Crack initiation and growth in AISI 4140H-a brake disc under thermo-mechanical fatigue by analytically and experimentally.

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Abstract: Fatigue failure of engineering components occurs due to growth of initial crack and its propagation at micro structural level under thermal and mechanical, cyclic loading. A certain number of motorbike disc shown the presence of small crack only after few thousand miles. Because of road conditions, harsh braking and uneven cooling cycles motorbike brake disc are subjected to cyclic temperature & mechanical loading. A complex combination of thermal and mechanical cyclic loading subjected to component for crack initiation and growth by thermal fatigue. This study focus on the evaluation of a surface crack in specimen like AISI 4140H expose to thermal and mechanical cyclic loading. The specimen is proposed in this study having initial surface crack both in plane stress and in plane strain condition. Analytical calculations are done to study effect of actual road conditions on disc material. Experimental facilities used for generating heating and cooling cycle. Heat flux in the specimen due to temperature gradient in both the conditions affects the crack growth.

Index Terms **- Fatigue Fracture, Crack initiation, Thermal and Mechanical Loading, Temperature Gradient, Stress Intensity Factor, Heat flux, Motorbike Disc.**

I. INTRODUCTION

A focus part of any vehicle design in the modern world is how to decelerate the moving vehicle or stop the moving vehicle. The braking system plays an important role. The brake system is one of the main components on a vehicle and proper operation is important to safety and performance of competition bikes &cars. Automotive brakes function from a force input applied by the driver which gets multiplied by the actuation system and enables the energy of the vehicle's motion to be transferred to the brake rotors where friction converts it into heat energy and stops the vehicle.

Friction brakes are required to transform large amounts of kinetic energy into heat energy at the contact surfaces between brake discs and pads. Wheel-mounted forged steel brake discs are exposed to heavy thermal and mechanical loadings and subjected to high thermal shock loading during routine braking and emergency braking. In fact, the distribution of high temperature zones caused by thermal shock loading is uneven on the friction surface during the heating and cooling steps of the braking action. After a series of braking cycles, the hotspots that exhibited signs of heating occurred on the friction surface. These hotspots have been investigated by many researchers over the years. The material properties of the hotspots were changed, including the Expansion coefficient, strength, hardness and so on.

II. ANALYTICAL CALCULATIONS

The material used for the brake disc is AISI 4140H, The material properties are listed below,

TABLE NO. 1: Physical Properties

Sr. No.	Physical Properties	Metric
1	Density	7.85 g/cc

TABLE NO. 2: Mechanical Properties

Sr. No.	**Mechanical Properties**	**Metric**
1	Hardness, Brinell	320
2	Hardness, Knoop	347
3	Hardness, Rockwell B	99
4	Hardness, Rockwell C	35
5	Hardness, Vickers	338
6	Tensile Strength, Ultimate	1140 MPa
7	Tensile Strength, Yield	965 Mpa
8	Elongation at Break	18 %
9	Reduction of Area	56 %
10	Modulus of Elasticity	205 GPa
11	Bulk Modulus	160 GPa
12	Poisson's Ratio	0.29
13	Machinability	65 %

14	Shear Modulus	80.0 GPa

TABLE NO. 3: Thermal Properties

Sr. No.	Thermal Properties	Metric
1	CTE , Linear	12.2 µm/m-°C @ 100 °C
		13.7 µm/m-°C @ 400 °C
		14.6 µm/m-°C @ 600 °C
2	Specific Heat Capacity	0.561 J/g-°C @ Temperature 550 - 600 °C
3	Thermal Conductivity	W/m-K

Design considerations of the brake disc are as follows, the one-time riding situations are considered for calculations,

TABLE NO.4: Design Parameters

Sr. No.	Description	Measure	Unit
1	Wheel base	1550	mm
2	Coefficient of friction	1.9	
3	Caliper piston diameter	29	mm
4	Track width front	1180	mm
5	Track width rear	1165	mm
6	Pedal length	200	mm
7	Mass	235	kg
8	Speed	120	Km/ph
9	Rotor outer useable dia.	170	mm
10	Rotor inner useable dia.	120	mm
11	Rotor thickness	4	mm
12	Coefficient of friction between pads & rotor	0.4	
13	Area of rotor	0.03920201	m2
14	Speed ratio between wheel and brakes	1	

