DYNAMIC RESPONSE BEHAVIOUR OF FRICTION DAMPERS

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ABSTRACT

The friction materials are being used in structures for better and effective performance as damping devices in the mechanical systems. They convert mechanical energy to heat energy either during vibratory motion/seismic excitation. The conversion product namely heat is dissipated through the friction damping material. There are several damping materials available, but there seems to be good scope to further improve the performance of damping during dynamic response. In this context, the use of new and advanced material schemes is required to be studied.

Hence, the present work focuses on the preparation of advanced composite damper materials like Carbon-Carbon (C-C) and silicon carbide fibers (SiC_f) in silicon carbide matrix (SiC_m) based ceramic matrix composites followed by evaluation of various properties such as friction coefficient, thermal and vibration characterstics. Establishment of correlation among the properties in comparison with conventional dampers for superior performance has been attempted. A steel frame has been designed and fabricated for evaluation of the damping characteristics. The frame with dampers attached to the steel frame bracings is tested using electro tri axial shake table with and with out dampers to evaluate the dynamic response of the friction dampers followed by the analysis of output parameters namely magnification factor, damping factor. The frictional properties and thermal properties have been evaluated using pin on disc setup and laser flash equipment, respectively. The results reveal that the C-C and SiC_f-SiC_m are having better damping characteristics in terms of damping ratio, resonant frequency, thermal conductivity and frictional properties compared to conventional one.

1. INTRODUCTION

The structural vibration control is defined as a mechanical system associated with it and achieve a desirable response to a given external load and modification of the excitation (i.e., to reduce structural vibrations) during loadings such as strong earthquakes, base excitations to machineries etc. The dampers are employed in order to reduce the structural vibrations in a mechanical system as the function of damper is to control the vibration level of structures either passively or actively.

The conventional supports such has rod hangers, guide supports etc., which are used to arrest the vibration levels caused due to the flow of fluid in pipes such as steam or water in nuclear power and hydro power generation can act either as restraint or allow free motion and can not serve both the purpose of allowing free motion during normal operation and restraining or energy dissipation during earthquake. However, utilities have strong incentives to remove snubbers from operating nuclear power plants. Therefore to overcome the above difficulties, modern damping devices called seismic response control devices called friction dampers are used. The application of friction phenomenon to several applications in general and in particular structural engineering has lead to the development of friction dissipaters or friction dampers [1]. These devices rely on the resistance developed between sliding solid interfaces to dissipate a substantial amount of the input energy in the form of heat. During severe seismic excitations, the friction device slips at a predetermined load, providing the desired energy dissipation by friction. The dampers absorbs kinetic energy induced in the structure and prevents the build-up of resonant vibrations and prevents coincidence of the natural frequency of the structure with a strong frequency present in the ground motion [2]. They generally exhibit rigid plastic behaviour and their force response can be modeled by simple coulomb friction law, so that the force displacement relations of these devices are rectangular loops [3, 4]. Passive friction dampers are control device which does not require an external power supply. These devices respond as per the structural response and dissipate the energy in the form of heat and eventually reduce the structural response [5].

The advantage of providing damper is to control the amplitude of vibration there by the occurrence of resonance is avoided [6].

The improvement in respect of the performance of dampers used in structures, machineries, turbines, piping applications, especially in the nuclear power plants is called for. Keeping this point in view advanced materials development followed by laboratory evaluation of various characteristics such as physical, thermal, mechanical etc., in comparison with conventional materials are required to be addressed. This would probably help to choose the right type of candidate materials for damping applications for improved performance.

In this particular work, laboratory developed materials i.e, silicon carbide and carbon based composites have been comprehensively characterized for frictional, thermal and vibration properties in comparison with the conventional damper namely asbestos.

2. MATERIALS AND METHODS

The materials developed for this investigation are silicon carbide fibers in silicon carbide matrix (SiC_f-SiC_m) and carbon-carbon (C-C) composites produced by chemical vapour infiltration and polymer impregnation pyrolysis processes respectively. The brief preparation procedures of the composites are given below.

