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Experiments Studies of MWCNTs as Lubricant Additives

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ABSTRACT

The Multi-Walled Carbon Nano-tubes (MWCNTs) are employed as anti-wear and anti-friction additives in mineral oil. The MWCNTs are known for their superior thermal conductivity, mechanical and optical properties. It is expected that hollow-core carbon nano tubes provide easy sliding as well as rotating action with respect to one another; therefore there is a need to explore the use of MWCNT as lubricant-additive. In the present research work, experimental investigations have been conducted to explore the importance of the MWCNTs as additives in the lubricating oils. Tests were performed on block on disk setup for five oil samples: Sample 1: Mineral oil, Sample 2: Pure MWCNT with surfactant mixed in base oil using sonication, Sample 3: Functionalized MWCNT with surfactant mixed in base oil using sonication, Sample 4: Pure MWCNT mixed in base oil using sonication and Sample 5: Functionalized MWCNT mixed in base oil using sonication. The performance was evaluated by measuring the viscosity, wear and friction.
To understand the effect the effect of functionalization on temperature, experiments were performed at (i)350C, (ii) 700C and (iii) 950C and the performance was evaluated by measuring the wear and friction coefficient. The comparison of different results are carried out and results are presented

Key words:MWCNTs, anti-wear, anti-friction, surfactant, functionalization.

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INTRODUCTION

Carbon nanotubes (CNTs), which are basically hollow cylinders of one or more layers of graphene, were discovered of by Lijima [1] in 1991. Carbon nanotubes (CNTs) are denoted as single-wall (SWCNT), or multiwall (MWCNT) [1, 2]. Diameters of SWCNTs and MWCNTs are typically 0.8 to 2 nm and 5 to 20 nm, respectively. Since the MWCNTs that contain graphene can be produced in much larger quantities at lower cost, there is a need to study the mechanism of MWCNTs as Lubricant additives.

Commercial activity related to CNT has grown most substantially during the past decade. Since 2006, worldwide CNT production capacity has increased at least 10-fold, and the annual number of CNT-related journal publications and issued patents continues to grow (as shown in Fig. 1).

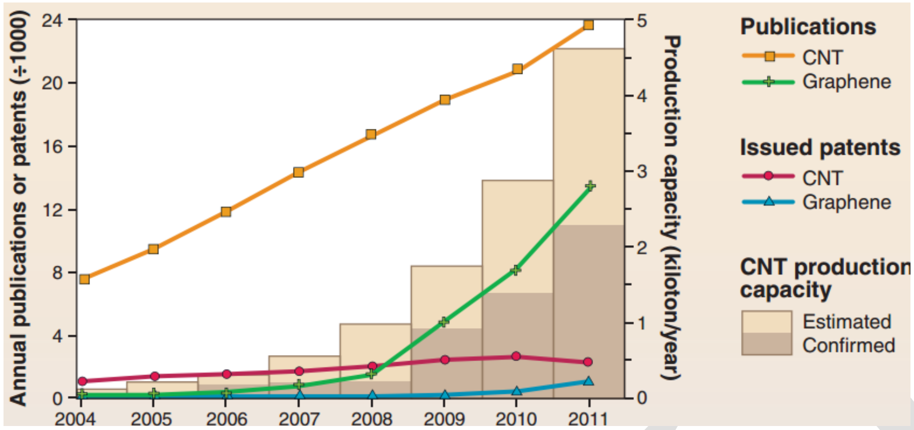


Fig. 1 Journal publications and issued worldwide patents per year, along with estimated annual production capacity [6]

CNTs possess unique structural, electrical and exceptional mechanical properties. Elastic modulus approaching 1 TPa and tensile strength of 100 GPa of MWCNTs [3] have been quoted. This strength is over 10-fold higher than any industrial fiber. MWCNTs can carry currents of up to $10^9 Acm^{-2}$ [4]. Individual CNT walls can be metallic or semiconducting depending on the orientation of the graphene lattice with respect to the tube axis, which is called the chirality. Individual SWNTs can have a thermal conductivity of 3500 $Wm^{-1}K^{-1}$ at room temperature, based on the wall area [5]. Due to these properties, CNTs are used in a wide range of applications including lightweight composite structures, field emission devices, electronics, micro/nano-electro-mechanical system (MEMS/NEMS) devices, sensors, actuators, nano-robotics and medical applications. However the literature available on implementation of CNTs in tribological application is very scarce and hence a detailed study is required to explore the CNTs as nano-lubricant additive.

