Comparative Study of Thermo-Mechanical Behavior of Different Designs of Brake Rotor Discs Made of Different Materials using ANSYS

Angamuthu. K, Anandu K B, Abhishek S, Lins Williams, Rouble Pius
Department of Mechanical Engineering,
Providence College of Engineering, Chengannur,
Kerala, India

***Abstract*—Braking is one of the top safety aspects of a vehicle. While braking, the kinetic energy is converted in to heat due to friction between the brake rotor and pad. This heat must be properly dissipated in order to obtain the desired braking effect. The total deformation of the disc must be minimum for its structural stability. In the present research work, a solid disc, a ventilated rotor disc with radial slots and a newly designed rotor consisting of aero foil grooves and radial holes in the body of the rotor and having fins with aero foil grooves on the circumference of the rotor are analyzed. Cast iron, titanium alloy and C/C-SiC dual matrices composite material are used as materials for all the three designs. The 3D modeling is done using Autodesk Fusion 360. The simulation and FEM analysis such as transient structural, transient thermal and combined structural and thermal analysis are carried out using ANSYS workbench to evaluate the total deformation and temperature distribution. It is found that the proposed new design made of C/C-SiC dual matrices composite material seems to be having better thermo-mechanical behavior compared to solid and ventilated disc rotors made of cast iron and titanium alloy**.

Keywords*—*FEM analysis, transient structural, transient thermal, temperature distribution, deformation, factor of safety, disc rotor and new design.

I. INTRODUCTION

A brake is an important mechanical element in automobile and other rotating machineries to retard or stop the rotational movement. An occasional emergency braking causes non-uniform temperature distribution in rotor leading to slipping of brake pads, hot spot generation and thermal cracks. Formation of squeal causes noise pollution, discomfort for the passengers and cause vibrations while braking. Less coefficient of friction increases braking distance [1-5].

Many investigations are carried out to study the influence of rotor materials on the thermal behavior such as heat generation, its distribution and dissipation through the rotor disc. It is reported that cast iron has maximum heat transfer capacity compared to aluminum or aluminum composite material and found to be used in majority of automobile vehicle as rotor disc material [1-2]. Disc rotor made of aluminum metal matrix composite, glass fiber composites, titanium alloys were also tested and their influence is reported. [6-9]. The aircraft industries use carbon-carbon composite as brake material and found to be the best choice for making brake discs [3, 10].

Investigations are also made on various rotor design such as solid disc, ventilated disc rotor having combination of different shapes of fins, cross drilled rotor disc fixed with caliper, a rotor disc with cylindrical extrusions in a drilled rotor having vanes for better heat transfer and proper air passage. The thermal capacity of discs having vents is lower than the solid disc and high thermal capacity of the disc rotor can decrease the maximum surface temperature and the maximum applied stress which in turn will increase the performance of the rotor [7, 11-12].

The rigidity of rotor disc in terms of total deformation tested in three rotors namely solid disc, disc with holes and rotor with airfoil pattern slots showed higher loss of rigidity in the air foil pattern slots due to material removal. The factor of safety varies with increase in thickness of the rotor with increase in temperature on the surface of the rotor. Transient thermal analysis was carried out to estimate the temperature distribution over the rotor surface and maximum temperature is found to be varying from 108ºC to 400ºC depending on the rotor material and its design [13-14].

II. PROBLEM STATEMENT

It is noticed from the literature that the solid and vented rotors were analyzed to study its thermo-mechanical behavior but still it needs further understanding because of conflicting results with respect to mechanical and thermal analysis. Most of the rotor disc analysis have been carried out on cast iron material and very few investigations were reported on some other materials. The improved design of rotor discs will always improve its performance. It is very important to analyze the structural and thermal behaviour of the brake rotor discs of different designs in order to make an efficient design.

In the present research work, cast iron, titanium alloy and carbon fiber reinforced carbon and silicon carbide dual matrices composite(C/C-SiC) material are selected. A new design of rotor disc is proposed in this study and analyzed. FEM analysis using ANSYS workbench are conducted on the new design, ventilated rotors and on the plane solid discs made of the above three materials. In the ANSYS analysis, study is made to estimate the total deformation and temperature distribution of the rotor discs. The rotors are analyzed for the transient structural, transient thermal and combined structural and thermal loading to estimate the total deformation. Combined structural and thermal loading is applied to estimate the temperature distribution of newly designed rotor made of all the three materials. The results are analyzed to evaluate the various mechanical and thermal behavior of different designs of rotor made of different materials.

III. METHODOLOGY

A. 3D Modelling

In the present study three designs of rotor discs are used such as solid disc, ventilated rotor and a new design of rotor which are designed using Autodesk Fusion 360. The material selections for various rotor designs are given in Table 1(a) and (b). The properties of cast iron can be found out elsewhere for the FEM analysis [7, 15] and also in the material library of ANSYS. The properties of proposed new design of rotor made of C/C-SiC composite material are given in Table.2 [16-18].

TABLE 1. MATERIAL SELECTION FOR DIFFERENT ANALYSIS AS WELL AS ROTOR DISC DESIGN

(a) Analysis using ANSYS for Total Deformation

Type of Design	Material
Solid design	Cast iron
Ventilated design	Cast iron
New design having Aero foil grooves with fins and radial holes	Carbon fiber reinforced silicon carbide dual matrices composite material (**C/C-SiC**)

(b) Analysis using ANSYS for Thermal Distribution

Type of Design	Material
New design having Aero foil grooves with fins and radial holes	Cast iron
	Titanium alloy
	Carbon fiber reinforced silicon carbide dual matrices composite material (**C/C-SiC**)

B. Calculations for New Design of Rotor

The following assumptions are made for calculations and the formulae are taken from the literature [19-20].

- Heat transfer mode is convection and radiation
- No heat generation within the fin
- Uniform heat transfer coefficient (h) over the entire surface of the fin
- Maximum surface temperature of disc (t_0) = 800°C = 1073 K
- Ambient temperature of air (t_a)= 30°C = 303 K
- Temperature to be maintained on the disc (t_s) = 500°C = 773 K
- Velocity of air = 15 m/s

  The properties of air at mean temperature are given in Table 3 [19].

