Stress and Temperature Distribution Study in a Functionally Graded Brake Disk

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Abstract

In this paper, finite element elastic contact analysis of a functionally graded (FG) hollow brake disk in contact with pad, subjected to rotation, contact pressure and frictional heat is presented. The material properties vary through the thickness according to a power-law characterised by a grading index, n. The material property is purely steel at the core part and gradually moves and approaches to the ceramic properties at the surfaces of the FGM disk. In this task, thermal analyses are performed on two ventilated disk brake one of them is constructed of functionally graded composite material and the other is a homogeny disk brake which is constructed of steel alloy. In this study three-dimensional finite element model and ABAQUS software is used. Through comparison of temperature and displacement fields the benefits of using functionally graded material is investigated. It is shown that temperature variation in FGM disk is much lower than steel disks, it may be concluded that FGMs disk restrain the growth of thermal perturbation and delay the contact separation..

Keywords: *Brake disk, FGM, contact pressure, thermal perturbation.*

1. INTRODUCTION

Functionally graded materials _FGMs_ are composite materials formed of two or more constituent phases with a continuously variable composition. FGMs possess a number of advantages that make them attractive in potential applications, including a potential reduction of in-plane and transverse through-the-thickness stresses, an improved residual stress distribution, enhanced thermal properties, higher fracture toughness, and reduced stress intensity factors. A number of reviews dealing with various aspects of FGM have been published in recent years [1,2].

At present, FGMs are usually associated with particulate composites where the volume fraction of particles varies in one or several directions. One of the advantages of a monotonous variation of volume fraction of constituent phases is the elimination of stress discontinuity that is often encountered in laminated composites and accordingly, avoiding delamination-related problems.

Functionally graded materials are attractive because of the additional possibilities they offer for optimizing the design of components in terms of material usage and performance. This paper explores, in part, the potential benefits of using functionally graded materials for rotating hollow brake disks.

Some researchers have studied the transient brake analysis [3–6]. Zagrodzki [3] analyzed sliding systems with frictional heating. The system exhibits thermoelastic instability (TEI) in friction clutches and brakes when the sliding speed exceeds a critical value. Zhu et al. [4] established the theoretical model of three-dimensional (3D) transient temperature field to predict the change of brake shoe's temperature field during hoist's emergency braking. Voldrich [5] postulated that exceeding the critical sliding velocity in brake disks causes formation of hot spots, non-uniform contact pressure distribution, vibration, and permanent damage of the disk. The analytical model of TEI development was published by Lee and Barber [6]. Choi and Lee [7] presented the distribution of temperature and contact pressure in brake disks where hydraulic pressure is applied. The brake disks are in contact with two pad disks on their sides. These works highlighted the importance of contact analysis of brake disk. Researchers began to use fully non-linear theory to solve the temperature distribution and contact pressure of thermoelastic FG brake disk. However, there are several works on the transient and contact analysis of pure and multi-layered brake disks, both analytically and numerically. Although there are some research works that has been presented for FG brake disk subjected to thermomechanical loads, due to its complexity, analysis on pad penetration and contact pressure in FG brake disk is still scarce.

In this paper, thermal stress analyses are performed on two ventilated disk brake one of them is constructed of functionally graded composite material and the other is a homogeny disk brake which is constructed of steel alloy. In this study three-dimensional finite element model and ABAQUS software is used. Through comparison of stress and temperature fields in these cases the benefits of using functionally graded material is shown.

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2. FORMULATION OF THE PROBLEM

2.1 Material properties in functionally graded material

The determination of material distribution in the FGM disk was reported in many studies. One of simple and promising method to select the distribution of material properties is to divide the domain into multi-layers with constant properties. In each layer, the material property which is a function of thickness of the disk y, is given by the distribution equation as equation (1)

$$P(y) = P_c + (P_s - P_c)V_f$$

In which (1)

$$V_f = (1 - \frac{y}{l})^n \qquad (2)$$

Where in this work P, Ps, and Pc are the material properties which vary with the thickness, the steel property, and the ceramic property, respectively. n denotes the nonhomogeneity parameter of FGM. In equation (2) y is measured from middle plane of disk and l is one half of the disk thickness. As the result the lower and upper surfaces of disk are mutually symmetric with respect to the middle plane of disk.

P is used for the elastic modulus, the thermal expansion, the thermal conductivity, and the thermal diffusivity in this paper.

From the distribution Eq. (1), it is known that the composition would vary continuously from 100% core material near the interface to 100% ceramic near the surface. Thus, the material property is purely steel at the core part and gradually moves and approaches to the ceramic properties at the surfaces of the FGM disk.

