ISSN 2395-1621

Fatigue failure analysis of a crack in disc brake of passenger vehicle

#1B.B.Kokane, #2M.A.Mohite

1bhaskar.kokane@yahoo.com
2mamohite.sit@sinhgad.edu

#12Mechanical Engg. Department, University of Pune
Sinhgad Institute of Technology, Lonavala, India.

ABSTRACT

Disc brakes are exposed to large thermal stresses during routine braking and extraordinary stresses during hard braking. High g-decelerations typical of passenger vehicles are known to generate temperatures as 900°C in fraction of second.
Brake disc is composed of two main parts, a flange and a bridge.The former faces pressure from pads and therefore is subjected to higher temperatures during braking; the latter works in cooler conditions and has the function of transferring brake torque to the wheel hub. Hence, the rotor is designed to withstand both the maximum possible deceleration (emergency braking) and a series of braking cycles. The main problem to deal with in braking cycles is the control of the fading phenomena. High frequency braking cycles lead a rising of the disc temperature.These large temperature excursions have two possible outcomes; thermal shock that generates surface cracks and/or large amounts of plastic deformation in brake rotor. In the absence of thermal shock, a relatively small number of high g braking cycles are found to generate macroscopic cracks running through rotor thickness and along radius of disc brakes. To study fatigue failure of the specimen material under thermal cyclic loading analytically & simulate it numerically by suitable simulation process for validation.Analysis shows that rotor failure is consequence of low cycle thermo mechanical fatigue. Analysis of vehicle dynamics was used to find a heat flux equation related to braking forces. Heat flux equation was then used in finite element analysis to determine the temperature profile in the brake.
Once the brake temperature was obtained, a simplified shrink fit analysis was used to estimate the stresses that arise during hard braking. This approach shows that plastic deformation occurs due to the large thermal strains associated with high g braking.The calculated Strain amplitude was then used in Coffin-Manson law to predict the number of high g braking cycles to failure.The crack shape and kinetics of propagation are modeled by analytical approach based on stress intensity factor. Analytical results are compared with numerical results.numerical simulation can be performed by using time dependent thermal analysis i.e. transient thermal analysis. Transient thermal analysis to be carried out using the direct time integration technique for the application of braking force due to friction for time duration of 4,5 and 6 seconds.

Keywords— **Fatigue Fracture, Crack Propagation, Thermo- Mechanical Loading, Thermal Gradient, Stress Intensity Factor, Passenger Car Disc**

ARTICLE INFO

Article History

Received :18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

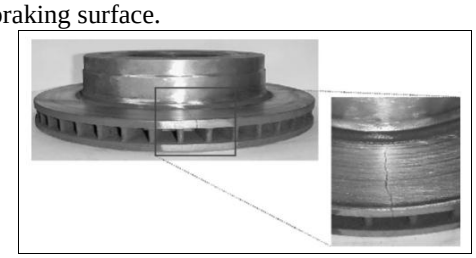
I. INTRODUCTION

Thermal cracking is commonly observed in disc brake rotors following high g braking events.The crack fall into two broad categories;a series of heat cracks that partially

penetrate the surface of the discs and thru-cracks that completely pass through the disc wall.Though it is well known that thermal cracks do arise from hard braking,there is no formal treatment of the problem of thru cracks.This paper presents a fatigue failure analysis of a crack in disc brake and estimation of the remaining life time of a disc brake.

Crack initiation and propagation by thermal fatigue has been identified as the cause of this leak.The incident has shown the need for research to understand the phenomenon. Different authors have shown that cyclic water cooling of the surface of the specimen can initiate crack network. Depending on the thermal loading and on the geometry of the specimen, the crack network can be stopped, or can propagate with a dominant crack crossing the specimen thickness; with a semi-elliptical shape. Thermal fatigue induces in-service damage in many industrial components, in aerospace, automotive and nuclear engineering. In particular, a thermal gradient from the surface to the heart of the structures may be induced. The prediction of the fatigue life-time of these cracked components requires further investigation on the evolution of the stress intensity factor with respect to the transient temperature distribution, as well as on the crack development behaviour.