TABLE 2. PROPERTIES OF CARBON FIBER REINFORCED CARBON AND SILICON CARBIDE (C/C-SIC) DUAL MATRICES COMPOSITES

Mechanical and Thermal Properties of C/C-SiC Dual Matrices Composite	
Young's modulus	230GPa
Thermal conductivity	60 $Wm^{-1}K^{-1}$
Tensile yield strength	320MPa
Compressive yield strength	436MPa
Tensile ultimate strength	480MPa
Compressive ultimate strength	450MPa
Specific heat	0 .87 J/gK
Density	2.05 gcm^3
Coefficient of thermal expansion	4.8×10^{-6}/K
Poisson ratio	0.38

Number of fins required
= Total heat to be dissipated from the rotor/Heat dissipated from one fin

$$= Q_{total}/Q_{fin} \quad (1)$$

$$Q_{fin} = \sqrt{PhkA_1}\,(t_0 - t_s)\left[\frac{\tanh(ml)+\frac{h}{km}}{1+\left\{\frac{h}{km}\times\tanh(ml)\right\}}\right] \quad (2)$$

Where,

$$m = \sqrt{[hp]/kA_1} \quad (3)$$

$$Q_{total} = Q_{convection} + Q_{radiation}$$
$$= [hA_2\,(t_o - t_s)] + [\varepsilon\sigma A_2 T^4] \quad (4)$$

Where,

P = Perimeter of fin (m)
h = Convective heat transfer coefficient (W/ (m^2 K))
k =Thermal conductivity of the material (W/ (mK))
A_1 = Cross sectional area perpendicular to heat transfer (m^2)
A_2 = Surface area of brake rotor (m^2)
L = length of the fin (m)
t_0 = Temperature at the base of the fin (K)
t_s = Surface temperature to be maintained on the disc (K)
t_a = Ambient temperature of air (K)
ε = Emissivity of the material
σ = Stefan-Boltzmann constant (W/m^2 K^4)
T = Surface temperature (K)

TABLE 3. PROPERTIES OF AIR AT T_{mean}

Properties of Air at T_{mean}	
Kinematic Viscosity (ν)	63.03 ×10^{-6} m^2/s
Prandtl Number (Pr)	0.678
Thermal Conductivity (k_1)	0.05210W/ (mK)

To calculate Q_{fin}

T_{mean} =[t_0+t_a]/2 =[1073+303]/2 = 688 K (5)

Reynolds number

Re =[u L]/v (6)

=[15×0.055]/[63.03×10^{-6}] =1.3090×10^4

Where, *u*= velocity of air (m/s)

L = characteristic length (m)

Since Re is less than 5x10^5, the flow is considered as laminar flow [19].

Nusselt Number

Nu = 0.45$Re^{0.5}Pr^{0.333}$ (7)

=0.453×$(1.3090×10^4)^{0.5}(0.678)^{0.333}$

= 45.537

Nu = [h L]/k_1 (8)

Where k_1 = Thermal conductivity of air (W/ (mK))

L= characteristic length (m)

Equating Eq 7 and Eq 8

h = [Nu×k_1]/L= [45.537×0.05210]/0.055

= 43.136 W/ (m^2 K)

From Eq 3,

m = √[[hP]/kA_1]

=√[[43.1362×0.153]/60×0.00035]

= 17.553

Substituting in Eq 2,

$$Q_{fin} = \sqrt{PhkA_1}\,(t_0 - t_s)\left[\frac{\tanh(ml)+\frac{h}{km}}{1+\left\{\frac{h}{km}\times\tanh(ml)\right\}}\right]$$

$$= \sqrt{0.153 \times 43.136 \times 60 \times 0.000357}\,(1073 - 773)$$

$$\left[\frac{\tanh(17.553\times0.055)+\frac{43.136}{60\times17.553}}{1+\left\{\frac{43.136}{60\times17.553}\times\tanh(17.553\times0.055)\right\}}\right]$$

= 85.838 Watts

To calculate Q_{total}

Reynolds number for a cylinder with diameter D is given by:

Re =[uD]/v =[15×0.278]/63.03×10^{-6} (9)

= 6.61589 × 10^4

Where, D = Outer diameter of the brake rotor

Since Re is less than 5x10^5, the flow is considered to be laminar flow [19].

Nusselt Number

Nu = CRe^m[$Pr^{0.62}$/$Pr^{0.25}$] (10)

= 0.25×$(6.61589×10^4)^{0.6}$[$0.703^{0.62}$/$0.673^{0.25}$]

= 172.86

From Eq 8:

Nu =[hL]/k_1

k_1 = Thermal conductivity of air (W/ (mK))

h =[Nu×k_1]/D= [172.86×0.05210]/0.278

h = 34.05 W/ (m^2K)

Substituting in Eq 4;

Q_{total} = $Q_{convection}$ + $Q_{radiation}$

= [hA_2 (t_o – t_s)] + [εσ$A_2$$T^4$]

= 34.05×0.07369×(1073-773)+0.9×(5.67×10^{-8})×0.07369×1073^4

= 752.743+ 4984.6309

= 5737.3739 Watts

Substituting in Eq 1;

Number of fins required =Q_{total}/Q_{fin} =[5737.3729]/85.838 =66.839 ≅ 67 fins

From the above calculations 67 fins are required to transfer 5737.3729 Watts of heat. But due to the space limitation in the circumference of the disc rotor, 30 fins are incorporated on the rotor circumference without overlapping in the new design.

Area calculations of fins

Surface area of one fin = 0.00157056 m^2

Surface area of 30 fins = 30 x 0.00157056

= 0.04711689 m^2

Area calculations of holes

Curved Surface Area (CSA) of one radial hole with 3.3 mm diameter and 37 mm length

= πdh

= π x 0.00330 x 0.037 = 0.00038339 m^2

CSA of 240 holes = 240 x 0.00038339 = 0.0920146 m^2

Area calculations of airfoil grooves

Surface area of one airfoil groove = 0.0002419 m^2

Surface area of 32 airfoil grooves = 32 x 0.0002419

= 0.0077419 m^2

Surface area for convective heat transfer without fins and holes = 0.07369 m^2

Percentage increase in surface area after addition of fins = 63.93%

Percentage increase in surface area after addition of holes = 124.86%

Percentage increase in surface area after addition of airfoil grooves = 10.5 %

The increase in surface area of contacts with air in the new design due to various additional features such as fins, aero foil grooves and radial holes are given in Table 4.