In science of lubrication, attempt is made to minimize the contact between rotating and stationary surfaces so that friction and wear can be minimized. Often avoiding contact between tribo-surfaces (i.e. fluid bearings used in sugar mills [7], cement-manufacturing plants [8], and steam turbines [9]) is not-possible and the tribo-surfaces operate in mixed lubrication regime. To avoid the metal to metal contact in such applications, either hybridizing of hydrostatic and hydrodynamic [10-53] mechanisms or use of nano-additives [54-56] have been researched. The hybridization of fluid bearing based on hydrodynamic mechanism with hydrostatic mechanism is not recommended as it increases the complexity (i.e. gear lubrication) of the system; and increases cost of the overall system. Therefore in the present work "use of nano-additives" in the lubricant will be explored.

Although the nanoparticles like ZnO, MoS_2 and WS_2 have good antifriction properties, their tribological performance reduce under high load conditions. The main reason of such behaviour is irreversible change in the shape and structure [57] of ZnO, MoS_2 and WS_2. On the other hand, hollow-core carbon nano tubes, provide easy sliding as well as rotating actions with respect to one another and due to such actions MWCNT form near ideal nano-bearings [58]. Repeated extension and retraction of telescoping nanotube segments revealed no wear and able to produce ultra-low friction [58]. The CNTs have high Young's modulus and stiffness in the direction of the nanotube axis; as well as considerable mechanical strength and great flexibility perpendicular to the axis [59].

Jeng*et al* [57], Peng*et al* [58], Chen *et al* [60-61] showed that a good dispersion of the CNT additives within the lubricant can be achieved by reducing the surface energy of the particles by surfactant and chemical modification using carboxyl (-COOH) and/or hydroxyl (–OH) functional groups. Garg and Susan [62] examined the effects of covalent chemical attachments on the mechanical properties of single-walled CNTs using classical molecular dynamics simulations. Authors found that covalent chemical attachments decrease the maximum buckling force by about 15% regardless of tubule helical structure or radius.

On reviewing literature, it has been found that MWCNTs has been used along with surfactants and functionalization. As per authors knowledge there has been no study performed till now to understand the tribological effect of nano-lubricant with and without surfactants and functionalization. Therefore in the present work five different samples: (i) Sample 1: Mineral oil, (ii) Sample 2: Pure MWCNT with surfactant mixed in base oil using sonication, (iii) Sample 3: Functionalized MWCNT with surfactant mixed in base oil using sonication, (iv) Sample 4: Pure MWCNT mixed in base oil using sonication and (v) Sample 5: Functionalized MWCNT mixed in base oil using sonication, were prepared and experiments were performed on block on disc experimental setup. The performance of the lubricant was evaluated by musing the weight loss of the block and friction data.

Using molecular dynamics Shenogin*et al* [63] showed that by functionalization MWCNTs leads to reduction of thermal conductivity due to the scattering of electrons and phonons [64], therefore it is worth verifying the tribological performance of nano-lubricant with and without functionalization at higher temperature, since all the earlier works has been performed under the room temperature. Block on disc experiment was repeated for Sample 1-3 and again the performance of the samples were evaluated by measuring the weight loss and frictional coefficient.

EXPERIMENTAL SETUP AND SAMPLE PREPARATION

The block on disc experimental setup used for the present work is shown in figure 1. The block is made of phosphorus bronze material and the disk is made of hardened steel. The diameter of the disk is of 40 mm and width of 15mm. It is driven by a single phase induction motor. The block is fixed in a holder that is attached to the loading platform. The static load is applied on the loading platform that causes the contact between the conformal block with the disk. The conformal block slides against the disk. The disk is partially immersed in the lubricant and the lubricant temperature was maintained by the help of heaters and a thermal cut-off switch. A combination of a load of 70 N and a sliding speed of 0.05 m/s corresponding to 25 rpm of the disk were considered for the test operating conditions that causes the operation in the mixed lubrication regime.