Disc brakes are fabricated from gray cast iron with typical geometry shown in fig 1. Material is chosen for its relatively high thermal conductivity,high thermal diffusivity and low cost.Brake rotor consists of a hub,which is connected to the wheel and axle and inboard and outboard braking surface.



Outboard braking surface is attached directly to the hat,while inboard surface is attached to outboard unit by a series of colling vanes.Inboard and outboard rotors are squeezed by the brake pads during braking.Braking events last on the orders of seconds,generating frictional heating in the rotors while leaving the hat very near rom temperature.

Furthermore ,the rotor yields in compression upon braking,while a residual tensile hoop stress sets upon cooling.This cycling between compression and tension in phase with temperature of the brakes,is the thermo-mechanical mechanism responsible for failure.

In addition, some authors have observed metallurgical phase transformations in grey cast iron brake discs. For example, Barta and Skrbek described a thermal cycle with three temperature ranges; in the mid- and high-temperature ranges, metallurgical phase transformations such as pearlite decomposition and auste- nitic transformation in martensite or bainite were observed. These phenomena led to high stresses, accelerated oxidation and changes in dimension. The author established a link with crack initiation. Other studies on braking have demonstrated the occurrence of different types of thermal localisation arising from contact instabilities and disc deformation. They have identified and modeled several kinds of heat flux distributions during braking tests, such as hot spots and hot bands. These authors have cited high temperature levels and thermal gradients as the reasons for brake disc damage. Indeed, high compressive stresses are produced in hot areas. This gives rise to plastic deformation, and the residual tensile stresses that appear after cooling lead to the formation of cracks. Thus, the global phenomena of brake disc failure have been identified.

The Transient state thermal analysis (FEA) performed to determine the temperatures profile in the disc as well as to estimate the stresses distribution during the braking also confirmed the relatively high temperatures reached during the braking actions and attributed to the residual tensile stress due to the repetition of the thermal stress cycles. In many applications, the finite element method (FEM) using ANSYS code is generally used to simulate the crack propagation. The stress intensity factor (SIF) is calculated for the cracked component and the kinetics of propagation can be obtained by integrating the Paris law.

II. ANLYTICAL APPROACH

a In analytical approach, temperature rise is estimated by calculating instantaneous heat flux.Crack growth rate calculated using paris law.And then Fatigue life time of cracked specimen is found by coffins mansons law.

A. Temperature Estimation

Braking must remove kinetic energy of moving vehicle in timely and repeatable fashion.In order to estimate temperature that arise during braking,it is necessary to calculate the forces acting on the brake rotors [1].

Vehicle mass M =1500 Kg
Initial Velocity V =30 m/s,Time to stop t(stop)=3 s
r(rotor)= 0.12m, r(tire) =0.38m

F(rotor)=(0.3xM)/{2x $\frac{r(rot}{r(ti}$ x(Vt(stop)- $\frac{V}{2t(st}$x $t(stop)$}

Instantaneous heat flux into rotor face is directly calculated using following,[1]

Qin(t)= {F (rotor)xV(rotor) ---------- (1)
= F(rotor)x $\frac{r(rot}{r(ti}$ {V-($\frac{V}{t(st}$)xt}

B Disc Brake Details

The automobile industry typically utilizes flake cast iron in braking applications.Minimum Hardness of the brake is near hat while maximum hardness is on the inboard,Average hardness of the disc brake is around 94 HRB,This different hardness are due to cooling rates associated with casting process.

TABLE I

Sr No	Disc Brake Specifications	
	Properties	**Cast Iron**
1	Thermal conductivity(w/m k)	55
2	Density, ρ(kg/m3)	6600
3	Specific heat , c (J/KgC)	380
4	Thermal expansion , (10-6 / k)	0.15
5	Elastic modulus, E (GPa)	110
6	Coefficient of friction, μ	0.5
7	heat transfer coefficient	120

	h(w/km2)	

Heat flux per unit area per unit time is calculated for time interval of ½ sec upto 3 sec

Single stop temperature rise Tmax is the temperature rise due to single braking condition.