TABLE 4. INCREASE IN SURFACE AREA DUE TO ADDITIONAL FEATURES IN THE NEW DESIGN

Features Added	% Increase in Surface Area
Fins	63.93%
Radial Holes	124.86%
Aerofoil Grooves	10.5 %

C. Design Features of the Rotor Disc

The solid rotor disc consists of a plain disc with no slots in the periphery of the disc as shown in Fig 1.The ventilated design consists of radial slots for the passage of air as shown in Fig 2. The dimensions of solid disc and ventilated disc are shown in Fig 3 and Fig 4. This design is very similar to the design reported in [4, 13, 21] but varied in the dimensions from the reported literatures. The proposed new design consists of aero foil grooves and radial holes in the body. It has fins which are arranged on the circumference of the rotor with equal space alignment. The fins are also having aero foil grooves in order to increase the heat transfer to the surrounding air. The radial holes are aligned approximately at an angle of 45 degree to the axis of rotor disc. The number of fins is 30 and radial holes are arranged by trial and error method without sacrificing the strength of the rotor as shown in Fig 5a, Fig 5b and Fig 5c. The advantages of aero foil groove design are that it may effectively wipe the water film during the wet braking condition and the fins will increase the heat transfer area. The expected heat transfer mode through the surface area of the rotor disc and fins are forced convection and radiation.

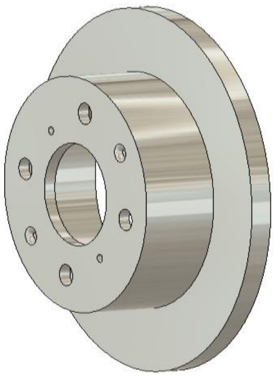

Fig 1. Solid disc

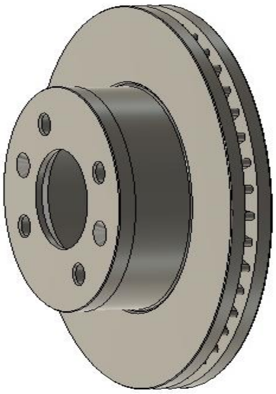

Fig 2. Ventilated disc

D. Transient Structural, Thermal and Combined Structural and Thermal Analysis

All the three models which are shown in Fig 1, Fig 2 and Fig 5b are divided into discrete finite elements by default mesh size available in the ANSYS workbench. The default mesh of one of the models is shown in Fig 6. All the rotor discs are subjected to three loading conditions to evaluate the total deformation.

In the transient structural analysis, the load in the form of gradually increasing pressure up to 11MPa is applied within 5 seconds on the faces of the rotor disc where the pads will be in contact as given in Table 5. Fixed constraints are applied on the faces where the wheel studs are in contact with the rotor to arrest the movement of the disc in space. This will reduce the degrees of freedom on the total surface of the hub and rotor to zero.

In the transient thermal analysis, the applied temperature is 800°C as a thermal load over a period of six seconds on the faces of the rotor disc where the pads will be in contact. It is reported that the heat generated due to friction while applying the brake will increase the temperature of the disc material between 300°C to 800°C [22]. The thermal loading history versus time is given in Table 6. The constraints and meshing in the model are same as that applied in the transient structural analysis. Though the assumption of temperature at the base of the fins while applying brake is 800°C, for determining the number of fins using the fundamental design calculations, the surface temperature is maintained at 500°C. This is to indicate that complete heat dissipation is not possible in practice from the rotor disc and the disc may be still at high temperature and it may need some external cooling.

In the combined transient structural and thermal analysis, similar parameters are used to model the rotor and both structural and thermal loads are applied simultaneously as given in Table 5 and Table 6.

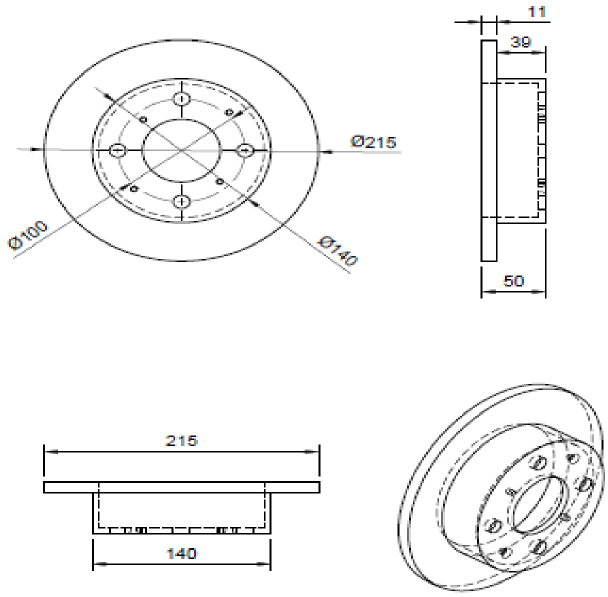

Fig 3. Dimensions of solid disc in mm

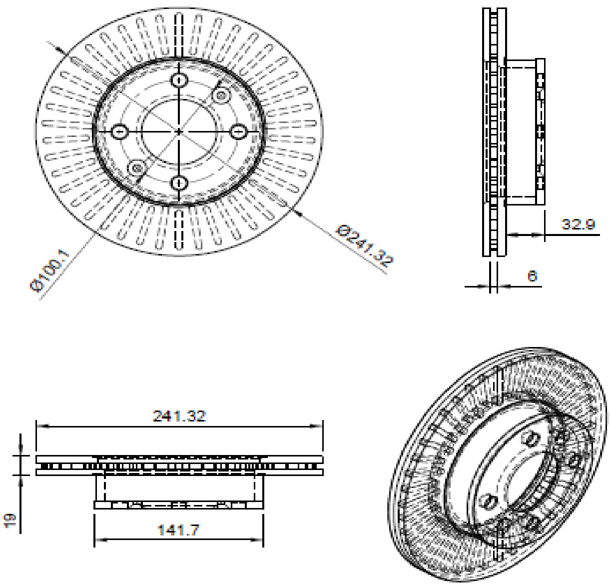

Fig 4. Dimensions of ventilated disc in mm

The temperature distribution in the rotor discs are analyzed using ANSYS. The new design made of cast iron, titanium alloy and C/C-SiC composites were subjected to combined structural and thermal analysis to estimate the temperature distributions in all the three rotor disc as given in Table 5 and Table 6. Here also the applied maximum temperature is 800°C.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 08, August-2019