2.1 Preparation of SiC_f-SiC_m composites

The SiC_f-SiC_m bi-directional composites have been made using isothermal and isobaric chemical vapour infiltration (ICVI) technique. The SiC_f/SiC_m ceramic matrix composites are fabricated through ICVI route using Nicalon ceramic grade bi-directionally woven cloth (8 harnesses satin, NL202 Nipon carbon, Japan) as reinforcement material. The fibre volume fraction (V_f) is maintained around 0.4. The typical preform dimensions used in the present study were 230 mm x 240 mm x 4 mm. The ICVI process involving the use of two dimensional 8 harness satin woven SiC_f/SiC composite with 2 hours of boron nitride (BN) interfacing has been adopted. Precursors used were 99% pure boron tri chloride ï BCl_3 ,99% pure Ammonia, for BN deposition and 99.8% pure methyl tri chlorosilane ï CH_3SiCl_3 99.999% pure H_2 were used for SiC deposition/infiltration. The BN interface was applied on the fibre surface by CVD reaction between BCl_3 and NH_3 with flow rate ratio of 1:1. A pressure of 1-2 mbar was used at a temperature of 850ºC. It is reported in the literature that the interface coating improves the mechanical bonding between the fiber and matrix [4]. The composite laminates were densified up to 90 % of theoretical density with frequent interruption of densification cycles.

2.2 Preparation of C-C composites

Carbon-carbon (C-C) composites are combination of carbon or graphite fibers in a carbon or graphite matrix and the samples have been made by multiple impregnation of porous carbon frames with a liquid carbonizable precursor i.e. pitch.

2.3 Characterization

The physical (density), tribological (friction coefficient), thermal (conductivity and diffusivity) characteristics have been carried out using conventional Archimedes principle, pin-on-disc test set up and laser flash technique, respectively. The damping (damping ratio and resonant frequency) characteristics in respect of these materials have been evaluated in the laboratory simulated conditions using a shake table assembly set up which has been designed and developed in house.

2.4 Friction measurements

The test set up used for coefficient of friction measurements of the materials under study is the pin-on-disc machine. A test sample of size 6mm X 6mm X 4.5 mm is fixed to a cylindrical pin holder of diameter 6mm using a suitable adhesive electronic digital weighing balance. The tests are carried out by selecting the test parameter viz., normal load, velocity and sliding distance. The test sample is fixed to a holder and it is dead weight loaded (normal load) through a string to which pan assembly is attached. A load cell is fixed tangential to the lever arm and the output of which is connected to a strip chart recorder to measure the frictional load. The coefficient of friction is calculated, by dividing the steady state frictional load by the test sample is made in such a way that the thickness side of the test sample is made to come in contact with disc. The sliding distance is maintained at 500 m for the samples. The load and velocity ranges from 1, 2, 3 kg and 1.2, 2.4, 3.6 and 4.8 m/s, respectively, are choose. Three test samples are run for each combination of the parameters employed. The results reported are thus the average of ten readings and the scatter band in the experiments is plotted for each of the velocity and load employed in this investigation.

2.5 Laser flash thermal conductivity measurements

The system consists of flash source, sample holder, environmental enclosure (optional), temperature response detector and recording device. Flash line 5000 thermal properties analyzer is used to measure the thermal diffusivity parameter. The system uses a high speed xenon discharge pulse. A high intensity short duration Xenon pulse is delivered on front surface of sample. The specimen ambient temperature is noted and the resulting temperature æT (t) rise of base line or rear surface of sample by a thermocouple is measured.

The method proposed by Parker assumes adiabatic sample (i.e., no heat loss). The thermal diffusivity is determined from the thickness L, of the sample in mm and the time (άô) the thermo gram takes to reach half of the maximal temperature increase.

$$\alpha = 0.1388 \frac{L^2}{t}$$

Where *'t'* is the time required for the back surface to reach half of the maximum temperature rise. The thermal diffusivity of the sample is determined for other two spots on the specimen to validate the result. This method is applicable only for homogeneous solid materials, in the strictest sense. The measurement of specific heat is done by knowing the energy absorbed in the front surface. Then from the measured values of thermal diffusivity, specific heat capacity and known density, Thermal conductivity may be calculated using formula,

$$k = \alpha \rho C_p$$

Where, k = thermal conductivity in W/mK.
Cp = specific heat capacity in J/Kg K
ɉ = Density of sample, Kg/m^3
Ŭ= Thermal diffusivity, m^2/s

2.6 Development of shake table assembly test setup

The friction damper system used in this study consists of the friction unit (a plate rubbing against other one), clamped together by one or more bolts, and a structural system for integrating the friction unit with the structure. The structural system used is steel braces bolted to corner regions of the open bay space in the frame member. The schematic representation of the shake table assembly experimental rig is shown in Fig. 2.1. The vibration damping tests were done by subjecting structure to vibratory motion that conservatively simulates that postulated motion during their actual field of application. The vibration tests are conducted using shake table on the scale down model of 3D-Steel framed structure. Sine sweep tests are carried out to identify the modal parameters like resonant frequencies in X axis, damping ratio of framed structure with and without friction dampers.