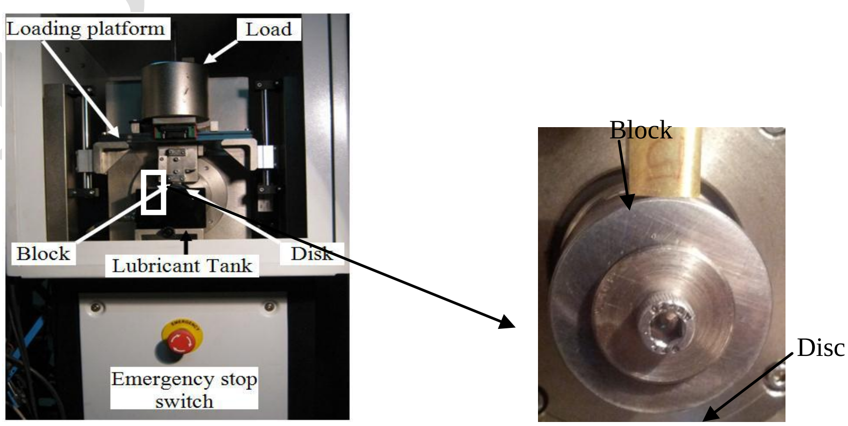
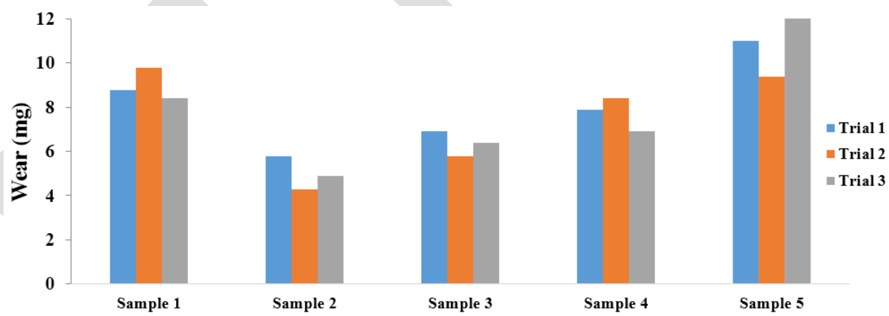


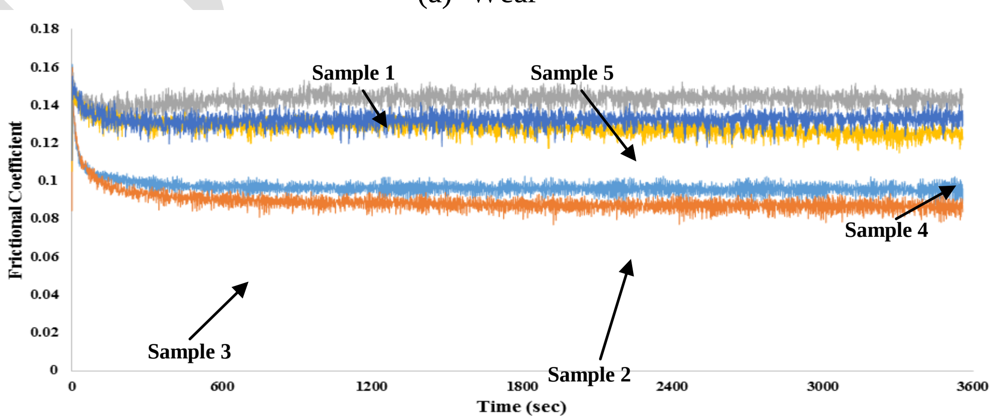
Fig. 1 Block on disc setup

In the present work COOH functionalized MWCNTs and Triton X-100surfactant was used. In the present work “Sample 4” and “Sample 5” nano-fluids were developed by adding 0.05 weight percentage of lubricant of MWCNTs and functionalized MWCNTs in the lubricant and the solution is homogenised using 250W homogenizer for half an hour. In the case of “Sample 2” and “Sample 3”, two times the weight of the MWCNTs were added in the lubricant along with 0.05 weight percentage of lubricant of MWCNTs and functionalized MWCNTs respectively.
The experiments were performed for one hour at 70^0C and the wear and frictional coefficient results are presented in figures 2(a) and 2(b) respectively.
From figure 2(a) following observations are made:

(i) MWCNTs with surfactant are able to reduce the wear; therefore the MWCNTs must be used with surfactant.
(ii) Functionalized MWCNTs without surfactant produced higher wear.
(iii) “Sample 2: MWCNT in mineral oil with surfactant” provided low wear.The problem with the introduction of functionalization is that, it degrade the mechanical strength of CNTs by an average value of 15% [18] and due to the hydrophobic nature of MWCNTs and hydrophobic lubricant, the functionalization is not required for proper dispersion if the particles are small.
(iv) The variation between the trials of the “Sample 1” was observed to be low while it is high in the case of other four samples. The reason for the variations in wear value is due to the differ orientation of the MWCNT’s between the block and disk. If the length of the MWCNT’s are in parallel to the disk and block surface, they act as roller bearing and reduce wear while if they are perpendicular they will result in higher wear. In the case of entangled MWCNT, it can be both and wear will varying.