IV. RESULTS AND DISCUSSION

A. Analysis for Total Deformation

1. Transient Structural Analysis

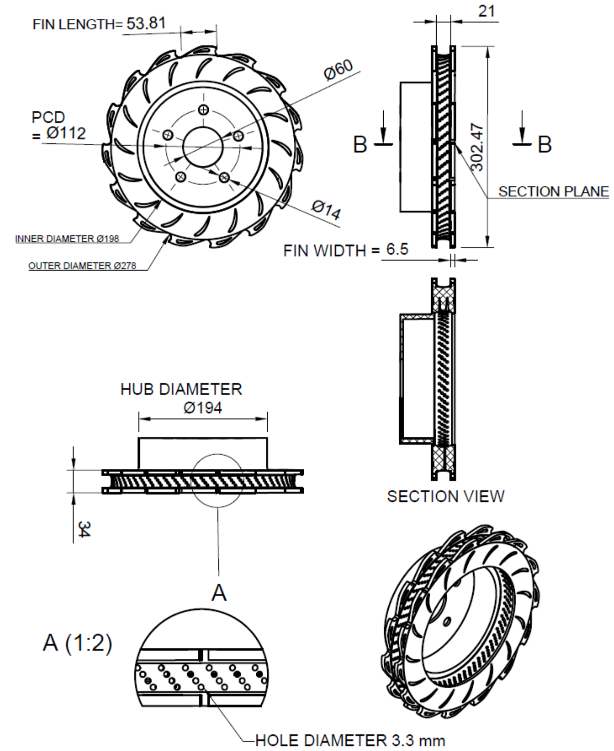

Fig 5a. Dimensions of new design in mm

Fig 5b. 3D modelling of new design in Autodesk Fusion 360

Fig 5c. New design showing radial holes starting from inner periphery to outside circumferentially

The transient structural analyses of solid and ventilated rotor discs are shown in Fig. 7 and Fig. 8 respectively. The same analysis with similar experimental parameters is carried out on the new design made of (C/C-SiC) material and the test results are shown in Fig. 9.

TABLE 5. TRANSIENT STRUCTURAL LOADING

Steps	Time (S)	Pressure (MPa)
1	0	0
2	1	3
3	2	5
4	3	7
5	4	9
6	5	11

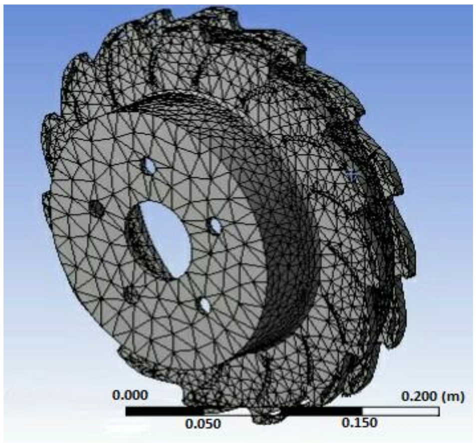

Fig 6. Default mesh of new design made of C/C-SiC Composite

TABLE 6. TRANSIENT THERMAL LOADING

Steps	Time (S)	Temperature (ºC)
1	0	0
2	1	100
3	2	200
4	3	300
5	4	400
6	5	500
7	6	600
8	7	700
9	8	800

The total deformation in all the three rotor designs are given in the bar chart in Fig. 10. It is seen from the above figures that the total deformation for solid disc is about 0.24818mm and that of ventilated disc is 0.008462mm which is lower than the solid disc. The total deformation in the new design made of C/C-SiC composite material is 0.007289mm which is lower than the solid disc and almost equal to ventilated disc.

It is reported in the literature that total deformation in the solid disc made of cast iron with holes on the surface of the rotor is higher than the solid disc made of same material. The disc with aero foil vents is also shown higher total deformation compared to solid disc and solid disc with holes due to more material removal for making the aero foil [13].
In the present work, the ventilated disc has the passage of air through the vents provided in between the disc. The view of

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 08, August-2019

sectional plane at the center and perpendicular to the axis of rotor is shown in Fig. 11 which gives how the air flows through the vent. Since there are supportive material between the vent taking the overall pressure in the ventilated design, the total deformation in this design is less than that of the solid disc.

The new design has grooves with aero foil shape, fins and radial holes as shown in Fig 5a to Fig 5c. The radial holes are aligned at an approximate angle of 45 degree to the line of action of pressure force as shown in Fig 12. It is reported that the deformation under static loading of similar composites is ductile with accumulation of considerable amount of strain in the material [23]. The dual matrices in the C/C-SiC composite material are subjected to more constraints in the matrices to the applied pressure force and this is allowing to take up more strain. Also, because of the inclined radial holes arrangement there are material available to take up the pressure force as compared to the design having holes in the direction of action of the pressure force [13]. This results in almost same total deformation as that of ventilated disc though the new design has more grooves and holes.