Tmax=(0.527xqx ·/ $\sqrt{P}$)+ Tamb

C. Fatigue failure and Crack Growth Rate

Braking causes rapid heating of rotor surface that lead to thermal shock in the skin of the brake. Furthermore ,the rotor yields in compression upon braking,while a residual tensile hoop stress sets upon cooling.This cycling between compression and tension in phase with temperature of the brakes,is the thermo-mechanical mechanism responsible for failure.

In order to estimate the fatigue failure of the rotor,we utilize the Coffin –Manson Law,

Low Cycle Fatigue:

$\Delta\varepsilon p/ 2 = \varepsilon f (2N)c$, c ~ -0.5 - -0.7

High Cycle Fatigue:

$\Delta\varepsilon E/ 2 = \sigma f (2N)b$, b ~ -0.05 - -0.12

σf is stress amplitude coefficient

εf is strain amplitude coefficient

N is number of cycles to failure.

No. of cycles to failure by Paris law :

da/ dN = A (ΔK)m

Nf = (1 /Aπm/2(Δσ) m) x $\int_{a0}^{af}$ (da/ Ym am/2)

Factors Affecting Fatigue Life are Mean Stress, Surface Effects (polished vs machined), Design Factors , Surface Treatments,hot peening,surface compressive stresses, case hardening etc.

III. FINITE ELEMENT ANALYSIS

The finite element method has become a powerful tool for the numerical solutions of a wide range of engineering problems.Certain steps in formulating a finite element analysis of a physical problem are common to all such analyses, whether structural, heat transfer, fluid flow, or some other problem. Although we do not necessarily refer to the steps explicitly in the following chapters. The steps are described as follows.

This involves three phases:

A Pre-processor phase

B Solution phase

C Post-processor phase

A. Pre-Processing

The preprocessing step is, quite generally, described as defining the model and includes

1 Define the geometric domain of the problem.

2 Define the element type(s) to be used.

3 Define the material properties of the elements.

4 Define the element connectivity (mesh the model).

6 Define the physical constraints (boundary conditions).

The preprocessing (model definition) step is critical.

B. Solution

During the solution phase, finite element software assembles the governing algebraic equations in matrix form and computes the unknown values of the primary field variable(s). The computed values are then used by back substitution to compute additional, derived variables, such as reaction forces, element stresses, and heat flow.

As it is not uncommon for a finite element model to be represented by tens of thousands of equations, special solution techniques are used to reduce data storage requirements and computation time.

C. Post Processing

Post - Possessing

Analysis and evaluation of the solution results is referred to as post processing. Postprocessor software contains sophisticated routines used for sorting, printing, and plotting selected results from a finite element solution. Examples of operations that can be accomplished include,

1 Sort element stresses in order of magnitude. 2 Check equilibrium. 3 Calculate factors of safety. 4 Plot deformed structural shape. 5 Animate dynamic model behavior.

While solution data can be manipulated many ways in post processing, the most important objective is to apply sound engineering judgment in determining whether the solution results are physically reasonable.

D. Meshing

Finite Element Analysis follows the Numerical Method to solve the engineering problem, thus, the theme of FEA is to calculate results at limited number of points and then the results are interpolated for the area or volume under study. For any continuous object, there are infinite degrees of freedom. No problem can be solved with infinite Degree of Freedom (DOF) and infinite equations. Thus there is need to reduce the no number of equations in order to find the solution for the system.

E. Transient State Thermal Analysis

Numerical simulations using the ANSYS Workbench 14.5 finite element analysis software package were performed in this study for a simplified version of a disc brake system.

Disc brake model DBA2893 of i20, 1.4L 2DR hatchback car is used for analysis.Model is made in Solid Edge and imported in ansys for analysis. The model is nothing but a part of brake disc having crack generated on it with the length of crack a=15mm & thickness of the crack t=7mm.The pre-generated crack is penetrate the full depth of the model. For the meshing automated meshing is used and meshing is generated.

Boundary Conditions are applied

1. Fix Support

There are two faces which are in the contact with friction material are suppose to be fixed. So that the fix support is applied to the two opposite faces of the part of the rotor disc which in the caliper.