In this task in the numerical model, the FGM layer is divided into five layers in each side of middle plane with the properties given by Eq. (1) and table

3. Finite element model and boundary conditions

In this paper in order to construct the finite element model of a rotating brake disk the following assumption is made;

(1) The brake pressure is uniformly distributed over the contact area of the disk and pads on both inboard and outboard surfaces therefore the central crossing plane of the disk is the plane of symmetric.

(2) The coefficient of friction is considered constant during braking.

(3) The material of pad is homogenous and a functionally graded material is considered for brake disk. Thermal properties are assumed to be invariant with temperature.

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Table.1 Material properties of disk brake system

	Density (kg/m3)	Young's Modulus (GPa)	Poisson's Ratio	Conductivity (W/m.K)	Specific Heat (J/kg.K)
Pad	2595	2.2	0.25	1.2	1465
Steel disc brake	7228	210	0.3	48.5	420
Ceramic	5700	151	0.2	2	400

Table.2 Material properties of each considered layer in FGM disk

	Density (kg/m3)	Young's Modulus (MPa)	Poisson's Ratio	Conductivity (W/m.K)	Specific Heat (J/kg.K)
Steel	7228	2100	0.3	48.5	420
Layer1(near steel)	6922	1982	0.28	38.8	416
Layer2	6617	1864	0.26	29.6	412
Layer3	6311	1746	0.24	20.4	408
Layer4	6006	1628	0.22	11.2	404
ceramic	5700	1510	0.2	2	400

The heat conduction equation in the Cartesian coordinates system attached to the disk is as follow [8]:

$$\rho_d c_d \frac{\partial T_d}{\partial t} = k_{dx}\frac{\partial^2 T_d}{\partial x^2} + k_{dy}\frac{\partial^2 T_d}{\partial y^2} + k_{dz}\frac{\partial^2 T_d}{\partial z^2}$$

Where □d is density, k_{dx} and k_{dz} are thermal conductivities in different direction and, c_d is the specific heat of the disk. The boundary condition can be specified as follow:

$$k_{dz}\frac{\partial T_d}{\partial z} = -[1-g(m)]h_{d1}(T_d - T_f) + g(m)q_d$$

where

$$g(m) = \begin{Bmatrix} 1 & \textit{in}\ \text{the domain of pad} \\ 0 & \textit{out}\ \text{of the domain of pad} \end{Bmatrix}$$

$$k_{dx}\frac{\partial T_d}{\partial x}n_x + k_{dy}\frac{\partial T_d}{\partial y}n_y = -h_{d3}(T_d - T_f)$$

Where q_d is the heat flux entering into the disk from the contact region, h_{d1} and h_{d3} are the convective coefficient out of the contact region and the brake disk surface. Tf, n_x and n_y are ambient temperature, and the normal unit vectors respectively

In order to perform thermal analysis in braking process it is essential to determine the frictional heat generation and distribution between pads and disk. In this task it is assumed that the total heat generated is equal to the heat absorbed by the disk and pads. As a result

$$q_d(r,t) = \gamma\mu p v(r,t) = \gamma\mu p \omega(t) r$$

Where □□, □ , r , P and, □□are the coefficient of friction, angular velocity, radial distance from center of the disk, normal pressure on the external surface of the pad□ and, the heat partitioning factor representing the fraction of frictional heat flux entering the disk, which is given in equation (7) respectively.

$$\gamma = \frac{1}{1+\sqrt{\rho_p c_p k_p / \rho_d c_d k_d}}$$

Where □ is density, c the specific heat and k is the thermal conductivity. The subscripts p and d mean the pad and the disk, respectively.

When a vehicle is braking, some of the frictional heats go out into the air by convection and radiation (the radiation is omitted in this paper on the assumption that the braking duration is short and thus the temperature will not reach a high value). Hence, the determination of the coefficients of convection is very important. It is, however, very difficult to calculate them accurately, as they are affected by the shape of the braking system, the velocity and hence, the air flow. In this work the coefficients of convection assumed to be fixed and equal to 100 w/m2.K [9].

4. NUMERICAL SIMULATION

In this stage as it is seen in figure 1 a 3-dimensional model of brake system has been constructed using the CAD capabilities in ABAQUS. The geometric and material properties of the used model are listed in figure 2 and Table I. In this model the pressure is applied directly over the brake pad area.

