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Original Research Article

Effect of pad and disc materials on the behavior of disc brake against dynamic high speed loading conditions

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Abstract

Braking system in an automobile plays an important role to control the vehicle. Now a day's, high speed vehicles with advanced technologies are launching in to the market by varying different design procedures. Therefore, an effective braking system is always required for a vehicle to have proper safety and comfort to the user in varying environmental climatic conditions. Effectiveness of the braking system has to be considered in addition to aesthetic consideration of an automobile in order to avoid accidents. After, the gradual phasing out of asbestos as a friction material, due its wide spread complaints as a carcinogenic material by world health organization, people and industries are looking for suitable alternatives to replace asbestos friction material. In this work, an attempt is made to check the performance of the brake by altering the materials of the disc and pad of the braking system, which are supposed to be major components of the brake. The behavior of the disc brake pad assembly is studied under high speed dynamic loading conditions. The results are compared with the experimental results available in literature, and the best combination of materials for disc and pad is suggested for the design related to high speed dynamic conditions of the automobile.

Key words: Fade, Squealing, dynamic analysis

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1. Introduction

Brake pads convert the kinetic energy of automobile to thermal energy by means of friction. The amount of heat generated at the contact region depends mainly on the application of pressure and stopping distance. The heat generated at the contact region between brake disc and pad has to dissipate properly to the atmosphere in order to avoid failure of the braking system. Therefore, friction material selected for a braking system has to possess the following important characteristics.

The main characteristics of friction material should [1]

(a) Maintain a sufficiently high coefficient of friction with the brake disc.
(b) Not to decompose or break down in such a way that the friction coefficient with the brake disc is compromised, at high temperatures.
(c) Exhibit stable and consistent coefficient of friction with the brake disc.
(d) Be wear resistant.
(e) Be able to dissipate heat to the surroundings.
(f) Have sufficient fade resistance.
(g) Induce less squealing action and should be operated over different atmospheric conditions.

The material selection for the brake disc and pad plays a prominent role in the design stage of braking system. Many of the researchers worked on material selection for brake disc and pad for minimizing the squeal generation at the interface between brake disc and pad. Mlaeque et al [2] reviewed on material selection for automotive brake disc to replace grey cast iron by means of Ti Alloy and Al alloy. It was observed from mechanical and thermal properties that, Al based metal matrix composites exhibited good results. Swapnil and et al. [3] studied on design and analysis of a disc brake to replace, existing gray cast iron disc material with CC composite disc. Based on thermal and modal analysis results, it was observed that, carbon ceramic matrix composite disc achieved good braking performance and it can be used to replace the existing gray cast iron material. Rabia and et al. [4] reviewed on experimental studies of automotive disc brake noise and vibration and proved that the experimental data gives good results compared numerical solutions. And author has conducted few investigations to change the cross sections of pad and disc material. Abu and et al. [5] investigated on the effect of pad shapes on temperature distribution for disc brake contact surface. It was observed that, flat pad and hatched pads are tested using a brake dynamometer and, identified that, hatched pad possess good fade resistance compared to flat pad. Yildiz and Duzgun [6] conducted a stress analysis on ventilated type disc brakes using the finite element method for cross drilled disc, cross slotted disc, and cross slotted with side groove disc and observed that C-SG disc showed best performance in terms of braking force output. Belocine and Bouchetara [7] performed thermo mechanical behavior of dry contacts in disc brake rotor with gray cast iron Composition. Three types of cast iron materials (AL FG 25, FG 20, and FG 15) are tested using ANSYS software, and observed that the temperature field decides the numerical and design parameters. Many studies are also contributed to squeal reduction through structural modifications of the brake disc and pad materials. Nouby and Srinivasan [8] studied about disc brake squeal reduction through pad structural modifications using FEM by complex eigen values. The geometric characteristics and chamfer would affect the squeal propensity and eigen modes. Huang and Krousgrill [9] evaluated a critical value of coefficient of friction using brake squeal analysis. In order to reduce automobile brake squeal mode, coupling analysis is performed. In this analysis, eigen values and eigen vectors are calculated for different types of mode couplings to estimate critical value of friction coefficient. A new method called reduced order characteristic equation is used to evaluate eigen values and their derivatives at $\mu=0$.This method can be accurately applied to predict the stability boundaries of brake. Wang and Mo [10] studied on squeal noise of friction material with groove textured surface, using experimental and numerical analysis by varying the pad profile. It was identified that cutting a135 deg groove can reduce unstable vibration and cutting a 45 deg or 90 deg groove on the pad surface shows a reduced squeal generation. The maximum contact pressure is low for the 90 deg groove textured surface, followed by the 45 deg groove texture surface. Renault and Massa [11] investigated on brake squeal analysis and observed that the pad topography and contact distribution plays an important role in the design of braking system. Liu et al. [12] performed an analysis of disc brake squeal using the complex eigen value method. The effect of system parameters like hydraulic pressure, rotational velocity of the disc and friction coefficient between pad and disc, stiffness of the back plates on disk brake squeal is studied in detail. It was observed that, the sqeal can be reduced by decreasing the friction coefficient, increasing the stiffness, modifying the shape of brake pads, and using damping material at the back of the pads. Nacivet et al [13]. Presented a new approach to study the modal amplitude stability analysis of a brake squeal system and identified that, this new method is easy to implement and takes less computing time for comlex Eigen values. Hui Lu et al [14] focused on reduction on brake squeal by considering uncertain parameters like friction coefficient, material properties and thickness of wearing component. It was observed that, a reliability based optimization model for improving the stability of vehicle is used based on RSM. Kang [15] proposed a new finite element brake squeal model for asymmetric automotive brake disc. It was observed that, rotation of an asymmetric disc can change the nonlinear behavior as well as the linear stability character. Dmitriev et al [16], formulated a model of brake pad disc by considering dynamics and deformation. This model gives information about crack formation and plastic deformation of metal to metal contact. Wamg et al [17] worked on disc surface with two types of groove textured surfaces on a pad disc system. It was concluded that, cutting a 45 deg groove on the disc surface can significantly reduce the friction noise. The groove textured surface can affect the contact pressure and squeal generation. Many studies are also reported to reduce squeal generation by selecting optimum operating parameters to achieve stability of coefficient of friction [19-41].