(a) Wear



(b) Coefficient of friction

Fig. 2 Wear and coefficient of friction for different samples with 0.05% MWCNT

From figure 2(b) following observations are made:

(1) The friction coefficient value is lesser for all types of nano-lubricant compare to mineral oil "Sample 1"
(2) The friction coefficient values for "Sample 1" was highest and lowest for "Sample 2"
(3) The friction coefficient value among the samples having surfactant "Sample 2" and "Sample 3" and samples without surfactant "Sample 4" and "Sample 5" were same.
(4) The friction values of samples with surfactant was lower compare to samples without surfactant.
(5) There is a steep decrease in thefriction coefficient value in the case of "Sample 2" and "Sample 3", indicating that the filling of MWCNT in the asperities [13].

From the above discussion it can be concluded that samples having MWCNTs with surfactant reduces both wear and friction. In the following section the effect of temperature on functionalized and non-functionalized MWCNTs will be studied.

EFFECT OF TEMPERATURE

The experiments were performed at lower (35^0C) and higher (95^0C) temperatures. The wear at different temperatures has been plotted in figure 3.

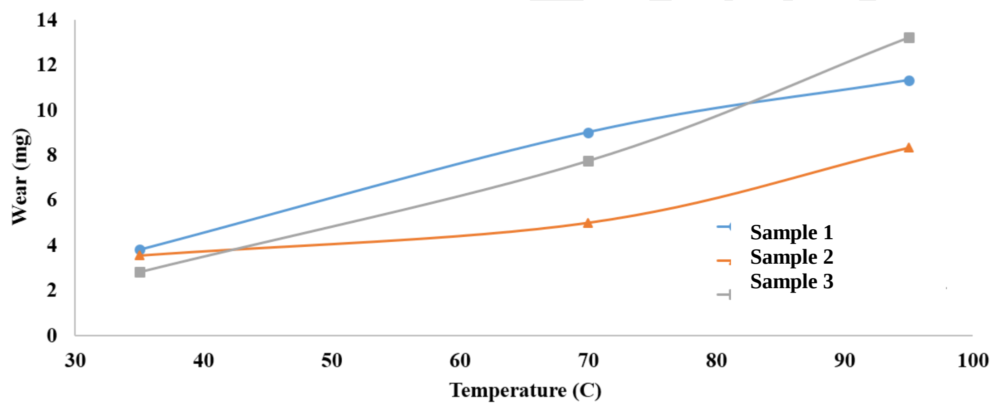
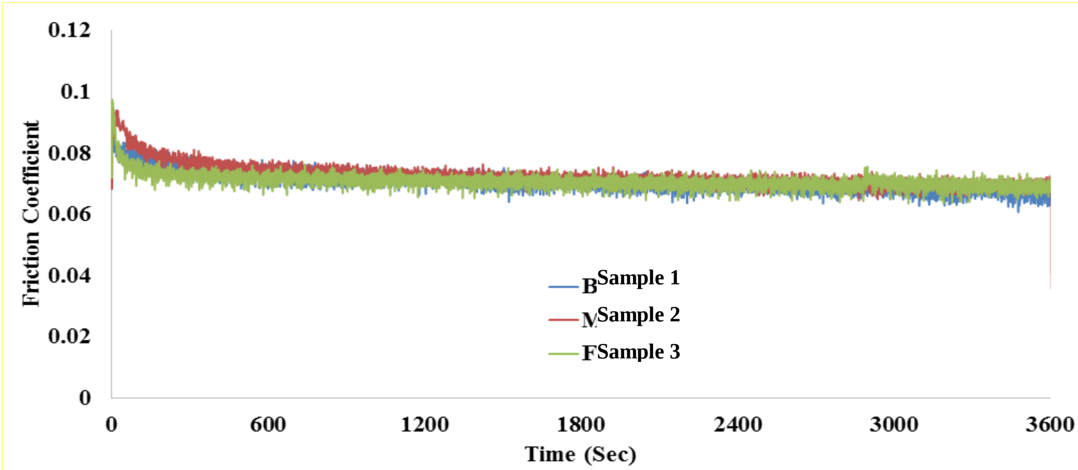