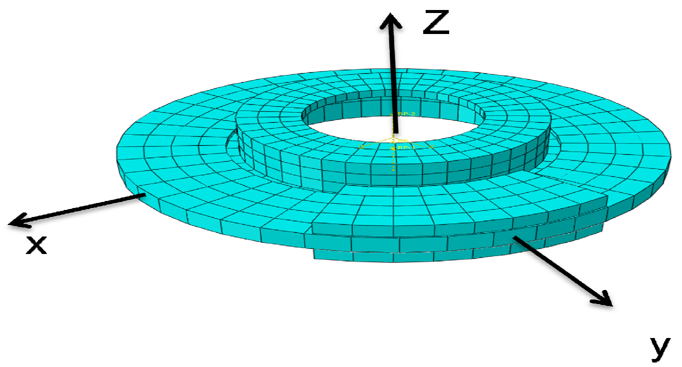

Fig1. FE model of disk brake system

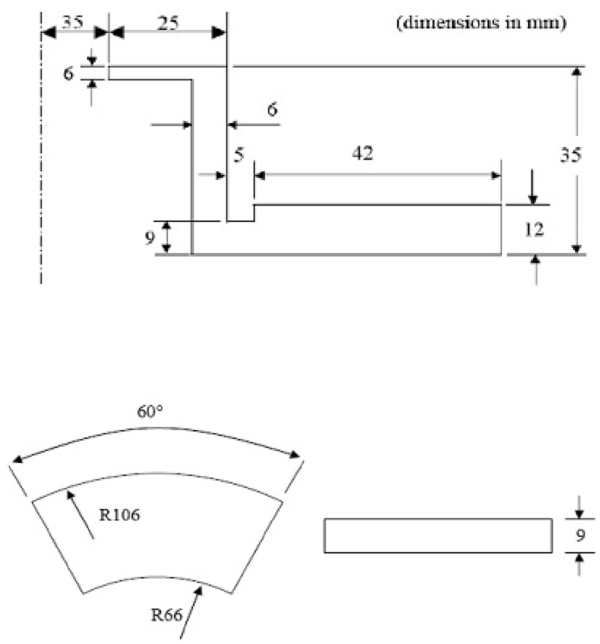

Fig2. the model of disk and pad, and simulation data used in the FE analysis

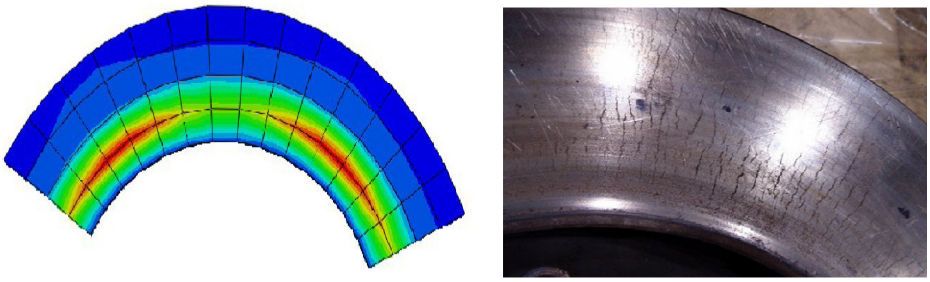

Fig3. comparison between the numerical and the test results.

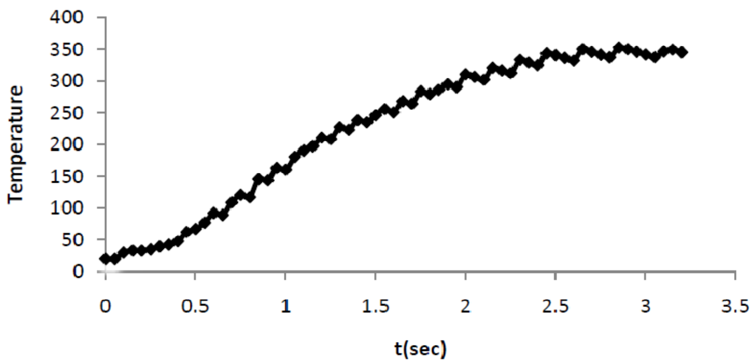

Fig4. Surface temperature variations versus time at □ =0, z = 12 mm and, x= 76 mm.

The full disk brake assembly consists of 515 elements. Three dimensional 8-noded solid brick elements with coupled thermal and stress capability have been used throughout. This type of element permit large scale sliding between contact surface (pad) and sliding target surface (disk). In order to simulate the axial movement of the pad, no constraint is applied in the direction normal to the disk surface. The centre of the disk is constrained in the normal direction only so that the disk is able to rotate.