Therefore, based on many studies reported by many researchers, it was observed that, the behavior of the disc brake pad assembly depends on materials selected for disc and brake pad assembly. The main challenge for the designer is to select different types of materials for the disk brake and pad to increase the life of the components under dynamic loading conditions and decrease the manufacturing cost. In this connection, many researchers worked on alternative materials for brake disc and pad and performed static, thermal and brake squeal analysis and observed that pad topography and disc material selection plays a vital role to have better fade resistance, recovery and less squeal propensity at the interface between brake disc and pad. In this work, an attempt is made to replace the existing material of gray cast iron disc and asbestos pad with alternate materials such as titanium alloy and carbon fiber, which exhibits high strength and high wear resistance compared to other materials. Here, in this analysis, actual working condition of the braking system is simulated using ANSYS under dynamic loading conditions with varying angular velocity. Generally, fading phenomenon and wear rate of friction material is critical at high speed dynamic loading conditions. Therefore, present analysis is carried out for high speed dynamic loading conditions acting on the disc brake pad assembly by considering different material properties for brake disc and pad.

2. Selection of Materials

Material selection for brake disc and pad plays a crucial role in the design of automobile disc brake. The materials selected for the application has to sustain the given loading conditions and satisfy all the characteristics required for a friction material and should be operated over different atmospheric conditions. The coefficient of friction at the contact region between brake disc and pad is assumed to be 0.3 for all the materials. The materials selected for the present analysis is given in Table1.

Table 1. Material properties

	Materials	**Properties**							
		ρ (kg/m^3)	**α / °C**	**E (Pa)**	**μ**	**S_{yt} (Pa)**	**S_{ut} (Pa)**	**S_{uc} (Pa)**	**Specific heat (J/kg°C)**
1	Ti Alloy	4620	$9.46\ 10^{-6}$	$9.6\ 10^{10}$	0.36	$9.3\ 10^{8}$	$1.7\ 10^{9}$	-	522
2	Ti Alloy	2830	-	$68.9\ 10^{9}$	0.3	$55\ 10^{6}$	$120\ 10^{6}$	-	-
2	Grey cast iron	7200	$1.1\ 10^{-5}$	$1.1\ 10^{11}$	0.28	-	$2.4\ 10^{8}$	$8.2\ 10^{8}$	447
3	Grey cast iron	1800	$1.7\ 10^{-6}$	$2.26\ 10^{11}$	0.27	-	$6\ 10^{8}$	$5.7\ 10^{8}$	644
4	Asbestos	2400	$5.26\ 10^{-6}$	$1.723\ 10^{11}$	0.26	-	$1.379\ 10^{9}$	$9.87\ 10^{8}$	879

ρ- Density of the material (kg/m^3), α -Coefficient of thermal Expansion /°C, E -Young's Modulus of the material (Pa), μ -Poisson's Ratio of the material, S_{yt} Yield strength of the material (Pa), S_{ut} Ultimate Tensile strength of the material (Pa), S_{uc} Ultimate Compressive strength of the material (Pa)

3. Design and Modeling of Disc Brake with Pad Material

Modeling of the disc brake was done using solid works. The dimensions of the disc brake are taken similar to the exact dimensions of four-wheel automobile car [18]. The disc brake pad assembly was designed, fig 3(a) and fig 3 (b) and assembled using solid works 2017 fig 3(c) and imported to ANSYS work bench show in fig 3 (d) for evaluating the performance of the brake disc under dynamic loading conditions. The behavior of the braking system is evaluated by using explicit dynamics in ANSYS work bench for the meshed model of automobile disc brake shown in fig 3(e).