2.6.1 Shake Table Assembly Test

The tri-axial shaker system consisting of a shaking-table facility is quite unique as it simulates the seismic conditions without any distortion. The facility features a 10-ton payload capacity shake table of all-welded steel construction. An advanced control system has been integrated with the shaker for reproduction of seismic ground motions with high fidelity. The structure to be evaluated is mounted on the vibration table in a manner that simulates the intended service condition. The mounting arrangement has been followed as per the recommended practice. The functional and vibration response parameters are considered for monitoring the structure during the testing. The types of motion available to simulate theseismicenvironment fall into two categories; single frequency and multiple frequencies. The method chosen will depend upon the nature of the expected vibration environment and also on the nature of the structure. In the case of single frequency test, a short duration steady state vibration may be the input excitation to the structure. Further, single frequency testing is used to determine (or verify) the resonant frequencies and damping of structure. If it is shown that the structure has no resonances, or only one resonance, or resonance are widely spaced and do not interact, or if otherwise justified, single- frequency test may be used to test the structure in full.

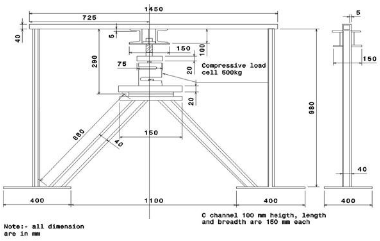
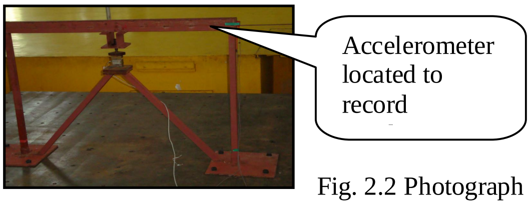


Fig. 2.1 Schematic diagram of friction damper assembly

The 3D-steel frame was designed and fabricated and the arrangements were made to place the frame on the shake table. The 3D-steel frame structure is made to sit on the shake table (Fig. 2.2). The 3D-steel frame structure with and without dampers is subjected to sinusoidal sweep test using shake table. During Pre-testing, the frame structure is thoroughly checked for any cracks or damage after placing it on the shake table. The frames are mounted on the shake table such that they are vertical in perpendicular plane to the table top and corresponding to the X-Z (horizontal) plane of the shaker table. The accelerometers and strain gauges are connected to the data acquisition system. The resistances of strain gauges, fixing methods and insulation levels are checked before connecting them to the terminals of data acquisition system. The scaled model accelerometers are mounted at the specified locations as in shown in the Fig. 2.2. During testing the output of accelerometers are recorded as acceleration response. Strain gauge has been fixed at the critical location in the steel frame structure to record the maximum strain at the respective point for different conditions. Before fixing the strain gauge, the location is marked and then the surface is rubbed with the help of sand paper and washed to make the surface smooth.



Accelerometer located to record

Fig. 2.2 Photograph showing the accelerometer location on the steel frame.

The sine sweep testing is done to measure the structural response at different points with controlled sinusoidal excitation. In this test, a sinusoidal input with continuously varying frequency is applied to the structure with and without dampers. The frequency covers the bulk range for which the frame structure has to be qualified. The percentage of steady-state resonance response mainly depends up on the sweep rate and the damping of the frame structure. Maximum response is gathered at every frequency in the entire test range. The resonant frequency search is done for input levels 0.1g, 0.2g, 0.3g. At the resonance frequency condition, the transfer function (TF) of response to input motion generally exceeds 2 and there will be a phase shift between the input and response motion. Also, there will be a sudden dip in the coherence at the point. Sine Sweep Testing provides a complete solution for frequency response function-based modeling of large and complex structures that are difficult to excite with sufficient energy. The resonance test parameters employed are Sinusoidal sweep in the X axis with frequency range from 1 to 50 Hz and acceleration of 1, 2 & 3 m/s^2 with logarithmic sweep rate of 1 octave/minute. The response of the structure at one location as accelerometer output is recorded during testing. In order to evaluate the damping values and identify the resonant frequencies in the X axis, the recorded accelerometers output are analyzed using data analysis package (DAP) software version 3.0. For each location, Transfer Function (TF) details of phase and coherence are obtained. From the Transfer function (frequency response function), the resonant frequencies are identified and the corresponding damping values are obtained using Half-Power Band width method.