The step by step calculations for the above considerations are as follows,

TABLE NO.5

SR NO	CALCULATED PARAMETER	CALCULATED VALUES	UNIT
1	Stopping distance (d)	7.4	m
2	Deceleration (a)	-17.89	m/s2
3	Center of gravity height	0.1176	m
4	Braking Force	41242.71	N
5	Braking torque (TB)	9423.95	N-m
6	Effective radius (Re)	0.0725	m
7	Clamping Load	162482.0617	N
8	Kinetic Energy	47000	J
9	Braking Time	t = 11.76	sec
10	Braking Power	3995	W
11	Heat flux	218981.0342	W/m2
12	Maximum rotor temperature	6008.825537	C

Thus by observing the rise in the temperature due to heat flux is the important design criteria. This heat flux due to power absorb by the brake during braking, nothing but kinetic energy of wheel converted into heat energy which is need to dissipate as fast as possible. The dissipation of the heat energy is depends upon the following criteria's,

a) Atmospheric temperature
b) Air flow rate on the disc
c) Heat absorption capacity of brake disc

It is necessary that constantly the heat generation and dissipation (including absorption) rate should be properly maintain so that the brake disc evenly heated and cooled and temperature of the brake disc is maintain. But this ideal conditions are not possible uneven heating and cooling are observed. The increase in the temperature shows the significant development of the thermal stresses induces in the brake disc.

III. EXPERIMENTATION

An experimental set up is made to evaluate the crack propagation by simulating the actual road condition in the laboratory.

3.1) Test Specimen

For the testing purpose we used the pre -crack brake disc of KTM DUKES motorbike. The material is used for the disc is AISI 4140H.This material presents a grain size of 100 lm. The faces were carefully polished prior to testing.

Figure-1: Specimen of Pre-crack Rotor for Test

A specimen made with the initial crack having 2a= 4mm, thickness of the crack is t= 1.5mm.The fine crack is generated using the wire cutting machine. The crack is not penetrating total thickness of the disc so that it is called as surface crack. It is to be taken care that both the sides of the plate is polished properly so no burr is present at the sharp edges of the crack.

3.2) Dimensions of rotor disc used for the test is as follows,

1.	Diameter	Outer-170 mm Inner-120 mm
2.	Thickness	minimum- 3.5mm maximum- 4mm

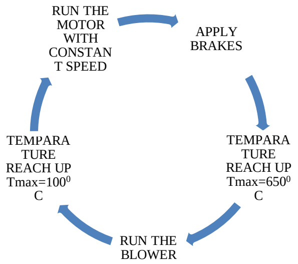
3.3) Rotor disc material is made by the composion of different material into it which is listed below,

TABLE NO.6: Component Elements Properties

Sr. No.	Component Elements Properties	Metric
1	Carbon, C	0.38 - 0.43 %
2	Chromium, Cr	0.80 - 1.1 %
3	Iron, Fe	96.785 - 97.77 %
4	Manganese, Mn	0.75 - 1.0 %
5	Molybdenum, Mo	0.15 - 0.25 %
6	Phosphorous, P	<= 0.035 %
7	Silicon, Si	0.15 - 0.30 %
8	Sulfur, S	

3.4) Design Parameters for the Experimental Set Up

Experimental facility is used to induce the thermal gradient in the thickness of the specimen due to the thermal cyclic loading. So



it needs to have facility in the experimental set up to measure the temperature of disc with the cyclic loading.

A continuous braking to the disc with the air cooling completes the cyclic loading in the experiment. To observe the crack testing facility need the microscope to evaluate the crack shape & growth.

3.5) Construction

To study the crack propagation in the disc brakes under thermal loading it needs to simulate the on road condition in the laboratory. Braking of vehicle depends on traffic conditions and road condition, also it's depend on the driver. To simulate these conditions in the laboratory, braking time should not be fixed so that uneven braking at different intervals of time was done. The coefficient of friction between tyre and road is fix (actually made as constant for all the time running conditions).The braking of rear wheel is started considering room temperature as initial condition.