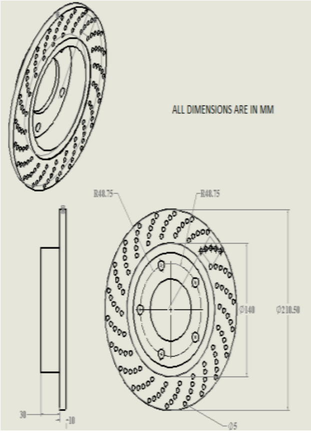

Fig 3 (a). Dimensions of ventilated disc brake

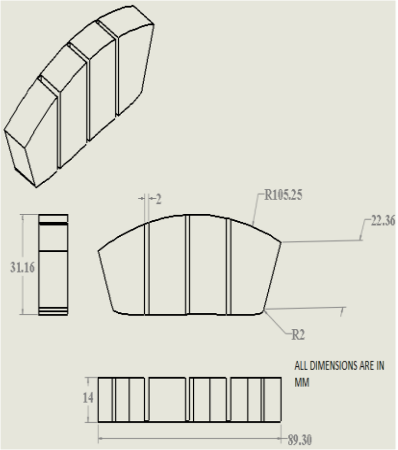

Fig 3 (b). Dimensions of brake pad

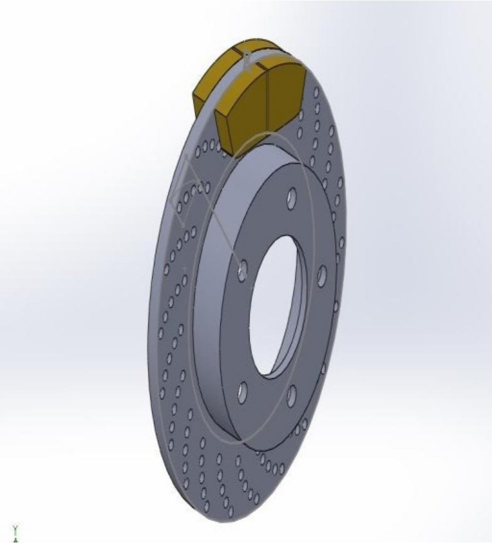

Fig 3 (c). Modelling of ventilated disc brake

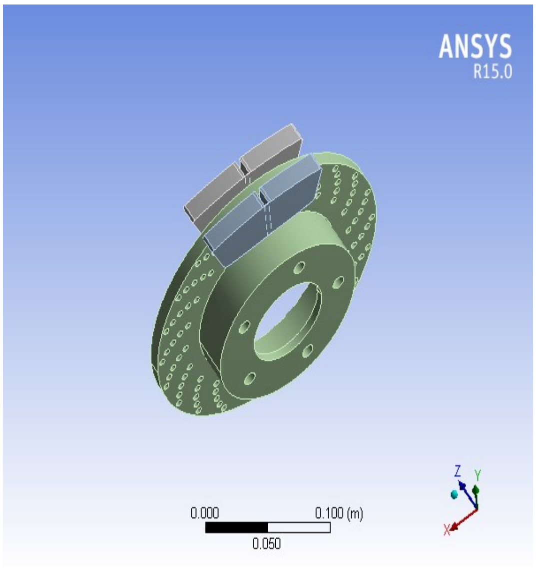

Fig 3 (d). ventilated disc brake imported to ANSYS

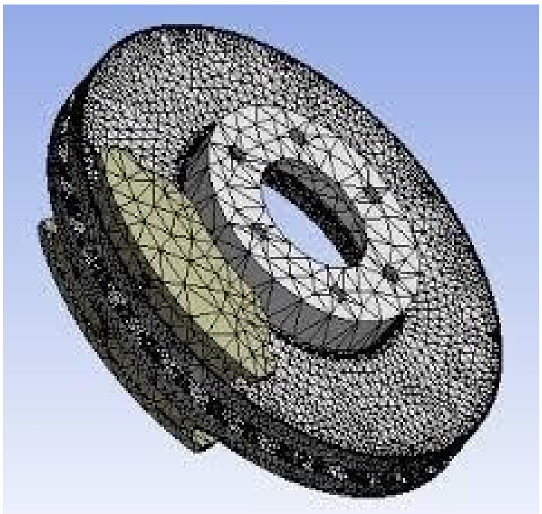

Fig 3 (e). Meshing of automobile disc brake

4. Loading and Boundary Conditions

The load acting on the friction material is considered as a high speed dynamic load acting on the friction material. The analysis is carried out for an angular velocity of 185.2 rad/s acting on the disc in clockwise direction, when viewing from the left side of the page. A high impact pressure with a velocity of 220 m/s is applied on both sides of the friction material [19]. The center portion of the disc and top and bottom portion of the friction material is fixed in all degrees of freedom. Mesh generation is created with fine size of tetrahedral elements to obtain accurate results for the given dynamic loading conditions. The behavior of these materials against dynamic high speed loading conditions is studied using ANSYS workbench using explicit dynamic analysis. All the values of deformation and vonmises stresses for different combination of materials of brake disc and pad are plotted against applied pressure.

During high speed dynamic load conditions of the automobile, brake pads wear rate will be predominant with increasing speed and pressure. Therefore, the wear rate of the pad depends on number of parameters like speed of rotation of rotor, pressure applied on the pad, contact surface and interface temperature, stability of coefficient of friction, ability to dissipate heat to the surroundings, weight acting on the assembly of disc brake, type of disc and pad materials, and mechanical properties of the material etc. Although, the number of parameters influencing the dynamic load acting on the pad is more but, the present analysis is performed by considering mechanical properties of the pad and disc and ignoring the remaining parameters. Below figure gives the high velocity impact load applied on the pad material along with angular velocity. Automobile disc brake applied with angular velocity and brake force are shown in figure 4 (a).

