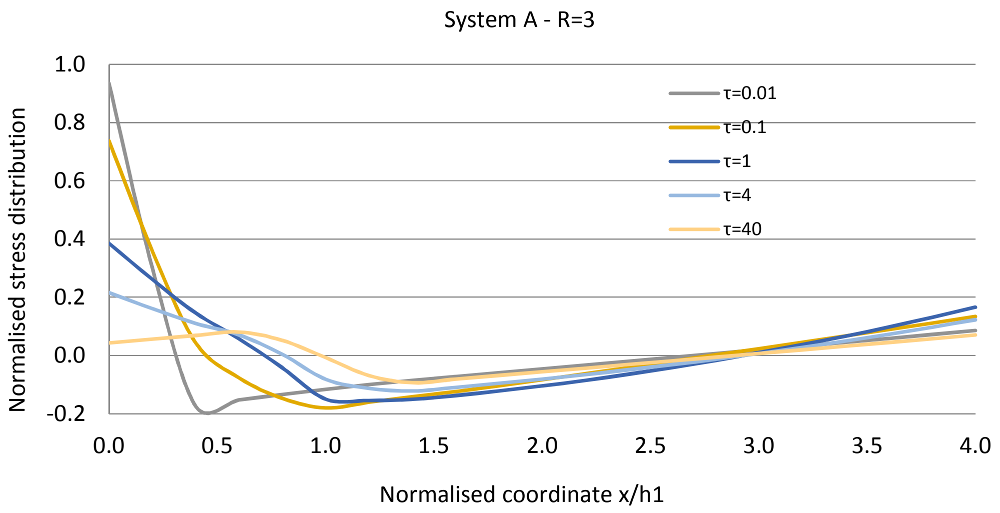


(a)

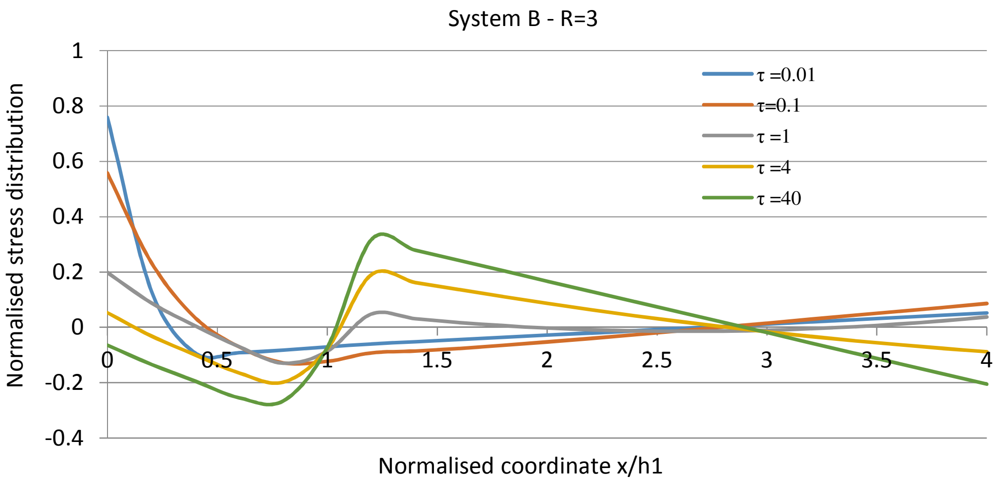
(b)

Fig. 4. Normalized transient temperature distribution for system A (a) FE results (b) Analytical results [2]

As τ increases within system A, nearly half of layer 1 undergoes tensile stresses while layer 2's interior remains under compressive stresses and its insulated surface undergoes tensile stresses. On the other hand, as τ increases within system B, nearly half of layer 1 undergoes tensile stress, then compressive stresses, switching again to an increasing tensile stress. As a result, layer 2 undergoes thermal stresses that are opposite to the initial behaviour.



(a)