2.6.2 Half-power band width method The classical method of determining the damping at a resonance, using a frequency analyzer, is to identify the half power points of the magnitude of the frequency response function. The well-known bandwidth method, especially the half-power bandwidth method (Fig. 2.6) seems to be the simplest method for the damping estimation from a frequency response function (FRF). The half power bandwidth method uses the transfer function plot to obtain the damping. This method is quite efficient for simple model test cases when modes are well separated.

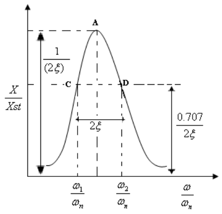


Fig. 2.6 Frequency response function showing half power poin

The damping ratio is given by, $\xi = \dfrac{\omega_2 - \omega_1}{2\omega_n}$

Angular frequency ω in radians per second is converted to temporal frequency, by using the formula, $\omega = 2\pi f$ Hertz.

Therefore, the damping ratio is

$$\xi = \frac{f_2 - f_1}{2f_n}$$

The data analysis packaged used will automatically generate the frequency response function in terms of temporal frequency, hence there is no need to convert angular frequency to temporal frequency before finding damping ratio. The above equation can be used directly.

3. RESULTS AND DISCUSSIONS

The data in respect of physical, tribological, thermal, mechanical and damping characterstics of the commercially available material i.e., asbestos and laboratory developed polymer and ceramic matrix composites i.e., silicon carbide based composites and carbonï carbon composites are discussed. These have been designated as SiC_f-SiC_m A & B and C-C composites respectively.

3.1 Physical Characteristics

The density & porosity measurements were made and the results are given in the following Table 3.1.

Table 3.1 Physical Properties

Description	C-C	SiC_f-SiC_m		Asbestos
		A	B	
Density g/cc	1.40 ï 1.49	2.4 ï 2.5	2.4 ï 2.5	1.5 - 1.7
Porosity %	-	12 - 14	12 - 14	.14 - 16

3.2 Friction Characteristics

Figs. 3.1 to 3.3 show the plots of coefficient of friction vs. sliding distance in respect to asbestos, C-C and SiC_f-SiC_m composites, respectively.

From Fig. 3.1 it is observed that the coefficient of friction increases with increase in sliding distance and is in the range 0.34-0.39. From Fig. 3.2 it is observed that the coefficient of friction increases from 0.28 to 0.32 as the sliding distance is varied from 1884 m to 7536 m. The coefficient of friction reported for this category of sample is in the range of 0.3 to 0.5 in the fibre direction.

From Fig. 3.3, it is observed that with the increase in sliding distance, the coefficient of friction also increases for both SiC_f-SiC_m A (0.49 to 0.53)and B (0.54 to 0.58) composites. However, composite B shows higher coefficient of friction compared to composite A at all the sliding distances (Fig. 3.3) This may be due to the interface bonding between the fibre and the matrix in composite B is weaker compared to composite A on account of matrix fragmentation, fibre pullout and fibre fracture as supported by the SEM features.