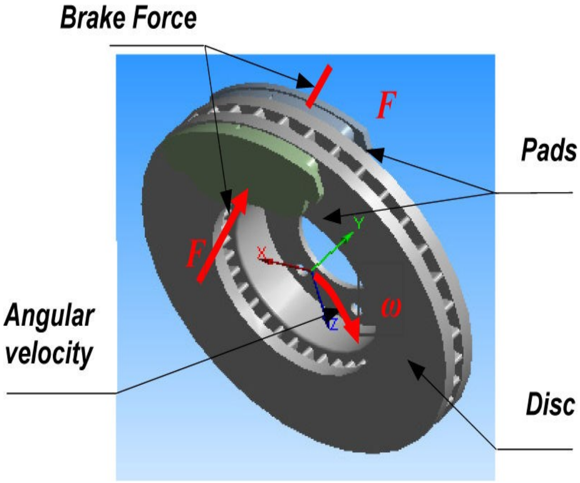

Fig 4(a) Automobile disc brake applied with angular velocity and brake force

5. Result

The behavior of the braking system is evaluated under high speed dynamic load acting on the friction material. The analysis is performed to meet the actual working condition of automobile running at high speed. The analysis is performed considering the wear rating of the automobile vehicle using explicit dynamic tool. Disc brake has to be designed and analyzed taking in to account of dynamic forces in such a way that the wear strength of the disc brake should always greater than the effective force transmitted by the disc brake. The entire analysis is performed with given high speed angular velocity of 185.2 rad/s and an impact load of velocity 220 m/s applied on the friction material. In the present analysis, inertia forces, weight distribution, damping behavior is assumed to be neglected. The surface destruction due to pitting of friction materials plays an important role under dynamic loading conditions. By altering the material properties of brake disc and pad, deformation and vonmises stress values are plotted for different configurations of materials and optimum materials are selected for brake disc pad assembly under high speed dynamic loading conditions for stabilizing the coefficient of friction at the interface between brake disc and pad.

5.1 High speed dynamic load acting on grey Cast Iron disc and Carbon fiber pad

This analysis is performed by considering grey cast iron as disc material and carbon fiber pad as friction material. Dynamic load with high velocity is applied on the friction material.

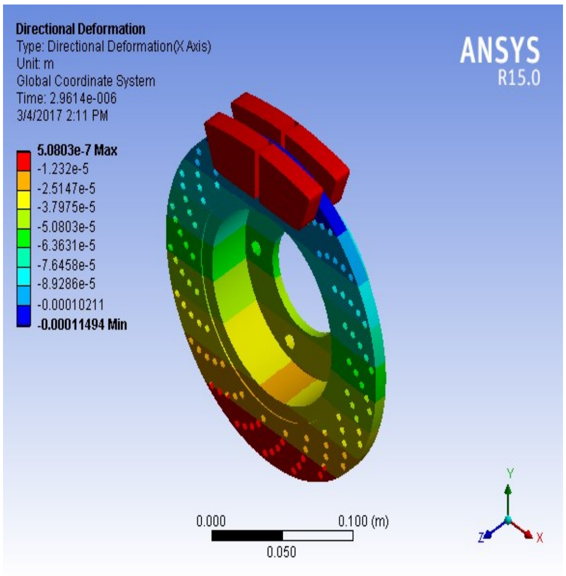

Fig 5.1 (a). Directional deformation

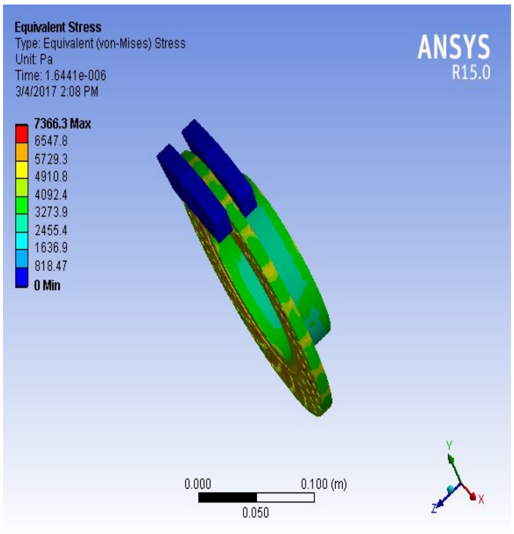

Fig 5.1 (b). Vonmises Stress

For the given dynamic load with high impact velocity acting on the grey cast iron disc and carbon fiber pad material, it was observed from fig 5.1 (a) and fig 5.1(b), that the directional deformation was observed to be 5.08E-04mm and vonmises stress as 7366.3MPa. It was observed that, directional deformation and vonmises stresses induced in the friction material are very less, which can be attributed directly due to superior mechanical and tribological properties of carbon fiber. The materials selected for the disc and pad can easily sustain the given dynamic loading conditions and the values obtained are well within the permissible values of the disc brake material.

5.2 Dynamic high speed load acting on grey Cast Iron disc and asbestos fiber pad

This analysis is performed by considering grey cast iron as disc material and asbestos fiber as friction material. Dynamic load is acted on friction material with angular velocity applied on disc.

For the given dynamic load acting on the grey cast iron disc and asbestos fiber pad material, it was observed from fig 5.2 (a) and fig 5.2 (b), that the directional deformation was observed to be 1.43E-04 mm and vonmises stress as 1.11E+03MPa. Under the given loading conditions, the friction material is subjected to low value of vonmises stresses for the given loading conditions compared to other material combinations. This proves that, the materials can easily sustain the given loading conditions and the values obtained are well within the permissible values of the disc brake material. The asbestos fiber material selected for the present application can sustain high dynamic loading conditions with ease and achieved better squeal propensity compared to other materials. This is mainly because of having high temperature with standing capability of asbestos material.