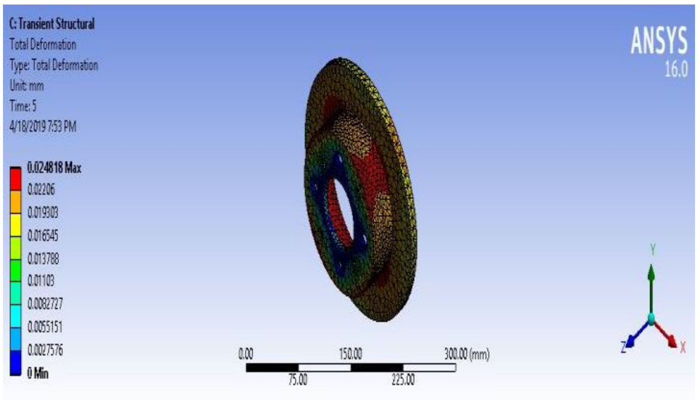

Fig 7. Total deformation of solid cast iron dics

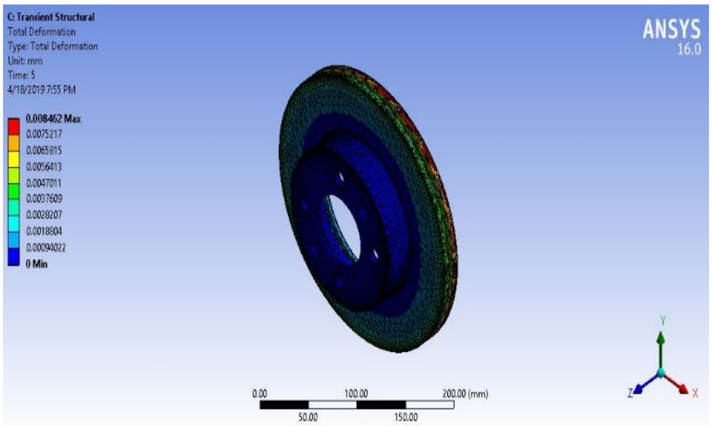

Fig 8. Total deformation of ventilated cast iron disc

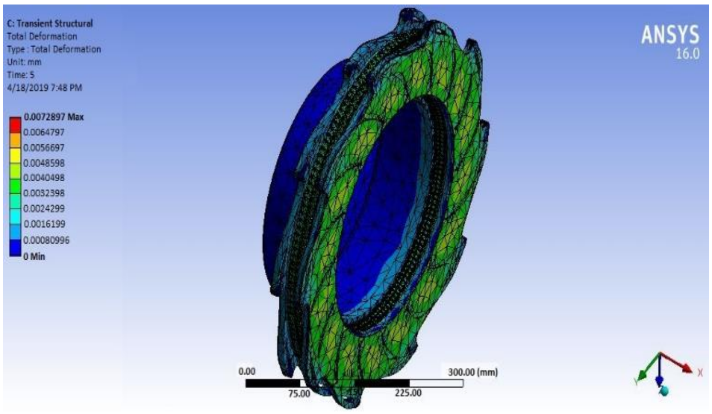

Fig 9. Total deformation of new design made of C/C-SiC

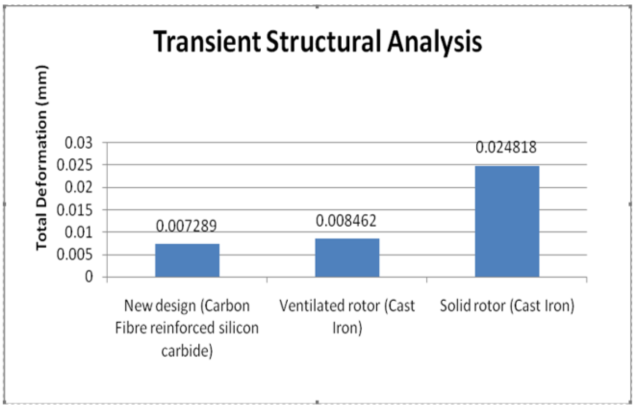

Fig 10. Total deformation from transient structural analysis

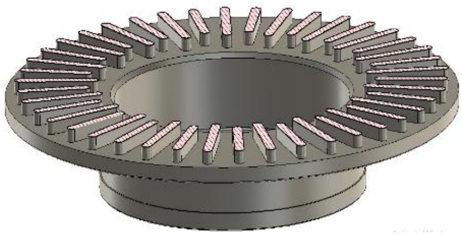

Fig 11. View of section plane perpendicular to the axis of rotor

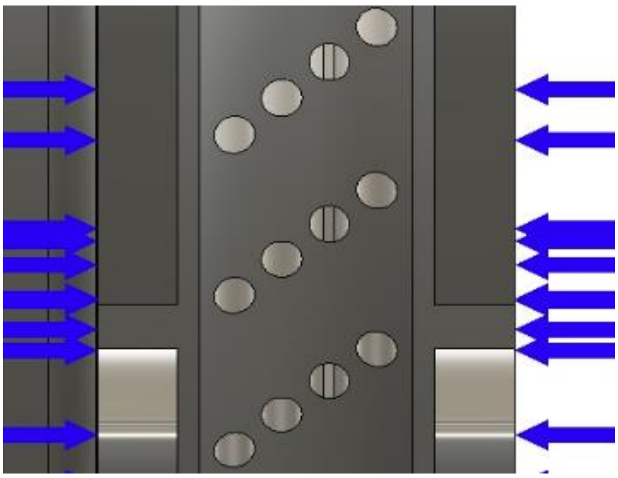

Fig 12. Position of radial holes with respect to the pressure force in the rotor of new design

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 08, August-2019

2. Transient Thermal Analysis

The results of transient thermal analysis are shown in Fig 13 to Fig 15 and the total deformation of the respective design is shown as bar chart in Fig. 16. It is seen from the bar chart that the total deformation under thermal loading is 0.40216 mm which is minimum for the new design made of C/C-SiC as compared to the corresponding value of 0.72788mm for solid disc and the intermittent value of 0.54365mm for the ventilated disc. It is recalled that the solid and ventilated rotors are made of cast iron. The heat capacity of C/C-SiC will be higher compared to cast iron as its thermal conductivity is higher. It is reported that high thermal conductivity and low Young's modulus can limit the damage of the disc rotor [7]. Since the C/C-SiC dual matrices composite material is able to with stand high temperature, and has lower coefficient of thermal expansion and high thermal conductivity, the total deformation under transient thermal loading of new design is lower than the cast iron rotor discs.

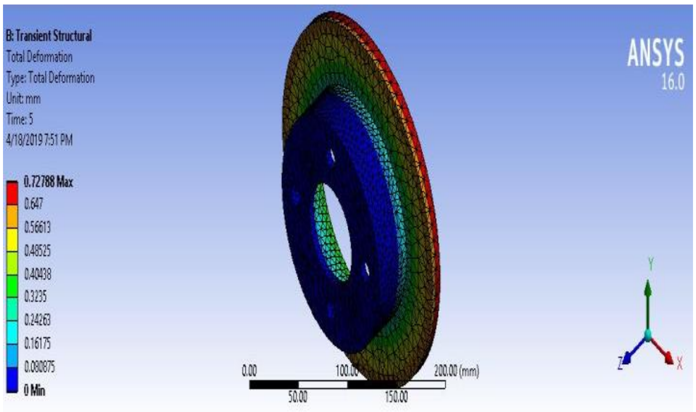

Fig 13. Solid disc (Cast Iron)