Fig. 3 Wear at different temperature

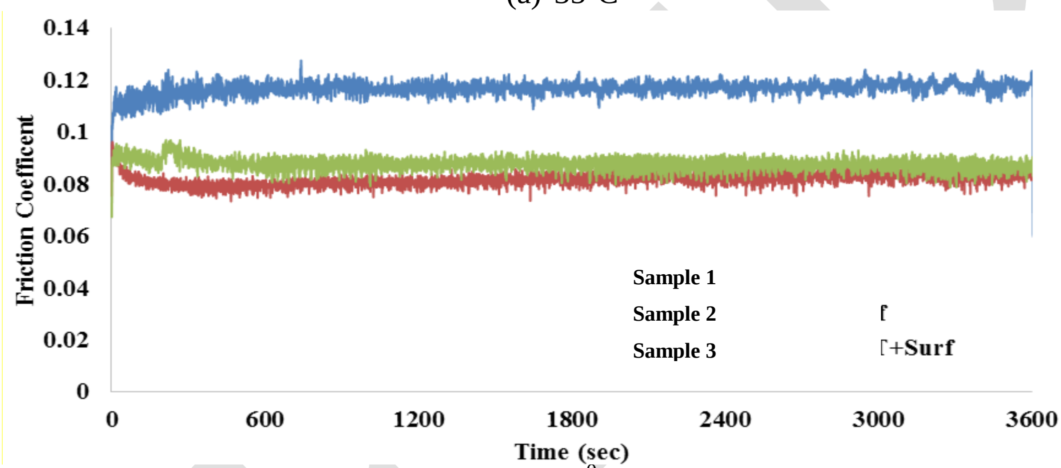
From the figure 3, following conclusions can be made:

(a) At lower temperature (35^0C) wear is the lowest. With increase in temperature, wear increases.
(b) Functionalized MWCNT show relatively lower wear rate at lower temperature while shows highest ware rate at higher temperature
(c) Lowest wear rate was observed for non-functionalized MWCNT at higher temperature.

The results of friction coefficient for base oil, functionalised and non-functionalized MWCNT at 35^0C and 95^0C temperature are plotted in figure 4(a) and 4(b) respectively. From figure 4(a) it is observed that the friction coefficient values for three samples are almost same. From figure 4(b) the samples operated at 95^0C it can be observed that the friction value for mineral oil is increasing with time while the friction coefficient of "Sample 2" and "Sample 3" lubricant with both MWCNTs were same and lesser than "Sample 1". The reason for the poor wear performance of the functionalized MWCNTs at higher temperature is due to the scattering of electrons and phonons [20] and also drop of thermal properties with increasing degree of functionalization due to the effect of sp3 defect [19].



(a) 35^0C



(b) 95^0C

Fig. 4 Frictional coefficient at 95^0C and 35^0C

CONCLUSION:

To understand the effect of functionalizing MWCNTs and importance of addition of surfactant to lubricant-MWCNTs solution, different experiments were performed for five different samples: (i) Sample 1: Mineral oil, (ii) Sample 2: Pure MWCNT with surfactant mixed in base oil using sonication, (iii) Sample 3: Functionalized MWCNT with surfactant mixed in base oil using sonication, (iv) Sample 4: Pure MWCNT mixed in base oil using sonication and (v) Sample 5: Functionalized MWCNT mixed in base oil using sonication. Viscosity of lubricant was measure using Rheometer and tribological properties wear and friction wear measured using "Block on Disc" Setup. Experiments were performed at 70^0C, for 70N and 25RPM and from experiments following conclusion were derived:

(i) Viscosity of the "Sample 1" was lowest and "Sample 4" was highest among all the five samples.
(ii) The wear of "Sample 4" was highest and "Sample 2" was lowest indicating that there is no relation of viscosity and wear in the case of nano-lubricant with MWCNTs as additives.
(iii) The frictional coefficient value is reduced by adding MWCNTs however "Sample 2" provided lowest frictional coefficient.

(iv) For nano-lubricant with MWCNTs as additives, addition of the surfactant is necessary while functionalization is not.

To understand the effect of the temperature on the functionalization of MWCNTs, the experiment was repeated for "Samples 1-3" at 35^0C and 95^0C. From the experiment following conclusion was observed:

(i) Wear of "Sample 3" (MWCNTs with functionalization) was lower at lower temperature (35^0C) while the wear of same sample is higher at higher temperature (95^0C)

(ii) The wear for "Sample 2" was lowest at higher temperature.

(iii) Friction coefficient values at lower temperature was same for all three samples while at higher temperature the frictional value was increasing for "Sample 1" and for samples and 3 the frictional coefficient values are almost constant.