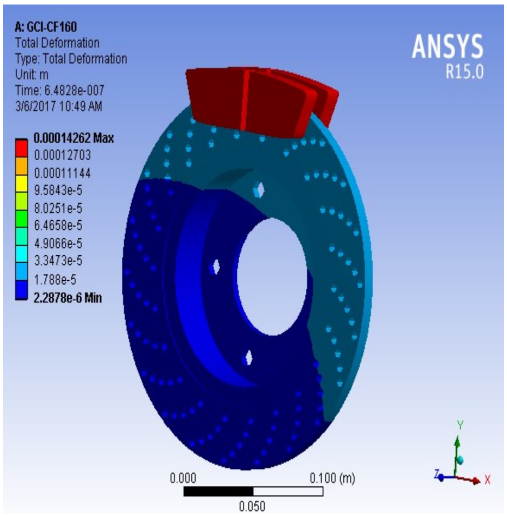

Fig 5.2 (a). Directional deformation

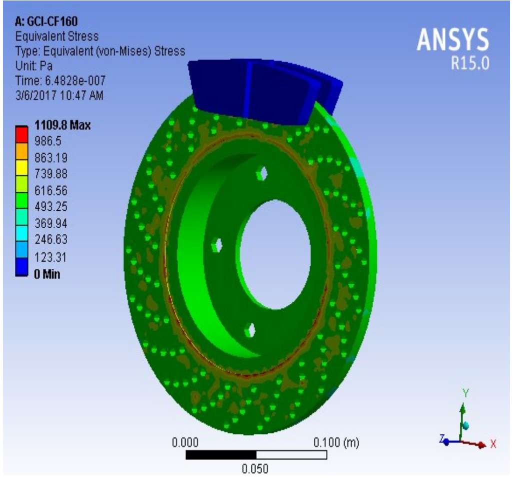

Fig 5.2 (b). Vonmises Stress

5.3 Dynamic high speed load acting on titanium Alloy disc and carbon fiber pad

This analysis is performed by considering titanium alloy disc as disc material and carbon fiber as friction material. Dynamic load is acted on friction material with constant angular velocity applied on the brake disc.

For the given dynamic load acting on the titanium alloy disc and carbon fiber pad material, it was observed from fig 5.3 (a) and fig 5.3 (b), that the directional deformation was observed to be 2.70E-04 m and vonmises stress as 4184MPa. It was observed that, vonmises stress and directional deformation values are less, mainly due to the inherent properties of Ti Alloy and carbon fiber. Ti Alloy and carbon fiber materials possess higher tensile strength values and good wear resistance compared to other formulations. The values obtained are well within the permissible values of the disc brake material. Therefore, this material combination possesses high fade resistance, recovery and less squealing action in high speed applications of the automobile.

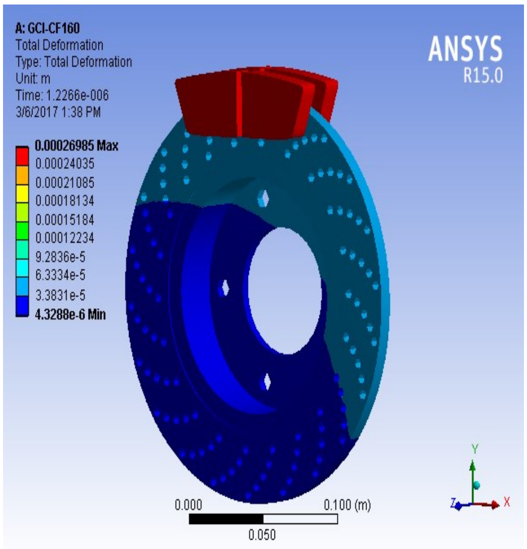

Fig 5.3 (a). Directional Deformation

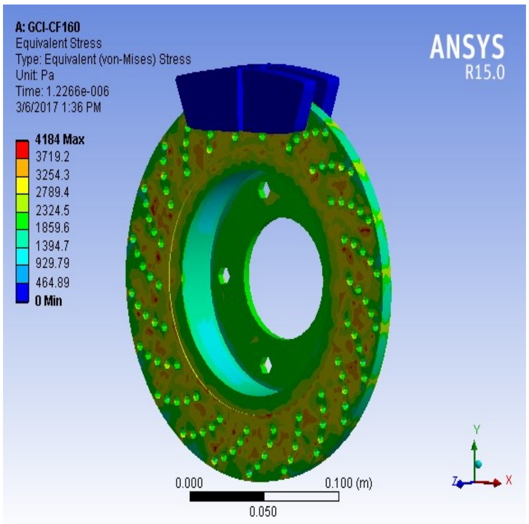

Fig 5.3(b) vonmises Stress

5.4 Dynamic high speed load acting on titanium alloy disc and asbestos fiber pad

In this analysis, the disc material is considered as titanium alloy and pad material as asbestos. Explicit dynamic analysis is performed on the disc brake pad assembly with dynamic load acting on the friction material and angular velocity applied on the brake disc.