The main Components of experimental set-up:-

1)Motor with regulator, 2) Permanent magnet direct current motor having power of 2 HP and rpm of 3800, 3)Bike's wheel with disc brake attached with Braking unit, 4)Air blower, 5)Temperature unit.

A chassis of KTM DUKES is used for the testing purpose. A properly cut swing arm of KTM DUKES bike is welded on a stand which provides the base for rear wheel assembly. Whole assembly of rear wheel like alloy wheel, hub, chain sprocket, disc plate was mounted over the swing arm. An angle plate is welded on the base for mounting master cylinder and is fitted by bolt. Electric motor is used as a drive instead of IC-engine. Wheel is attached to the motor by using chain & sprocket arrangement. Sprocket is welded to both shaft of the motor & shaft of wheel. Motor is attached to the regulator. A fixed caliper type disc brake is attached to the wheel on the either side to which the sprocket is attached. A paddle is attached to the brake caliper by cable to felicitate braking action. Electric motor is mounted over the stand & Motor was bolted on it such that the height of the centers of wheel shaft and motor shaft differ by 80mm. The shaft of motor is 80mm above the shaft of wheel &center distance between two shafts is 640mm as like in bike. Whole setup is mounted on a rubber pad. Rubber pad is used to absorb the vibration. Non-Contacting type thermometer is used for the temperature measurement of brake disc.Figure-2 shows the experimental set-up for the above described testing,

Figure-2: Experimental Test Rig

3.6) Working

Run the motor with a constant speed; regulate the speed of motor by regulator is nothing but AC dimerstat. Blower position in such a way that it throws air with a constant speed over the disc. The speed of the motor & blower should be directly proportional to each other. Also temperature of the air should be at ambient temperature. Now after running some time provides braking action through brake paddle. Release the paddle this is done between some time intervals. Provide braking action till the temperature of the disc is achieving the value T_{max}. As soon as temperature reaches T_{max} release the brake paddle completely. Run the motor & blower

Figure-3: One Complete Cycle during Experimentation

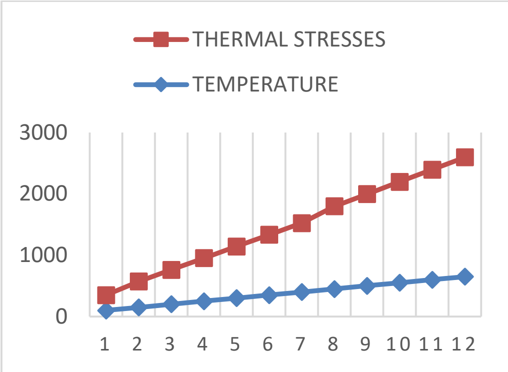
to cool disc brake. Note the cooling rate of the disc .As the temperature reduces to Tmin stop the motor & blower his completes one heating cooling cycle.

Repeat the procedure for other cycles. This experimental set-up felicitates the heating cooling thermal cycle to effect of uneven heating and cooling.

IV. RESULTS

4.1) Analytical Calculation

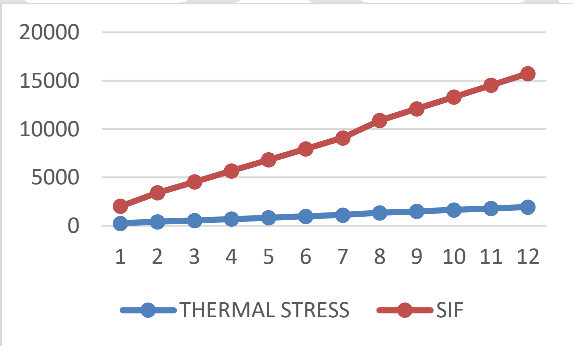
4.1.1) Graph of Thermal Stresses Vs Temperature



Graph No 1: (бmax vs Tmax)

From above graph it shows that as temperature increases thermal stress also increases with temperature.

4.2.2) Graph of Stress Intensity Factor Vs Thermal Stresses



Graph No 2: (Kmax Vs бmax)

From above graph it shows that as thermal stress increases stress intensity factor also increases.