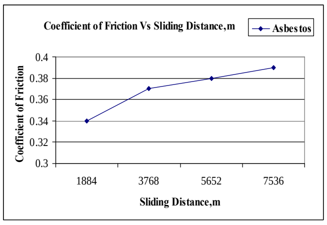


Fig : 3.1Coefficient of friction vs Sliding distance for asbestos

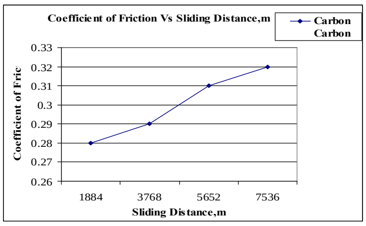


Fig. 3.2 Coefficient vs. sliding distance for C-C composite

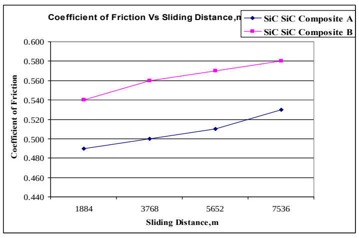


Fig. 3.3Coefficient of friction vs. sliding distance for SiC_f-SiC_m composites

3.3 Thermal Characteristics

Thermal conductivity, specific heat and thermal diffusivity data of the materials studied at ambient temperature are shown in Table 3.2.From the Table 3.2 it is observed that thermal conductivity for asbestos is in the range 0.24 to 0.29 W/mK as compared to the reported values of 0.16 ï 2.07 W/mK. For C-C composites is in the range 7.0 to 7.3 W/mK and the reported values is in the range 6 to 7 W/mK, respectively. The difference in thermal conductivity of C-C composite may be attributed to the fiber orientation, volume fraction of fibers in the required direction, processing method and densification temperature. The thermal conductivity measured for SiC_f-SiC_m composite A and B are in the range 2.7 to 3.0 W/mK for SiC_f-SiC_m Composite A and 6.2 to 6.5 W/mK for SiC_f-SiC_m Composite B, respectively lays ranges from 1.5 to 2 W/mK..

Table 3.2 Thermal properties

Description	C-C	SiC_f-SiC_m		Asbestos
		A	B	
Thermal Conductivity W/m°K	7.0 ï 7.3	2.7 ï 3.0	6.2 ï 6.5	0.24 - 0.29

3.4 Resonance results using shake table

The resonance frequency is the easiest modal parameter to determine. A resonance is identified as a peak in the magnitude of the frequency response function. The following are the Resonance Frequency of vibration and corresponding damping ratio for 3D mild steel frame structure without and with friction dampers made of asbestos and advanced ceramic fiber ceramic matrix composites like C-C and SiC_f-SiC_m.

$$\text{Transfer Function} = \frac{Output}{Input} = \frac{\left(\dfrac{Accelerometer\,output, m/s^2}{Ground\,Acceleration, m/s^2}\right)}{Input\,frequency, Hz} \text{ é é é é é é é é é é é .(1)}$$

The transfer functions of 3D mild steel frame with & without dampers have been determined for different g levels at a resonance frequency of 25 Hertz and based on this, the modal damping calculation is done using the equation (2).

$$\xi = \frac{f_2 - f_1}{2 f_n} \text{ é é é é é é é é é é é é é é é (2)}$$

The resonant frequency and damping ratio of the composites studied for damping behaviour for different ógô and load levels is tabulated in Table 3.3 to 3.6, respectively.

3.4.4 Resonance search test results tabulated for without and with dampers

The Tables 3.3, 3.4, 3.5 and 3.6 give the load, resonance frequency and damping characteristics of 3D steel frame without damper and with asbestos, SiC_f-SiC_m based composites and C-C composites as dampers, respectively.

Table 3.3 Resonance data without damper

Bare Frame (without Dampers)						
Sl No.	**Acceleration(g)**	**Load (Kg)**	**Resonance Frequency (Hz)**	**Magnification Factor**	**Damping Ratio ,ξ**	**%Damping Ratio ,ξ**
1	0.1g	NIL	19.0	21.31	0.0389	3.89
2	0.2g	NIL	18.5	21.37	0.0395	3.95
3	0.3g	NIL	18.5	20.87	0.0382	3.82

Table 3.4 Resonance data with asbestos damper

With Asbestos Damper						
Sl No.	**Acceleration(g)**	**Load (Kg)**	**Resonance Frequency (Hz)**	**Magnification Factor**	**Damping Ratio ,ξ**	**%Damping Ratio ,ξ**
1	0.1g	50	20.5	04.58	0.042	4.2
2		100	31.0	05.69	0.0319	3.19
3		150	40.5	12.63	0.043	4.3
1	0.2g	50	25.0	07.28	0.045	4.5

2		100	36.5	9.1084	0.03	3.0
3		150	31.0	10.6588	0.0386	3.86
1	0.3g	50	24.5	5.8286	0.0471	4.71
2		100	30.5	9.195	0.0492	4.92
3		150	33.5	9.029	0.0517	5.17