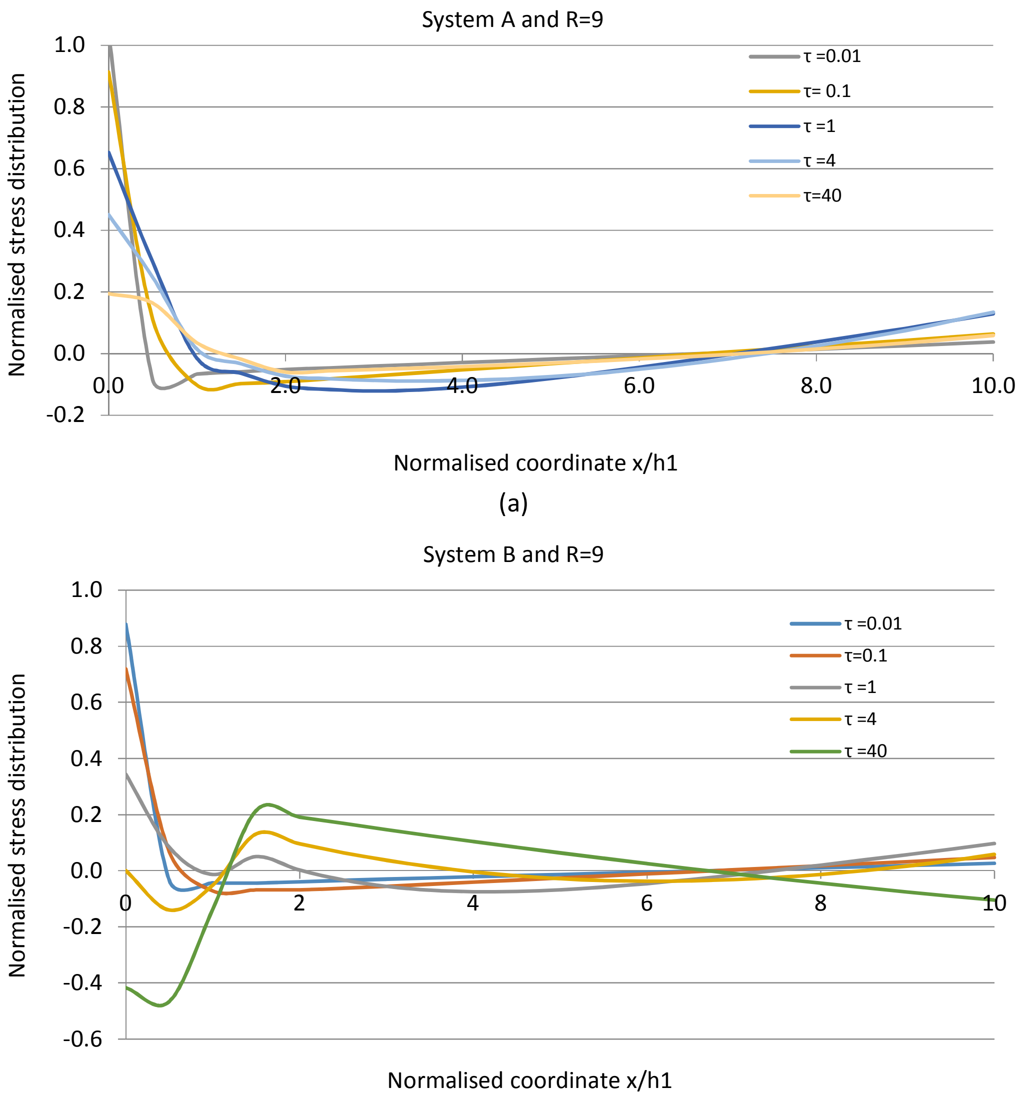


(b)

Fig. 5. Normalized transient thermal stresses (a) system A (b) system B for R=3

3.3 Stress Intensity Factor

Figure 7 and Figure 8 present the stress intensity factor variation for an edge-cracked problem i.e., $b/h1 < 1$ defined by normalised stress intensity factor versus normalised time. Normalised stress intensity factor is calculated by using $K(b)/\sigma_0^T\sqrt{b}$. The Ansys results for bi-material systems, A and B are presented for some values of normalized crack length $b/h1 = 0.1, 0.3, 0.5$ and for two different ratios. The stress intensity factor increases to a maximum with smaller timing and then started decreasing as τ increases to larger timing in both systems. A reduction in thermal stresses causes the stress intensity factor to decrease as crack length increases. In system A, the stress intensity factor has different values at both crack face temperatures but both follow a similar trend. In system B, the stress intensity factor also follows a similar trend with differing values.