To simulate the contact scheme between the pad and disk surface, surface-to-surface contact surfaces have been defined using the finite sliding contact algorithm. The master-slave approach is adopted where the disk surface is chosen as the master surface since it has a coarser mesh and is stiffer than the pad. The contact surface frictional behavior is simulated by the penalty method.

In this study the pressure on the pads, angular velocity and the coefficient of friction has been considered to be 1.83 Mpa, 92.6 rad/sec and 0.35 respectively. In figure 3 a numerical model of a homogeny steel disk is considered and the location of hot spot on this model is compared with the available test data in literature [10]. Since the location of the cracks on the real steel disk is similar to the location of hot spots in numerical model it could be concluded that crack initiation in disk is due to hot spot formation.

5. NUMERICAL RESULTS

The normalized temperature variations in the circumference direction versus □□ at z=12 and r =76mm for steel and FGM disks, considering linear variation of material properties, after 1.6 sec are shown in Figure 5, it is seen that temperature variation in steel disk versus □ is larger than FGM disk. As a result local contact between pads and disk and hot spot formation in steel disk is more prevalent than FGM disk.

In figure 6 vertical displacements due to pad pressure versus non-dimensional radius for steel and FGM disks after 1.6 sec are shown. In this figure 0 means r=65 mm and 1 means outer perimeter of disk or r= 107mm (figure 7).

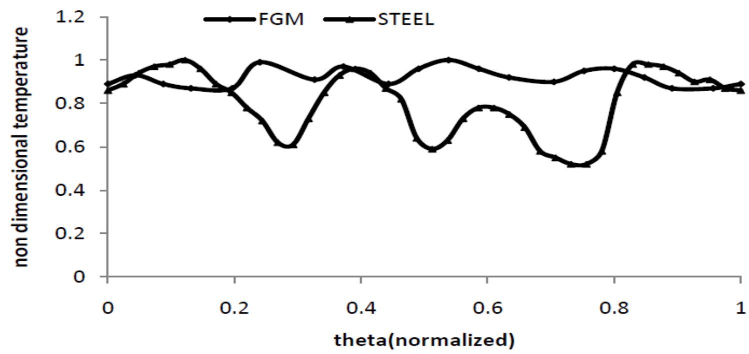

Fig5. normalized temperature distribution comparison between steel and FGM disk

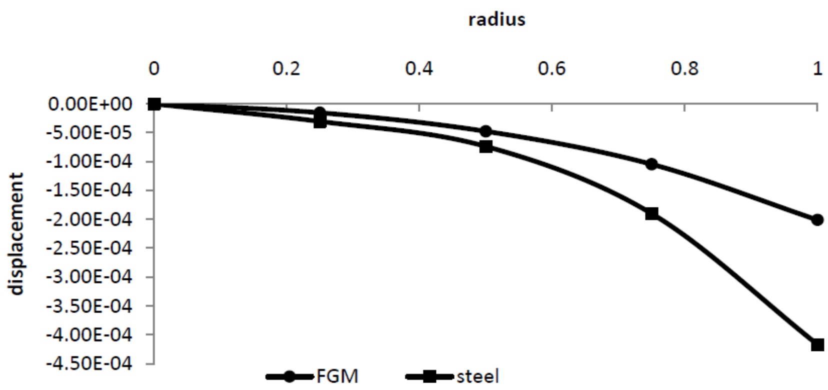

Fig6. vertical displacement versus non-dimensional radius for steel and FGM disks

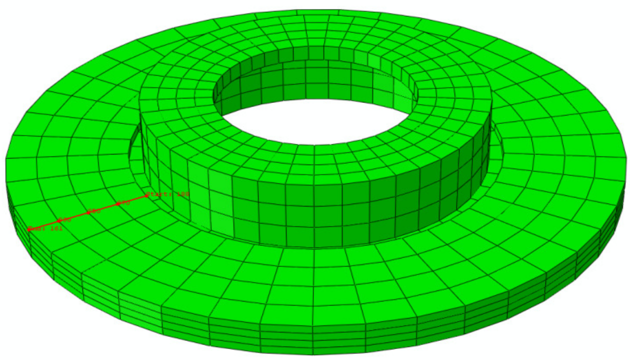

Fig7. Used radial path on the disk

It is seen that vertical displacement for steel disk is greater than FGM disk

Figure 8 shows normalized temperature distribution versus non-dimensional radius for steel and FGM disks after 1.6 see c. The maximum temperature in steel and FGM disks at this moment are 310 oC and 700oC respectively. In order to compare the temperature distribution in these two disks the temperature distributions are normalized by these maximum values. It may be seen that temperature gradient and heat localization are too greater in steel disk than FGM disk.