References

[1] S. Iijima, Helical Microtubules of graphitic carbon. Nature 354, 56 (1991).
[2] A. Y. Cao, P. L. Dickrell, W. G. Sawyer, M. N. Ghasemi-Nejhad, P. M. Ajayan, Super-compressible foamlike carbon nanotube films. Science 310, 1307 (2005).
[3] B. Peng, M. Locascio, P. Zapol, S. Li, S.L. Mielke, G. C. Schatz, and Espinosa, H. D., Measurements of near-ultimate strength for multiwalled carbon nanotubes and irradiation induced crosslinking improvements. Nat. Nanotechnol. 3, 626 (2008).
[4] B. Q. Wei, R. Vajtai, P. M. Ajayan, Reliability and current carrying capacity of carbon nanotubes. Appl. Phys. Lett. 79, 1172 (2001).
[5] E. Pop, D. Mann, Q. Wang, K. Goodson, H. J. Dai, Thermal conductance of an individual single-wall carbon nanotube above room temperature. Nano Lett. 6, 96 (2006).
[6] De Volder, M. F., Tawfick, S. H., Baughman, R. H., & Hart, A. J. (2013). Carbon nanotubes: present and future commercial applications. Science, 339(6119), 535-539.
[7] Muzakkir, S.M., Hirani, H., Thakre, G.D., Tyagi, M.R. (2011), Tribological Failure Analysis of Journal Bearings used in Sugar Mill, Engineering Failure Analysis, 18(8), 2093-2103.
[8] S. Singhal, (2008), Sleeve bearing design for slow speed applications, Tech Conf Rec IEEE, 283–290.
[9] K.F. Dufrane, J.W. Kannel, (1983), Wear of Steam Turbine Journal Bearings at Low Operating Speeds, J. LubrTechnol, 105, 313-317.
[10] Hirani, H., Athre, K., Biswas, S. (1998), Rapid and Globally Convergent Method for Dynamically Loaded Journal Bearing Design, Proc. IMechE (UK), Journal of Engineering Tribology, vol. 212, pp. 207-214.
[11] Hirani, H., Athre, K., Biswas, S. (1999), Dynamic Analysis of Engine Bearings, International Journal of Rotating Machinery, vol. 5, no.4, pp. 283-293.
[12] Hirani, H., Athre, K., Biswas, S. (2000), A Hybrid Solution Scheme for Performance Evaluation of Crankshaft Bearings, Trans. ASME, Journal of Tribology, vol. 122, no. 4, pp. 733-740
[13] Hirani, H., Athre, K., Biswas, S. (2001), A Simplified Mass Conserving Algorithm for Journal Bearing under Dynamic Loads, International Journal of Rotating Machinery, vol. 1, pp. 41-51.
[14] Hirani, H., Athre, K., Biswas, S. (2001), Lubricant Shear Thinning Analysis of Engine Journal Bearings, STLE, Journal of Tribology Transaction, vol 44, no. 1, pp 125-131.