Table 3.5 Resonance data SiC_f-SiC_m dampers

With SiC_f-SiC_m Damper A						
Sl No.	**Acceleration (g)**	**Load(Kg)**	**Resonance Frequency (Hz)**	**Magnification Factor**	**Damping Ratio ,ξ**	**%Damping Ratio ,ξ**
1	0.1g	50	24.5	07.64	0.0492	4.92
2		100	32.0	08.11	0.0508	5.08
3		150	33.5	19.68	0.0517	5.17
1	0.2g	50	22.5	07.65	0.0421	4.21
2		100	31.0	08.62	0.0541	5.41
3		150	31.0	13.44	0.0562	5.62
1	0.3g	50	20.5	09.46	0.0437	4.37
2		100	28.5	10.22	0.0582	5.82
3		150	31.0	12.03	0.0593	5.93
With SiC_f-SiC_m Damper B						
1	0.1g	50	22.0	03.34	0.0497	4.97
2		100	30.5	09.77	0.0513	5.13
3		150	32.5	12.93	0.0525	5.25
1	0.2g	50	29.5	06.99	0.0452	4.12
2		100	28.5	07.48	0.0562	5.62
3		150	30.5	09.52	0.0581	5.81
1	0.3g	50	21.5	27.44	0.0448	4.48
2		100	27.5	08.46	0.0591	5.91
3		150	28.5	07.58	0.0612	6.12

Table 3.6 Resonance data C-C damper

With Carbon Carbon Damper						
Sl No.	**Acceleration (g)**	**Load (Kg)**	**Resonance Frequency (Hz)**	**Magnification Factor**	**Damping Ratio ,ξ**	**%Damping Ratio ,ξ**
1	0.1g	50	30.0	08.77	0.0561	5.61
2		100	40.5	12.35	0.0581	5.81
3		150	43.0	14.41	0.059	5.90
1	0.2g	50	27.0	07.62	0.0572	5.72
2		100	38.5	09.41	0.0584	5.84
3		150	41.0	11.59	0.0598	5.98
1	0.3g	50	25.0	07.96	0.069	6.90
2		100	36.5	07.96	0.0623	6.23
3		150	40.0	10.36	0.0676	6.76

It is evident from the above Table 3.6 that the damping characteristics of C-C materials are superior in terms of magnification factor & damping ratio compared to SiC_f-SiC_m based composites (Table 3.5) as well as asbestos materials (Table 3.4) investigated in the work. The data shows that C-C is showing higher damping ratio and higher magnification factor followed by SiC_f-SiC_m, asbestos in the descending order. The reason for this type of behaviour may be attributed to higher coefficient of friction & thermal conductivity obtained for C-C and SiC_f-SiC_m composites compared to asbestos material. The SiC_f-SiC_m A sample has shown lower % damping ratio compared to SiC_f-SiC_m B sample in view of lower thermal conductivity obtained for the former sample. The C-C shows % damping ration higher than that of SiC_f-SiC_m B sample. The C-C and SiC_f-SiC_m B show higher thermal conductivity values compared to SiC_f-SiC_m A and asbestos samples. It is reported in the literature that higher the friction & thermal conductivity [7], better is the heat transfer rate and in turn decrease the vibration [8] level (lower damping). Because of higher heat transfer characteristics obtained for SiC_f-SiC_m B and C-C samples, the damping behaviour is superior compared to SiC_f-SiC_m A sample.

It is summarized that the SiC_f-SiC_m and C-C samples are exhibiting better damping behaviour compared to asbestos sample. However, C-C samples shows the best damping characteristics in view of higher thermal conductivity and moderate friction coefficient levels.

4.0 CONCLUSIONS

The following are the key points, which emerge from this work programme.

1. The shaker assembly to conduct the seisemic qualification tests has been designed & developed.
2. Among the damper materials evaluated, SiC_f-SiC_m composites shows higher friction & thermal conductivity and better damping characterstics compared to asbestos.
3. However, C-C composites show superior damping behaviour compared to SiC_f-SiC_m based composites in view of higher thermal conductivity and in turn higher heat dissipation obtained. As it is known that higher the thermal conductivity greater is the potential to dissipate the kinetic energy in the form of heat during the relative motion/vibration of sample with respect to its counter part.
4. SiC_f-SiC_m based composites also serve as good damping materials for structural and seismic conditions. Improvement in the matrix characterstics may result in higher damping capability, which needs to be explored.

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