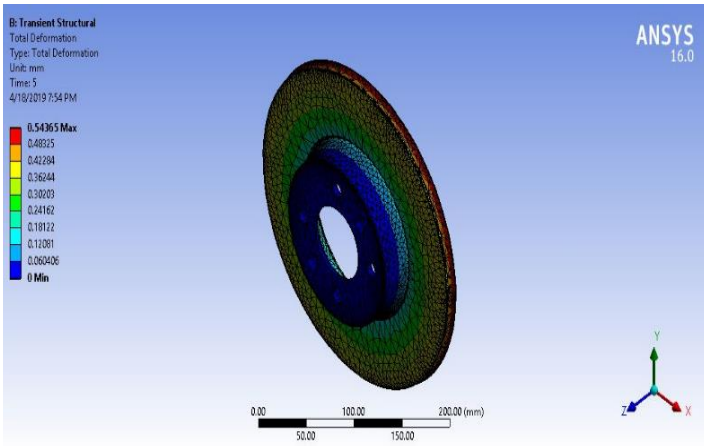

Fig 14. Ventilated disc (Cast Iron)

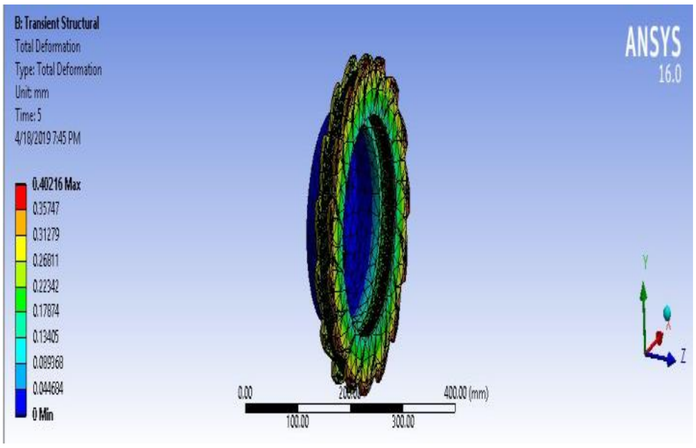

Fig 15. New design made of C/C-SiC composite

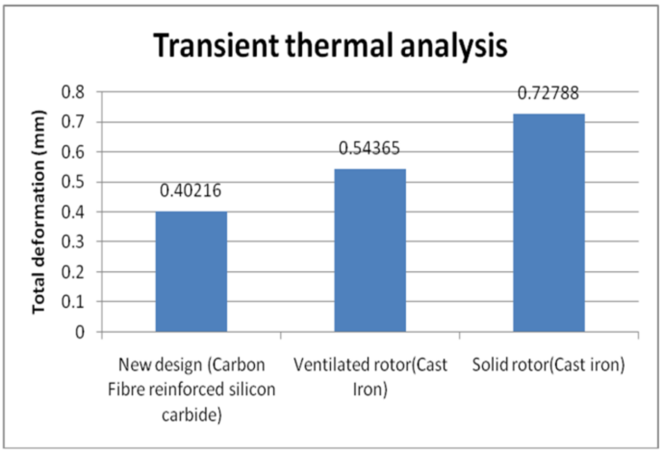

Fig 16. Total deformation from transient thermal analysis

3. Combined Structural and Thermal Analysis

The results of combined structural and thermal analysis are shown in Fig 17 to Fig 19. The bar chart in Fig 20 shows the total deformation of all the three designs under combined structural and thermal loading. It is seen that the total deformation under the combined loading for the solid disc, it is 0.7415mm and for ventilated disc it is 0.54266mm and for the new design made of C/C-SiC composite material, it is 0.40885mm. C/C-SiC composite material has high heat capacity, high thermal conductivity and moderate modulus and also it has dual matrices [24] which under combined loading, might have influenced very much to reduce the total deformation by keeping its thermal stability during braking.

It is seen very clearly that the new design made of C/C-SiC composite material has less total deformation compared to the solid and ventilated rotor discs indicating better structural stability under combined loading.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 08, August-2019

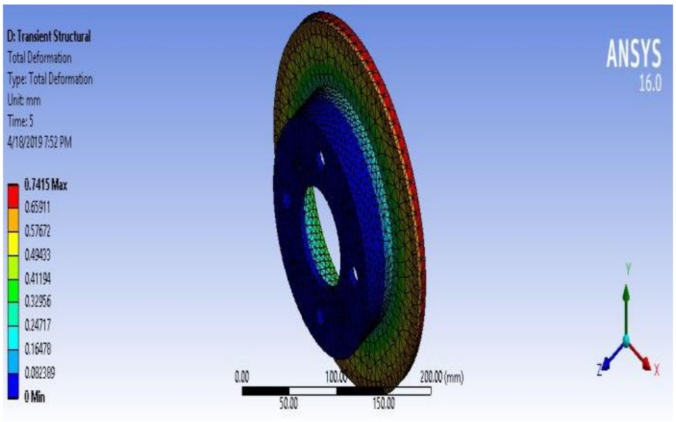

Fig 17. Solid rotor (cast iron)

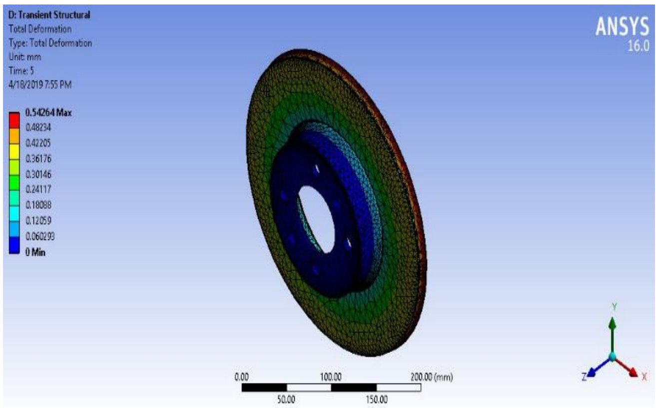

Fig 18.Ventilated rotor (cast iron)