[15] Muzakkir, S.M., Hirani, H., Thakre, G.D., Tyagi, M.R. (2011), Tribological Failure Analysis of Journal Bearings used in Sugar Mill, Engineering Failure Analysis, vol. 18, no. 8, pp. 2093-2103.
[16] Hirani, H., Athre, K., Biswas, S.(2002), Comprehensive Design Methodology for Engine Journal Bearing, IMechE (UK), Part J, Journal of Engineering Tribology, vol 214, pp. 401-412.
[17] Hirani, H.(2004), Multi-objective Optimization of a journal bearing using the Pareto optimal concept, Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, vol. 218, no. 4, pp. 323-336.
[18] Hirani, H.(2005), Multiobjective optimization of journal bearing using mass conserving and genetic algorithms, Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, vol. 219, no. 3, pp. 235-248.
[19] Hirani, H., Suh, N. P. (2005), Journal Bearing Design using Multi-objective Genetic Algorithm and Axiomatic Design Approaches, Tribology International, vol. 38, no. 5, pp. 481-491.
[20] Hirani, H., Verma, M. (2009), Tribological study of elastomeric bearings of marine shaft system, Tribology International, vol. 42, no. 2, pp. 378-390.
[21] Muzakkir, S.M., Hirani, H., Thakre, G.D., (2013), Lubricant for Heavily-Loaded Slow Speed Journal Bearing, Tribology Transactions, vol.56, no. 6, pp. 1060-1068.
[22] Muzakkir, S.M., Lijesh, K. P., Hirani, H., Thakre, G.D. (2015) Effect of Cylindricity on the Tribological Performance of Heavily-Loaded Slow Speed Journal Bearing, Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, 2015, vol 229, no.2, pp.178-195.
[23] Rao, T. V. V. L. N., Hirani, H., Athre, K., Biswas, S.(2000), An Analytical Approach to Evaluate Dynamic Coefficients and Non-linear Transient Analysis of a Hydrodynamic Journal Bearing, STLE Tribology Transactions, vol. 23, no.1, pp. 109-115.
[24] Muzakkir, S. M., K. P. Lijesh, and Harish Hirani. (2015).Effect of Base Oil on the Anti-Wear Performance of Multi-Walled Carbon Nano-tubes (MWCNT), International Journal of Current Engineering and Technology, vol.5, no.2, pp.681-684.
[25] R. K. Burla, P. Seshu, H. Hirani, P.R. Sajanpawar, and H.S. Suresh ,(2004), Three Dimensional Finite Element Analysis of Crankshaft Torsional Vibrations using Parametric Modeling Techniques, SAE transactions, SAE 2003-01-2711.
[26] Lijesh, K. P., Hirani, H.,(2014), Stiffness and Damping Coefficients for Rubber mounted Hybrid Bearing, Lubrication Science, vol. 26, no.5, pp. 301-314.
[27] Lijesh, K. P., Hirani, H.,(2015), Development of Analytical Equations for Design and Optimization of Axially Polarized Radial Passive Magnetic Bearing, ASME, Journal of Tribology, vol. 137, no. 1, (9 pages).
[28] Lijesh, K. P., Hirani, H.,(2015), Optimization of Eight Pole Radial Active Magnetic Bearing, ASME, Journal of Tribology, vol.137, no.2.
[29] Lijesh, K. P.& Hirani, H. (2015), Design and Development of Halbach Electromagnet for Active Magnetic Bearing, Progress In Electromagnetics Research C, vol. 56, 173–181.
[30] Desai C., Hirani H. and Chawla A., (2014), Life Estimation of Hip Joint Prosthesis, Journal of the Institution of Engineers (India): Series C, 1-7. DOI: 10.1007/s40032-014-0159-4

[31] Lijesh K.P. and Harish Hirani, (2015), Probabilistic Design of Spur Gear, IJCET, Vol.5, No.2, pp. 1125-1147, E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
[32] Muzakkir, S.M., Lijesh, K. P.& Hirani, H. (2014), Tribological Failure Analysis of a Heavily-Loaded Slow Speed Hybrid Journal Bearing, Engineering Failure Analysis, vol. 40, pp.97–113.
[33] Samanta, P., Hirani, H., (2007), A Simplified Optimization Approach for Permanent Magnetic Journal Bearing, Indian Journal of Tribology.
[34] Lijesh K.P. and Harish Hirani, (2015), Magnetic Bearing Using RMD Configuration, ASME, Journal of Tribology, Accepted.
[35] Samanta, Pranab, and Harish Hirani. (2008), Magnetic bearing configurations: Theoretical and experimental studies. Magnetics, IEEE Transactions on vol. 44, no. 2, pp. 292-300.
[36] Shankar, S., Sandeep, Hirani, H. (2006), Active Magnetic Bearing, Indian Journal of Tribology, pp 15-25.
[37] Hirani, H., Samanta, P. (2007), Hybrid (Hydrodynamic + Permanent Magnetic) Journal Bearings, Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, vol. 221, no. J8, pp. 881-891.
[38] Lijesh, K. P., and Hirani, H. (2014). Design of eight pole radial active magnetic bearing using monotonicity. In Industrial and Information Systems (ICIIS), 2014 9th International Conference on IEEE, pp. 1-6.
[39] Lijesh, K. P., and Hirani, H. (2015), Modeling and Development of RMD Configuration Magnetic Bearing, Tribology in Industry.
[40] Lijesh, K. P., and Hirani, H. (2015), Modeling and Development of RMD Configuration Magnetic Bearing, Tribology in Industry.
[41] S SGoilkar and H Hirani, (2010),Parametric Study on Balance Ratio of Mechanical Face Seal in Steam Environment, Tribology International, vol. 43, no. 5-6, pp. 1180-1185.
[42] Hirani H and Goilkar S S, (2009),Formation of Transfer Layer and its Effect on Friction and Wear of Carbon-Graphite Face Seal under Dry, Water and Steam Environments, Wear, vol. 226, no. 11-12, pp.1141-1154.
[43] Goilkar S S, and Hirani H., (2009) ,Design and development of test setup for online wear monitoring of mechanical face seals using torque sensor, Tribology Transactions, vol. 52, no.1, pp. 47-58.
[44] S SGoilkar and H Hirani, (2009), Tribological Characterization of Carbon Graphite Secondary Seal Indian Journal of Tribology, vol. 4, no. 2, pp. 1-6.
[45] C Sarkar and H Hirani, Development of magnetorheological brake with slotted disc, Proc. IMechE, Part D: Journal of Automobile Engineering, DOI: 10.1177/0954407015574204.
[46] C Sarkar and H Hirani, (2013),Theoretical and experimental studies on a magnetorheological brake operating under compression plus shear mode, Smart Materials and Structures, vol.22. no.11, art. no. 115032.
[47] C Sarkar and H Hirani, (2013), Synthesis and Characterization of Antifriction Magnetorheological Fluids for Brake, Defense Science Journal, vol. 63, no.4, pp.408-412.
[48] C Sarkar and H Hirani, (2013), Design of a Squeeze Film Magnetorheological Brake Considering Compression Enhanced Shear Yield Stress of Magnetorheological Fluid, Journal of Physics: Conference Series, vol.412, no.1, 012045.