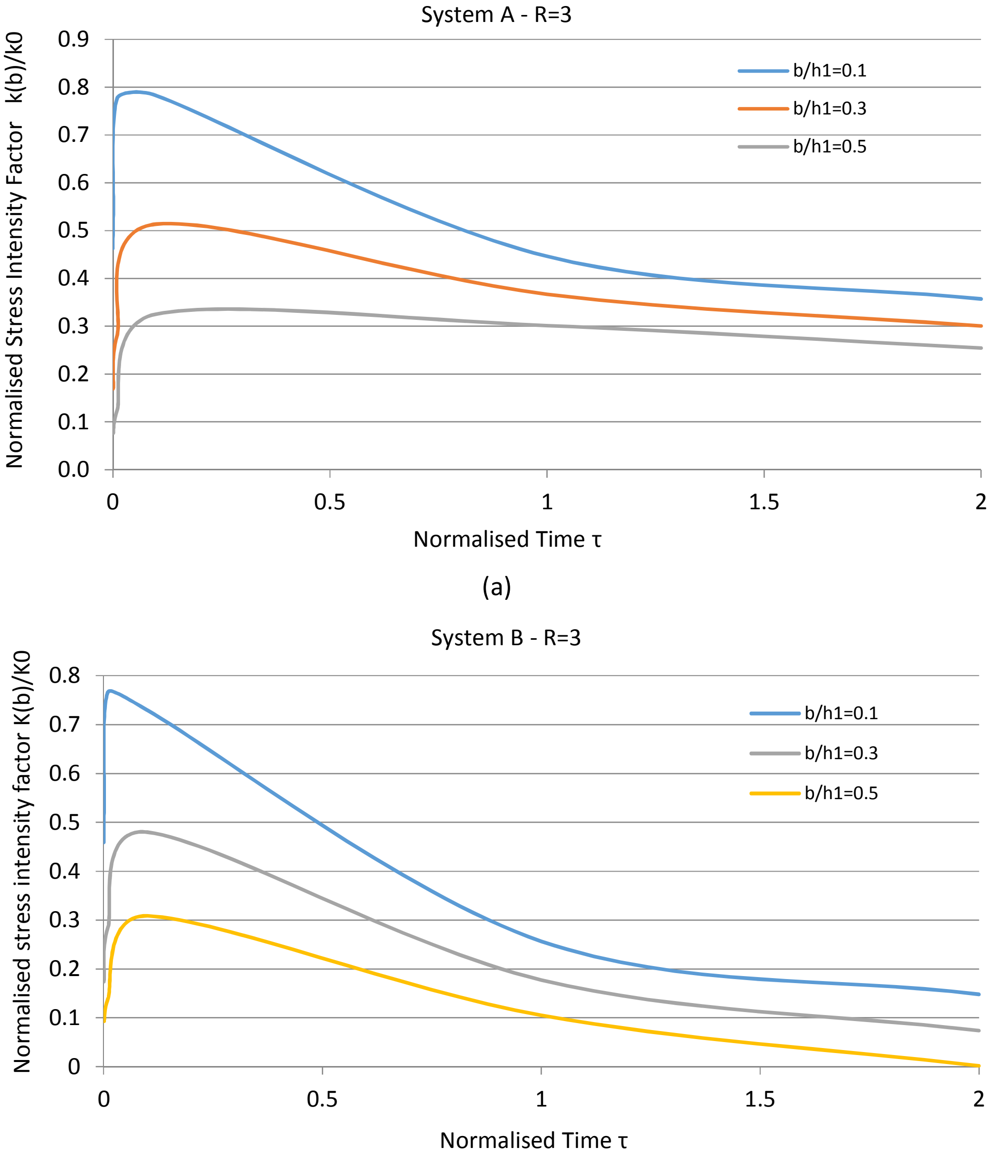
(a)

(b)

Fig. 6. Normalized transient thermal stresses (a) system A (b) system B for R=9

4. Conclusions

The finite element method was used to solve problems with bi-material systems containing a crack that was normal to the interface, undergoing cooling on the cracked surface. Two separate bi-material systems were investigated with various crack lengths in order to assess crack propagation behaviour changes with increasing stress intensity factor as the crack grew. Both systems were observed to have initial increases in stress intensity factor, followed by a start of a decline with the increase in the normalized time. In particular, the results showed that the transient thermal stresses and consequently the corresponding stress intensity factors were strongly depending on the material properties and that the film coefficient heat transfer has a great effect on the stress intensity factors.



(a)

(b)

Fig. 7. Normalized stress intensity factor (a) system A (b) system B

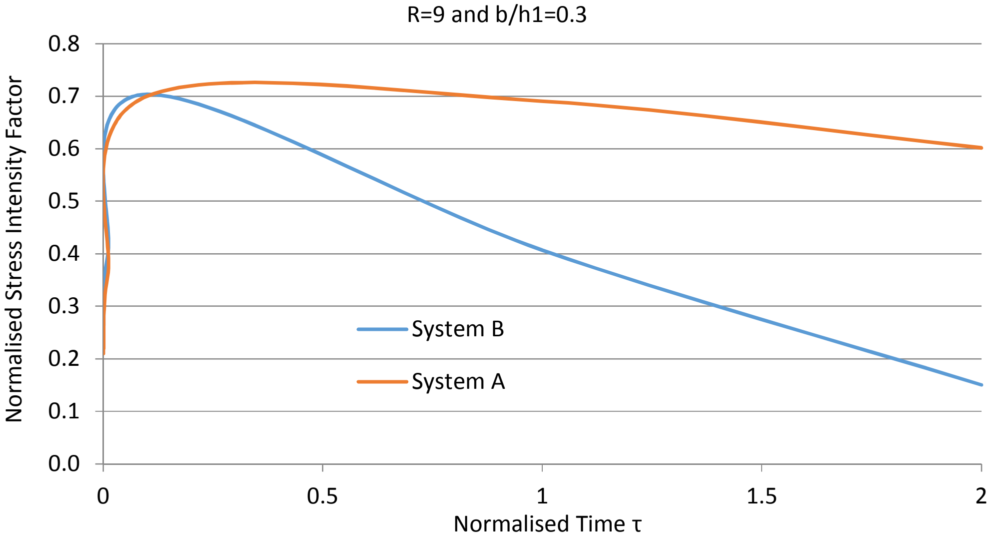


Fig. 8. Normalized stress intensity factor for two different systems

Acknowledgement

This research was funded by a grant from Ministry of Higher Education of Malaysia (FRGS Grant: FRGS16-066-0565).

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