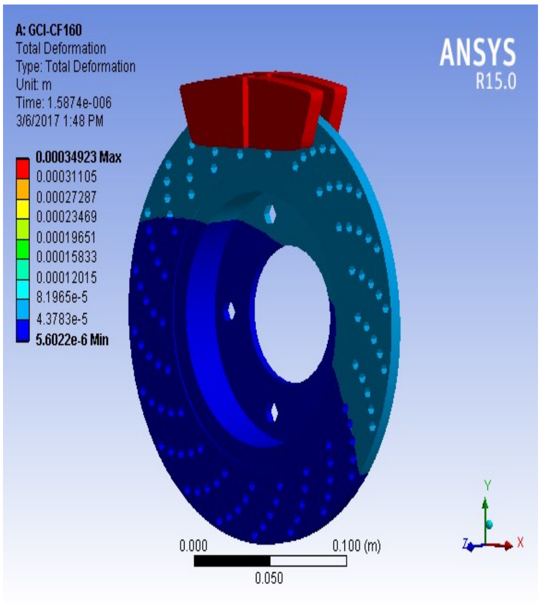

Fig 5.4 (a). Directional Deformation

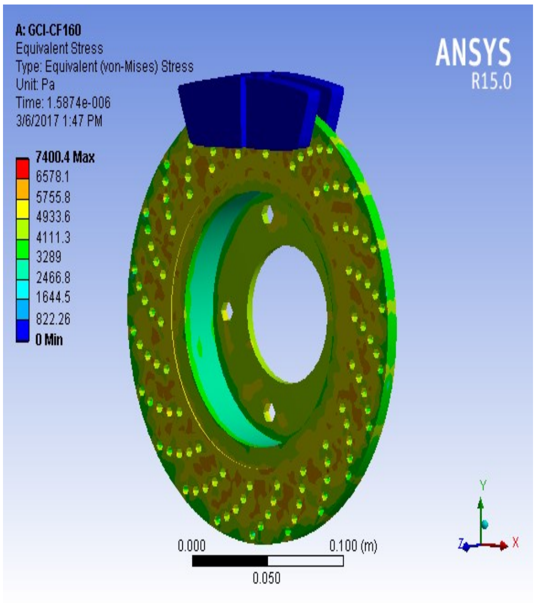

Fig 5.4 (b). Vonmises Stress

For the given dynamic load acting on the titanium alloy disc and asbestos pad material, it was observed from fig 5.4 (a) and fig 5.4 (b), that the directional deformation was observed to be 3.50E-04 m and vonmises stress as 7.40E+03MPa. It was observed that, the value of directional deformation was observed to be less but the severity of stresses encountered at the contact region of the brake disc is critical. This is mainly due to poor interfacial properties and in ability to have consistent coefficient of friction between Ti Alloy and asbestos fiber pad combination. Although, the values obtained are well within the permissible values of the disc brake material. But, the material combination of titanium alloy and asbestos pad exhibits moderate deformation values with high stress values compared to other formulations. Therefore, this material combination has chances for squeal propensity to propagate over the friction material at high speeds.

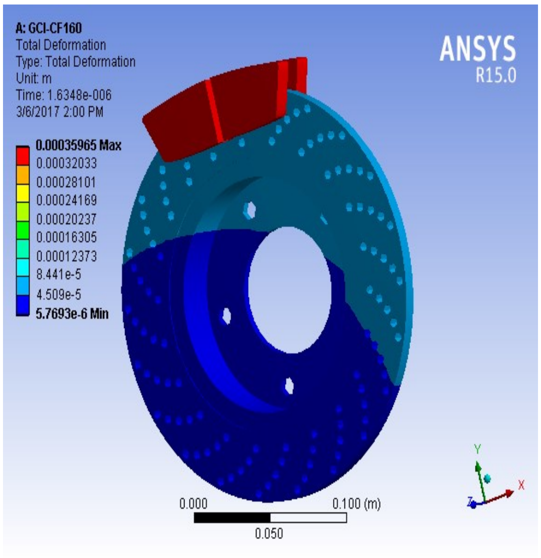

Fig 5.5 (a). Directional Deformation

5.5 Dynamic high speed load acting on aluminum alloy disc and carbon fiber pad

In this analysis, the disc material is considered as titanium alloy and pad material as asbestos. Explicit dynamic analysis is performed on the disc brake pad assembly with dynamic load acting on the friction material and angular velocity applied on the brake disc. For the given dynamic load acting on the aluminum alloy disc and asbestos pad material, it was observed from fig 5.5(a) and fig 5.5(b), that the directional deformation was observed to be 3.60E-04 m and Vonmises stress as 5568. 3MPa. The deformation and Vonmises stress values are observed to be lesser due to good mechanical and tribological properties of the carbon fiber. The stresses and deformation values are well within the permissible values of the material. Hence, this combination of material can exhibit good wear resistance and fade resistance under dynamic loading conditions. The values obtained are closer to Ti Alloy disc and CF pad combinations.