[49] V K Sukhwani and H Hirani, (2008),A Comparative Study of Magnetorheological-Fluid-Brake and Magnetorheological-Grease-Brake, Tribology Online, vol 3, no.1, pp. 31-35.
[50] V K Sukhwani, and H Hirani, (2008),Design, Development and Performance Evaluation of High Speed MR Brake, Proc. Institute Mech. Engineers.,Part L, Journal of Materials: Design and Applications, vol. 222, no.1, pp. 73-82.
[51] H Hirani, and C S Manjunatha, (2007),Performance Evaluation of Magnetorheological Fluid Variable Valve, Proc. of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering, vol. 221, no.1, pp. 83-93.
[52] H. Shah and H Hirani, (2014),Online Condition Monitoring of Spur Gear, International Journal of Condition Monitoring, vol 4, no. 1, pp.15-22.
[53] H Hirani, (2009), Online Wear Monitoring of Spur Gear Indian Journal of Tribology, vol 4, no.2, pp.38-43.
[54] M.A. Omer, T. V. V. L. N. Rao, A. M. A.Rani, T. Nagarajan, and F.M. Hashim, (2014), Pressure Distribution in Hydrodynamic Journal Bearing with Lubricants Additives, In MATEC Web of Conferences, 13, 05006-050012
[55] A. K. Kohli and B. Prakash, (2001), Contact Pressure Dependency in Frictional Behaviour of Burnished Molybdenum disulphide coatings, Tribol Trans, 44, 147–151.
[56] Y. R. Jeng, Y. H. Huang, P.C. Tsai and G.L. Hwang, (2014). Tribological Properties of Carbon Nanocapsule Particles as Lubricant Additive. Journal of tribology, 136(4), 0418011-0418019.
[57] Peng, Yitian, and Zhonghua Ni. (2013), Tribological properties of stearic acid modified multi-walled carbon nanotubes in water." Journal of Tribology 135.1: 012001.
[58] Cumings, John, and A. Zettl. (2000) Low-friction nanoscale linear bearing realized from multiwall carbon nanotubes, Science 289.5479: 602-604.
[59] C. S. Chen, X. H.Chen, L. S. Xu, , Z. Yang, and W.H. Li, (2005). Modification of multi-walled carbon nanotubes with fatty acid and their tribological properties as lubricant additive. Carbon, 43(8), 1660-1666.
[60] C.S. Chen, X.S. Chen, HU Jing, H. Zhang, W.H. Li, L.S. Xu, and Z. Yang, Effect of multi walled carbon nanotubes on tribological property of lubricant, Trans Nonferrous met. Soc. China, Vol. 15, No. 2, 300-305,2005
[61] Ajay Garg, Susan B. Sinnott, (1998), Effect of chemical functionalization on the mechanical properties of carbon nanotubes, Chemical Physics Letters, 295(4), 16, 273-278,
[62] Shenogin S, Bodapati A, Xue L, Ozisik R, Keblinski P. Effect of chemical functionalization on thermal transport of carbon nanotube composites. ApplPhysLett 2004;85:2229–2231.
[63] Liu CH, Fan SS. Effects of chemicalmodifications on the thermal conductivity of carbon nanotube composites. ApplPhysLett 2005;86, 123106/1–3.
[64] S M Muzakkir, K P Lijesh, H Hirani, and G D Thakre, "Effect of Cylindricity on the Tribological Performance of Heavily-Loaded Slow Speed Journal Bearing", Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, 2015, Vol 229(2), pp.178-195.