When the specimen is heated to the temperature Tmax then due to the thermal gradient induced in thickness of the specimen it creates the thermal stresses & indirectly SIF in the cracked specimens which are lead to the crack initiation & its propagation.

4.3) Experimental Observations

In the test procedure the specimen disc is heated up to the temperature Tmax=6500C.Then it is cool by air or water spraying on it up to the temperature Tmin=1000C.This is called as one thermal cycle. By continuing the same no. of cycles we get the following observations,

Figure-4: Primary & secondary cooling zones

As per the observations near about 1200 cycles primary & secondary cooling zone were detected. Primary cooling zone is area near the crack edges along length & crack tip whereas secondary cooling zone is the area outer to edges that is on the surface of the rotor disc.

TABLE 7: Experimental Observations

SR.NO.	No. of Cycles	Observations
1	100-1100	No thermal localization was observed
2	1200	Thermal localization was observed under the microscope

Thermal Localization (Initiation stage of Hot Spots)

In the course time of brake operation, frictional heat is generated dissipated into pads and a disc. Due to uneven cooling, uneven temperature distribution occurs on brake disc. It is induce several thermal & elastic distortion of the disc.

This type of the uneven heating and cooling due to frictional heating, gives at the particular area is expanded, at this area pressure increases as the result of expansion. If further frictional heat is increases then the pressure also increase. When this process indicates to faster change of contact pressure distribution, the unpredicted hot roughness of thermal falsification may grow which resulting in resident hot spots and which may parting into cracks on the disc. This is nothing but thermal cracks.

V. CONCLUSION

Fatigue failure of motorbike disc made of AISI 4140H was focusing on crack initiation & propagation under thermal loading, In this study thickness reduction of the friction surface due to wear which in calipers is not consider. It can be concluded that when the cracks run along the thickness direction to the specified distance, they will cease to run along this direction and begin propagating mainly in the direction of the radius. Analytically, during the running condition it is observed that as due to braking temperature is increases thermal stresses are also increases which further leads to increases Stress Intensity Factor (SIF).The experimental set-up developed here allowed for generating heating & cooling cycles i.e. thermal cycling which induced thermal gradient in the thickness. During experimentation thermal localization are observed around crack length & crack edge which is starting of hot spot. This is due to the high value of heat flux induced in the specimen.

It is used to developed brake disc with increase its life cycle for safety & reliability of such components.

VI. REFERENCE

[1] Thomas J. Mackin, Steven C. Noe, K .J. Ball, B. C. Bedell "Thermal cracking in disc brakes" Engineering Failure Analysis 9 (2002) 63-76.

[2] S. Courtin , C. Gardin "Advantages of the J-integral approach for calculating stress intensity factors when using the commercial finite element software ABAQUS" Engineering Fracture Mechanics 72 (2005) 2174–2185

[3] Hoai Nam Le, Catherine Gardin "Analytical calculation of the stress intensity factor in a surface cracked plate submitted to thermal fatigue loading."Engineering Fracture Mechanics 77 (2010) 2354–2369.

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

[5] G. Fajdiga, M. Sraml "Fatigue crack initiation and propagation under cyclic contact loading" Engineering Fracture Mechanics 76 (2009) 1320–1335.

[6] Ali Belhocine, Mostefa Bouchetara "Thermal analysis of a solid brake disc" Applied Thermal Engineering 32 (2012) 59-67.

[7] C. Gardin, D. Bertheau "Crack growth under thermal cyclic loading in a 304L stainless steel – Experimental investigation and numerical prediction"International Journal of Fatigue 32 (2010) 1650–1657.

[8] Thomas J., Mackin, et al., Thermal cracking in disc brakes, Engineering Failure Analysis, 9.1, 63-76 (2002).

[9] Hong, Y., Jung, T., Kim, C., Hong, Y. and Cho, C., An experimental study for machined patterns of friction surface on two-pieces disc brake rotor in performance aspect. Trans. Korean Society of Automotive Engineers 25, 5, 581−589 (2017).

[10] Fuad, K., Daimaruya, M. and Kobayashi, H., Temperature and thermal stresses in a brake drum subjected to cyclic heating. J. Thermal S tresses 17, 4,515−527.