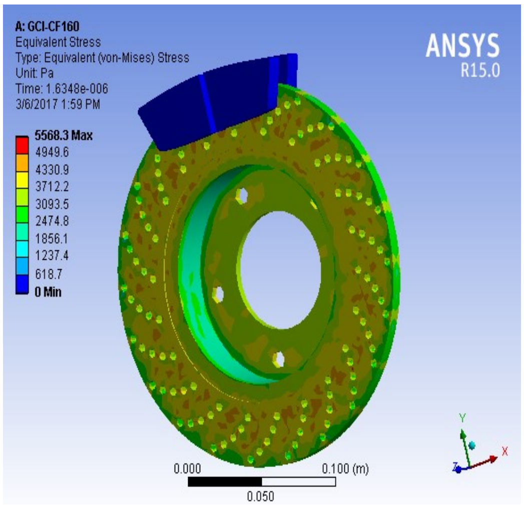

Fig 5.5 (b).VonMises Stress

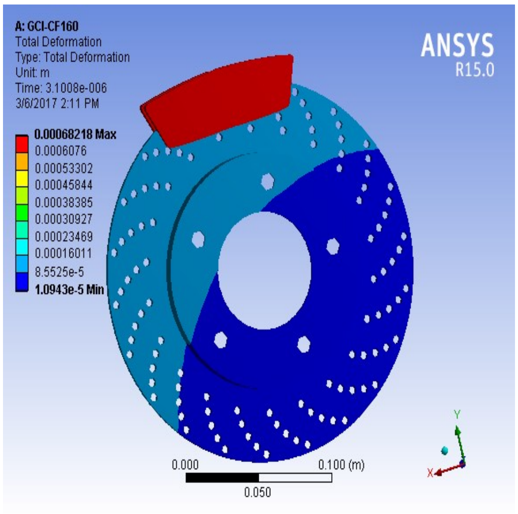

Fig 5.6 (a). Directional Deformation

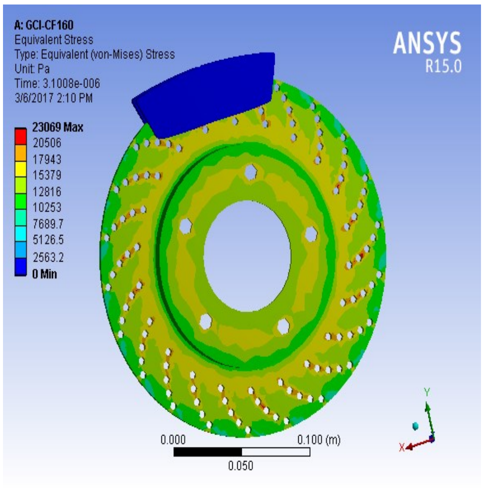

Fig 5.6 (b). VonMises Stress

5.6 Dynamic high speed load acting on aluminum alloy disc and asbestos fiber pad

In this analysis, the disc material is considered as aluminum alloy and pad material as asbestos. Explicit dynamic analysis is performed on the disc brake pad assembly with dynamic load acting on the friction material and angular velocity applied on the brake disc. For the given dynamic load acting on the aluminum alloy disc and asbestos pad material, it was observed from fig 5.6 (a) and fig 5.6 (b), that the directional deformation was observed to be 6.82E-04 m and Vonmises stress as 2. 31E+04MPa. The deformation value is observed to be very lesser value and vonmises stress value is observed to be more at the interface between brake disc and pad. This is mainly due to poor heat dissipation at the contact region between Al alloy and asbestos fiber pad materials due to poor recovery and damage in grain structure at high dynamic loads, which is responsible for increasing the wear rate and stresses at the contact region of brake disc.

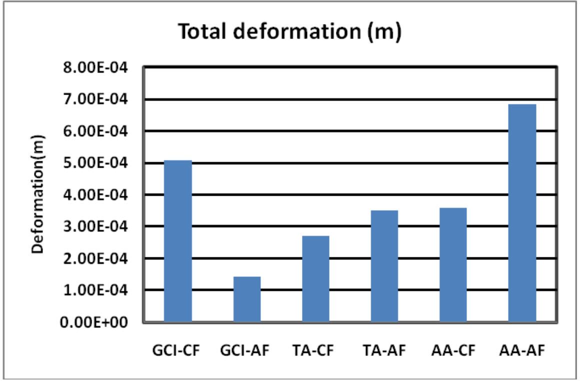

Fig 5.7 (a). Total deformation

5.7 Comparison graphs for dynamic high speed load acting on disc brake assembly

Based on dynamic load acting on disc brake assembly, it was observed from table 3, that the vonmises stress distribution is having a low value for titanium alloy and carbon fiber pad materials having a magnitude of 4184MPa. The value of directional deformation for Titanium alloy and carbon fiber was observed to be 2.70×10^{-4} mm from table 2. It was observed, from the graph of fig 5.7(a) and fig 5.7(b) that, the values of total deformation and stress withstanding capability for the given loading is more for titanium alloy disc and Carbon fiber pad combinations.

Table 2. Total deformation for different materials

Materials	Total Deformation(m)
GCI-CF	5.08E-04
GCI-AF	1.43E-04
TA-CF	2.70E-04
TA-AF	3.50E-04
AA-CF	3.60E-04
AA-AF	6.82E-04

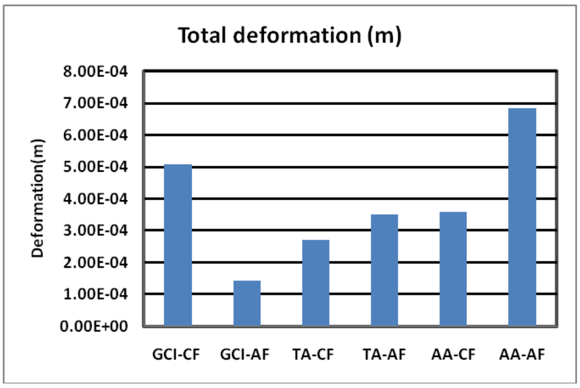

Fig 5.7 (a). Total deformation

Table 3. Vonmises stress distribution for different materials

Materials	Total Deformation(m)
GCI-CF	7366.3
GCI-AF	1.11E+03
TA-CF	4184
TA-AF	7.40E+03
AA-CF	5568.3
AA-AF	2.31E+04