2. Pressure

As the air is continuously flows over the disc which is responsible for the cooling of disc so that consider the MPa pressure is applies over the free faces of the disc.

3. Thermal Load

Consider initial body temperature at 300k.

Analysis was conducted to obtain an estimate of temperature distribution in brake rotor.A stepped heat flux was applied to brake surface in contact with brake pad.Convection was applied to the other surfaces in stepped

manner with convection coefficient decreasing from 30w/m2k.Transient analysis was performed over interval of 3 sec in half sec time steps using heat flux formula given by eqn(1).A plot of temperature profile through the width of outboard rotor after 1.5 sec of braking.

IV. CONCLUSION

In this study of the crack propagation under thermal loading inducing a thermal gradient in thickness of the specimen has been treated analytically and numerically.

Thermal cracking in the disc brake rotors is a low cycle thermo-mechanical fatigue problem.Braking causes temperature to rise in the rotor,Due to which compressive stresses are developed in the inboard and outboard rotor surfaces during braking.After release of brake rotors get cool down during which tensile stresses are set in the rotors.The subsequent braking cycles exceeds the yield point over the certain time leading to a proble of low cycle fatigue

In Analytical approach, instantaneous heat flux calculated per unit area per unit time. Crack propagation in the transient state is studied.Using coffin-mansons law, the remaining life time of the cracked disc brake can be calculated. In the transient state thermal analysis it is found that directional heat flux flows along the thickness & the length of crack.The stress intensity factor maximum at the point leads to the crack propagation.

The finite element gives a good prediction in terms of crack shape evolution, and kinetics of crack growth. In addition, it is much less time consuming. This advantage allows using this approach in parametric study and in industrial applications.

REFRENCES

Gardin C, Le HN, Benoit G, Bertheau D.,"Crack growth under thermal cyclic loading in a 304L stainless steel – experimental investigation and numerical prediction", Int J Fatigue,32,1650–57, 2010

[3] M. Madia, S. Beretta, M. Schodel , U. Zerbst, M. Luke, I. Varfolomeev, "Stress intensity factor solutions for cracks in railway axles", Engineering Fracture Mechanics,78,764–792,2011.

[4] Raju Sethuraman,G. Siva Sankara Reddy, I. Thanga Ilango,"Analyzing the mechanisms of fatigue crack initiation and propagation in CRH EMU brake discs",International Journal of Pressure Vessels and Piping 80 ,43 859,2003.

[5] S. Courtin, C. Gardin, G. Be´zine, H. Ben Hadj Hamouda ,"Advantages of the J-integral approach for calculating stress intensity factors when using the commercial finite element software ABAQUS",Engineering Fracture Mechanics,72, 2174– 2185,2005.

[6] Hoai Nam Le, C. Gardin, "Analytical prediction of crack propagation under thermal cyclic loading inducing a thermal gradien the specimen thickness – Comparison with experiments and numerical approach ", Engineering Fracture Mechanics, 78, 638–652, 2011.

[7]Igor Varfolomeev, Michael Luke, Sergii Moroz,"Experimental and Numerical Investigations of Fatigue Crack Growth in Various specimen Geometries, Procedia Engineering, 2, 1829–1837, 2010.

[8] M. Boniardi , F. D_Errico , C. Tagliabue , G. Gotti , G. Perricone ,"Failure analysis of a motorcycle brake disc", Engineering Failure Analysis, 13, 933–945,2006.

[9] M.Collignon,A-.Cristol,P.Dufre´noy,Y.Desplanques,D.Balloy,"Failure of truck brake discs: A coupled numerical–experimental approach to identifying critical thermomechanical loadings"Tribology International 59 .

[10] Johan Lansinger, Thomas Hansson, Olle Clevfors ,"Fatigue crack growth under combined thermal cycling and mechanical loading ",International Journal of Fatigue ,29 , 1383–1390,2007.

[11] K. Vor, C. Sarrazin-Baudoux, C. Gardin and J. Petit, "Wake history effect on closure of short and long fatigue crack in 304L stainless steel ",Procedia