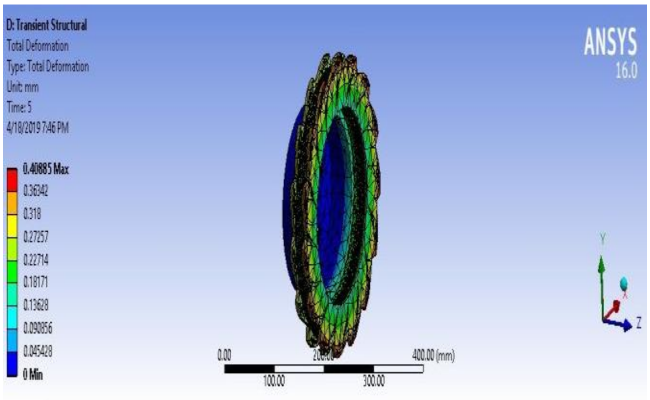

Fig 19. New design made of C/C-SiC composite

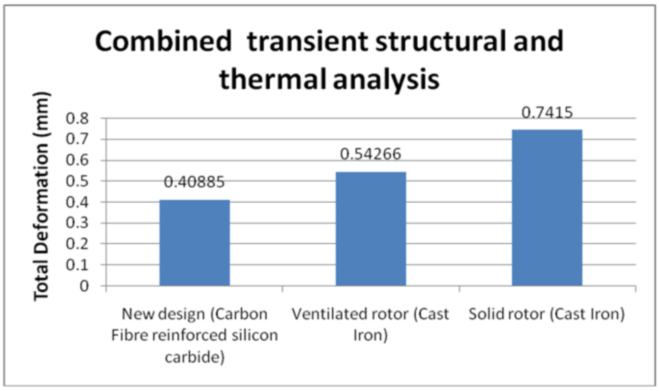

Fig 20. Total deformation from combined transient structural and thermal analysis

B. Analysis for Temperature Distribution in the Rotor Disc of New Design Made of Different Materials

Temperature distribution in the rotor discs made of cast iron, titanium alloy and C/C-SiC composite material are shown in Fig 21-Fig 23 respectively revealing the minimum surface temperature to the range of temperature that the rotor has experienced. The maximum temperature is fixed as 800°C for all the materials in the new designs.

The temperature distribution in cast iron and titanium alloy showed wide range of temperature varying between 32°C to 800°C from the hub area to the fins as shown in Figs 21 and 22 respectively. The temperature distribution in the new design made of C/C-SiC composite material is seen to be almost uniform as shown in Fig 23. The temperature range is between 638°C to 800°C from the hub area to the fins and this range is very narrow. Since the thermal conductivities of cast iron and titanium alloy is lower than the C/C-SiC composite material, the temperature distribution is found to be non-uniform in both cast iron and titanium alloy. Due to higher thermal conductivity of this composite material the temperature distribution is found to be uniform. The surface of the disc and fins are showing the same temperature indicating the uniform temperature distribution.

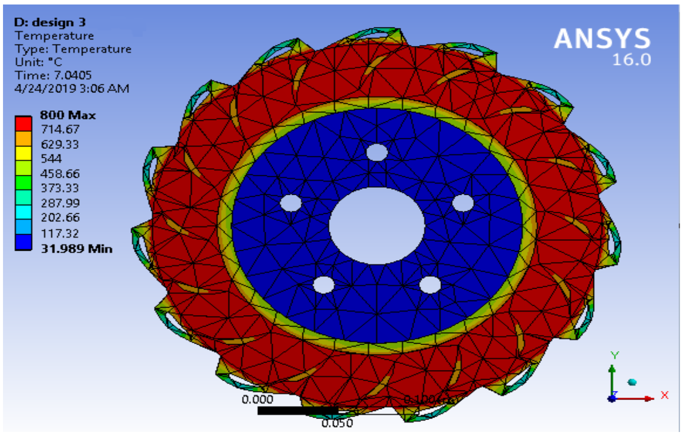

Fig 21. Temperature distribution in the new design made of cast iron material

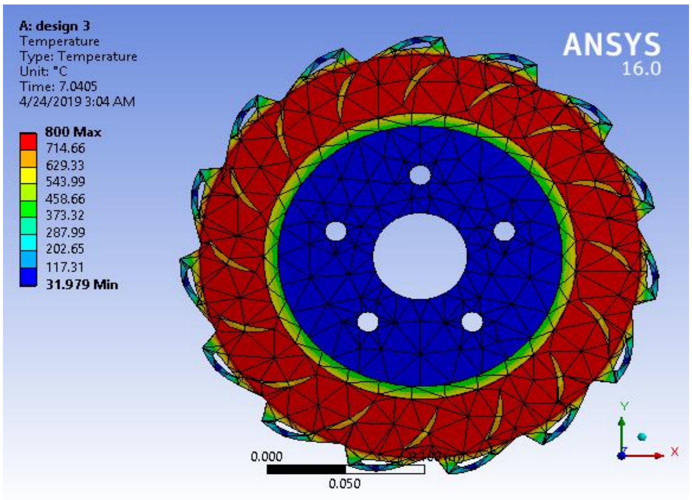

Fig 22. Temperature distribution in the new design made of titanium alloy material

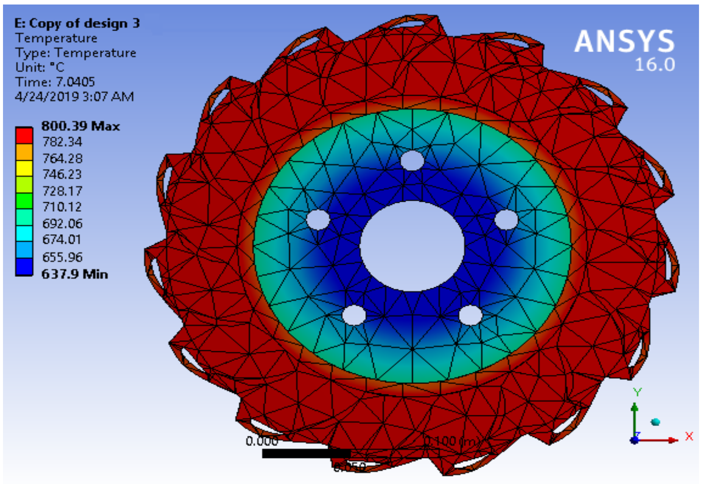

Fig 23. Temperature distribution in the new design made of C/C-SiC composite material

V. CONCLUSIONS

The finite element analysis of brake rotor disc made of cast iron, titanium alloy and C/C-SiC dual matrices composite material were carried out. Three designs of rotor were analyzed. Solid disc, ventilated disc with radial slots and a new design of rotor disc with aero foil grooves and radial holes in the main body and aero foil grooves in the fins arranged at the outer periphery of disc have been used in this study. The total deformation of the discs and temperature distribution on the surface of rotor discs were analyzed using ANSYS work bench. Various structural and thermal loading conditions were used to study these parameters. The following conclusions are made in this study.