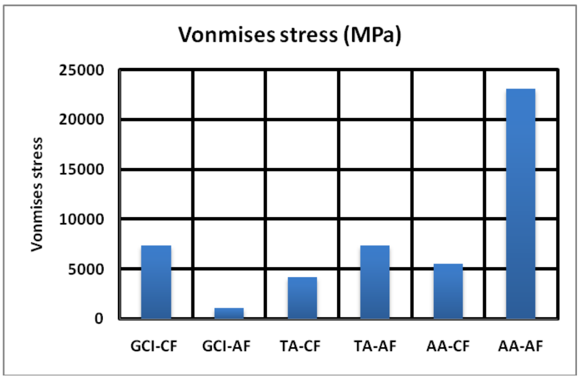

Fig 5.7 (b). Vonmises stress

The comparison graph indicates the values of different mechanical properties by altering the materials for disc brake rotor and friction materials.

The above comparison graph, fig 5.7 (c) represents the values of directional deformation and Vonmises stress for brake disc and pad. It was observed that GCI rotor and AF combination exhibits less deformation and vonmises stress values compared to other formulations. This is mainly due to the ability of high heat dissipation capacity of asbestos pad material to the surroundings. Although, asbestos material exhibits good properties in terms of deformation and vonmises stresses, But, it is recognized as carcinogenic material by world health organization and should be banned throughout the world to eliminate diseases caused by the asbestos. Therefore, based on analysis results, Ti alloy disc and carbon fiber pad can easily sustain dynamic loading conditions and the values of deformation and vonmises stresses are closer to CGI-AF combination. Hence, Ti alloy disc and CF pad can replace the existing materials under dynamic loading conditions.

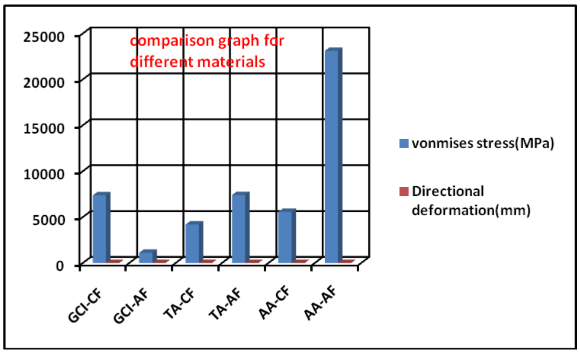

Fig 5.7(c). Comparing different values by altering the material properties

Table 4. Comparison table for different values obtained at 3Mpa pressure

Material Combinations	Directional Deformation (mm)	Vonmises Stress (MPa)
Grey Cast Iron- Carbon Fiber	5.08E-04	7366.3
Grey Cast Iron- Asbestos Fiber	1.43E-04	1.11E+03
Titanium Alloy- Carbon Fiber	2.70E-04	4184
Titanium Alloy- Asbestos	3.50E-04	7.40E+03
Aluminium Alloy – Carbon fiber	3.60E-04	5568.3
Aluminium alloy – Asbestos fiber	6.82E-04	2.31E+04

From the above table 4, it was observed that Titanium alloy disc and carbon fiber pad material exhibited less value of vonmises stress and better load with standing properties than other combinations. And Aluminum alloy and asbestos fiber exhibits better directional deformation values compared to other formulations. Hence based on the results, Ti alloy and carbon fiber material can sustain high dynamic loads with ease and possess acceptable low deformation values compared to other formulations.

6. Conclusion

Explicit dynamic analysis is performed with constant high impact load and angular velocity applying on combinations of disc made of titanium alloy, gray cast iron, and aluminum alloy materials and pad materials are taken as carbon fiber and asbestos. From the above analysis, it was concluded that ventilated disc made of grey cast iron and combination of pads, made from asbestos showed best vonmises stress values and low directional deformation compared to other combinations. But carcinogenic nature of asbestos pad material, limits its usage in automobile industry. Therefore, Titanium alloy disc and carbon fiber pad material can easily sustain high dynamic impact loads and the values of deformation and vonmises stresses are closer to GCI- AF combinations. By comparing with the experimental results available in literature, the stresses obtained with the Ti alloy disc and carbon fiber pad materials are well within the permissible stresses. Based on the obtained values, it was observed that Ti alloy disc and carbon fiber pad combination exhibits 26% increase in tensile strength and 18% lower value in directional deformation. The properties of the Carbon fiber and titanium alloying element present in an alloy is the main reason to have better wear resistance and fade resistance and less squealing propensity during braking under dynamic loads. Further, experimental analysis is needed to check the actual behavior of the braking system by considering all the derating factors that affect the squeal propensity and wear rate of disc brake and friction material. Finally, it was concluding that disc made of Ti alloy and brake pads made of carbon fiber can be used to replace existing material of GCI disc and asbestos pad for automobile applications under high dynamic impact loads.

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