In figure 9 contact situation between pad and disk after 1.6 sec is shown. It is seen that although the mean temperature is higher in FGM disk but separation does not occur between pad and disk. In steel disk as a result of non uniform temperature distribution separation between disk and pad arise. This situation may accelerate wear and damage in disk brake.

Figure 10 shows normalized Von-Mises stress distribution versus non-dimensional radius for steel and FGM disks after 1.6 sec. The maximum Von-Mises stress in steel and FGM disks at this moment are 14 Mpa and 2.2Mpa respectively. In order to compare the Von-Mises distribution in these two disks the Von-Mises stress distributions are normalized by these maximum values. It may be seen that the stress gradient and concentration are too greater in steel disk than FGM disk

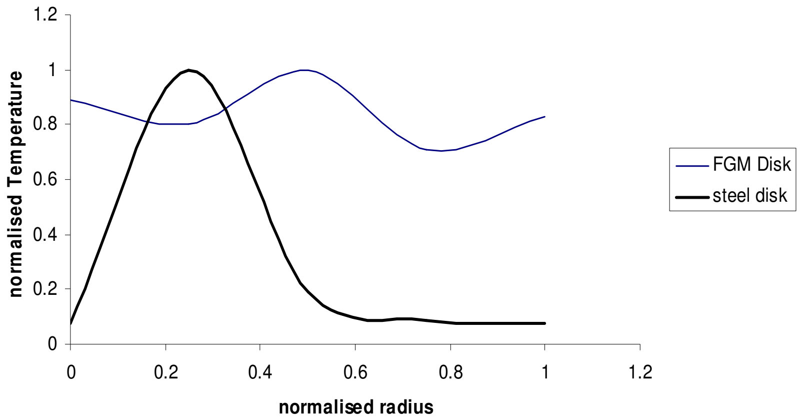

Fig8. normalized temperature distribution versus non-dimensional radius for steel and FGM disks after 1.6 sec.

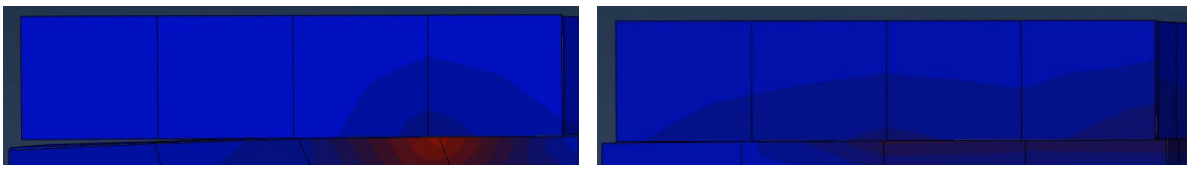

Fig9. contact situation between disk and pad after 1.6 sec in steel and FGM disks

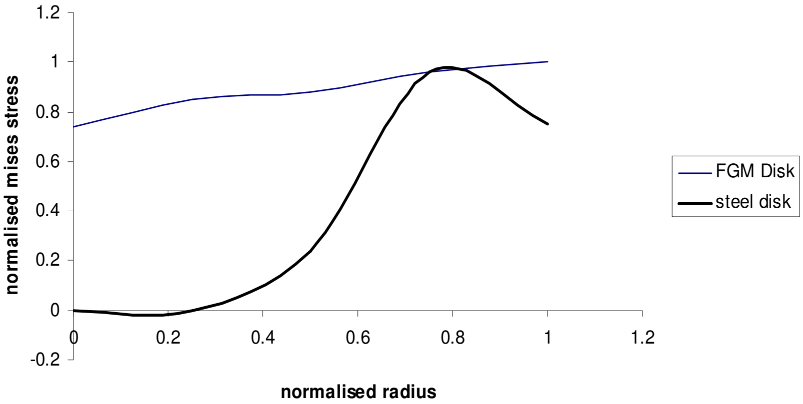

Fig10. vertical displacement versus non-dimensional radius for steel and FGM disks.

6. CONCLUSIONS

The simulation results show that the material properties of the disk brake exert an essential influence on the surface temperature, Von-Mises stress distribution and vertical displacement of the disk.

It is shown that the temperature variation and vertical displacement in FGM disk is much lower than steel disk. Besides von-mises stress distribution in radial direction grows gradually and has not shown a maximum value in FGM disk. As a result the FGMs disk restrains the growth of thermal perturbation and delay the contact separation. Furthermore it is shown that localized contact is not as prevalent in FGM brake disk as steel disk and use of FGM brake disk may eliminate thermal cracking and wear in localized contact point or hot spots.

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