1. The new design made of C/C-SiC showed lowest total deformation under the combined loading conditions compared to solid and ventilated rotor designs in the ANSYS analyses.

2. The temperature distribution using ANSYS in the new design made of C/C-SiC composite material is more uniform compared to new design made of cast iron and titanium alloy.

3. The new design of rotor made of C/C-SiC dual matrices composite material showed better thermo mechanical behavior in this analysis.

AKNOWLEDGEMENT: The authors acknowledge the support given by Mr. Cyril. J. and Mr. Rojo Kurian Daniels, Assistant Professors, Department of Mechanical Engineering, Providence College of Engineering during this research study.

REFERENCES

[1] Maurice I. Ripley and Oliver Kirstein (2006) Residual stresses in a cast iron automotive brake disc rotor, Physica B 385–386 604–606.
[2] Cueva.G, Sinatora.A., Guesser.W.L and Tschiptschin.A.P (2003) Wear resistance of cast irons used in brake disc rotors Wear 255 1256–1260.
[3] Hailiang Deng, Kezhi Li, Hejun Li, Pengyun Wang, Jing Xie and Leilei Zhang (2010) Effect of brake pressure and brake speed on the tribological properties of carbon/carbon composites with different pyrocarbon textures Wear 270 95–103.
[4] McPhee.A.D and Johnson.D.A (2008) Experimental heat transfer and flow analysis of a vented brake rotor International Journal of Thermal Sciences 47 458–467.
[5] Thomas J. Mackin, et al (2002) Thermal cracking in disc brakes Engineering Failure Analysis 9 63-76.
[6] Hiroaki Nakanishi, Kenji Kakihara, Akinori Nakayama and Tomiyuki Murayama (2002) Development of aluminum metal matrix composites (Al-MMC) brake rotor and pad JSAE Review 23 365–370.
[7] Baskara Sethupathi P., Muthuvel A., Prakash. N and Stanly Wilson Louis (2015) Numerical analysis of a rotor disc for optimization of the disc materials Journal of Mechanical Engineering and Automation, 5(3B):5-14 DOI: 10.5923/c.jmea.201502.02.
[8] Shiva Shanker.P (2018) A review on properties of conventional and metal matrix composite materials in manufacturing of disc brake Materials Today: Proceedings 5 5864–5869.
[9] Jun Qu, Peter J. Blau, Brian C. Jolly (2009) Oxygen-diffused titanium as a candidate brake rotor material Wear 267 818–822.
[10] Zhuan LI, Xiao Peng, Xiong Xiang and Huang Bo-yun (2010) Manufacture and properties of carbon Fiber-reinforced C/SiC dual matrix composites New Carbon Materials Volume 25 Issue 3 Jun 2010 25(3):225–231.
[11] Masahiro Kubota, Tsutomu Hamabe, Yasunori Nakazono, Masayuki Fukuda and Kazuhiro Doi (2000) Development of a lightweight brake disc rotor: a design approach for achieving an optimum thermal, vibration and weight balance JSAE Review 21 349-355.
[12] Jung, S. P., Park, T. W., Kim, Y. G. (2012) A study on thermal characteristic analysis and shape optimization of a ventilated disc International Journal of Precision Engineering and Manufacturing 13 (1) (2012) 57–63.
[13] Daanvir Karan Dhir (2018) Thermo-mechanical performance of automotive disc brakes Materials Today: Proceedings 5 1864–1871.
[14] Harshal Nikam, Prem Mishra & Sayali Bharambe (2014) Design and analysis of brake rotor with parameter optimization International Journal of Automobile Engineering Research and Development (IJAuERD) Vol. 4 Issue 4 Aug 2014 21-30.
[15] Kharate.N.K and Chaudhari.S.S (2018) Effect of material properties on disc brake squeal and performance using FEM and EMA approach Materials Today: Proceedings 5 4986-4994.
[16] Katsumi yoshida (2010) Development of silicon carbide Fiber-reinforced silicon carbide matrix composites with high performance based on interfacial and microstructure control Journal of the Ceramic society of Japan 118[2] 82-90.
[17] Yongdong Xu, Litong Zhang and Laifei Cheng Anddantao Yan (1998) Microstructure and mechanical properties of three-dimensional carbon/silicon carbide composites fabricated by chemical vapor infiltration Pergamon Carbon Vol. 36, No. 7-8 pp. 1051-1056.
[18] Yongdong Xu, Laifei Cheng and Litong Zhang (1999) Carbon/ silicon carbide composites prepared by chemical vapor infiltration combined with silicon melt infiltration, State Key Laboratory of Solidification Processing Northwestern Polytechnical University Xi'an Shaanxi 710072 People's Republic of China 30 April 1998 Carbon 37 1179–1187.
[19] Kothandaraman.C.P and Subramanyan.S (2018) Heat and mass transfer data book, New Age International 9th 2018.
[20] Rajput.R.K. (1999) Heat and mass transfer Eurasia and Vikas 1999.
[21] Ali Belhocine and Mostefa Bouchetara (2012) Thermal analysis of a solid brake disc Applied Thermal Engineering 32 (2012) 59-67.
[22] Mit Patel, Mansi Raval and Jenish Patel (2016) Design of disc brake's rotor, IJEDR | Volume 4 Issue 4 919-926.
[23] Wei Zhu, Hua Fu, Zhongfeng Xu, Rongzhen Liu, Ping Jianga, Xinyu Shao, Yusheng Shi and Chunze Yan (2018) Fabrication and characterization of carbon fiber reinforced SiC ceramic matrix composites based on 3D printing technology Journal of the European Ceramic Society 38 4604–4613.
[24] Guan-yi Chen, Zhuan LI, Peng Xiao, Xi Ouyang, Wen-jie MA, Peng-tao LI, Jin-wei LI and Yang LI (2019) Tribological properties and thermal-stress analysis of C/C−SiC composites during braking Trans. Nonferrous Met. Soc. China 29 123−131.