OPEN ACCESS

International
Journal
Of Modern Engineering Research (IJMER)

Effect of Molybdenum Disulphide on Physical Properties of Neodymium-Iron-Boron Bonded Magnet

Lijesh K.P.[1], Harish Hirani[2], Samanta P.[3]
[1] (Mechanical Department, Indian Institute Technology Delhi, India
[2] (Mechanical Department, Indian Institute Technology Delhi, India
[3] (Surface Engineering and Tribology, CMERI Durgapur, India

ABSTRACT: *The present paper reports the effect of molybdenum disulfide (MoS_2) on magnetic and mechanical properties of neodymium iron boron (NdFeB) bonded magnet. Powder metallurgy process has been used to prepare the test samples containing 0.0, 0.5, 1, 1.5 and 2 percentage of MoS_2. Compact and hardness tests have been performed to measure the physical properties of samples. Saturation magnetization, remanence and intrinsic coercivity have been checked using vibrating sample measurement (VSM) test*

Keywords: *Neodymium iron boron, Molybdenum disulfide, Magnetic Property, Mechanical property*

I. INTRODUCTION

Bearings can be classified into three categories: (i) Rolling bearing, (ii) Fluid film bearing and (iii) Magnetic bearing. The rolling bearings are known for their efficient performance particularly at high load and low speed conditions. The major disadvantages of such bearings are: (i) Inability to handle misalignment [1, 2], (ii) Requirement of regular maintenance and (iii) Performance sensitivity towards dusty environment. Fluid film bearing provides low friction and wear [3] by limiting the metal to metal contact. A well designed fluid film bearing can tolerate some misalignment, fluctuation in speed/load/moisture and unexpected dirt. Such bearings provide high damping [4, 5] due to liquid lubricants. However on increasing load and/or reducing the relative speed decreases the thickness of fluid film and increases the chances of bearing wear. In other words, the performance of fluid film bearing decreases drastically at "low speed [6] and high load [7,8]" conditions.

Magnetic bearings provide frictionless and zero wear operations, due to which their applications in industries is increasing. Magnetic bearings can be classified into (i) Active magnetic bearing and (ii) Passive magnetic bearing. Active magnetic bearings [9, 10] support the rotor using magnetic flux produced by current carrying wire wound around the stator core and provide complete separation between rotor and bearing metals. A major drawback of these AMBs is the essential requirement of closed feedback control system to locate the position of rotor ([11]), which means high initial as well as running costs [8, 12] of these bearings. High running cost is due to: high bias current, hysteresis, eddy-current particularly at high speed and windage losses. In addition AMBs require supplementary set of bearings (i.e. rolling element bearings) to support the rotor when AMB fails, so that the rotor does not hit the AMB surface and damage the working of whole system. Alternatively a lesser costly magnetic bearing [13,14], termed as "passive magnetic bearing" as it does not require any control system, which relies on the repulsion between two permanent magnets (stator and rotor) to levitate the rotor from stator can be employed as frictionless bearings. Low load carrying capacity [15], is one of the drawback of permanent magnet bearings, which can be enhanced by using high power rare earth magnets. However, the neodymium magnetic materials are highly brittle [16, 17] and are highly porous in nature. Porosity of magnet inherently comes from powder metallurgy processes [18]. These porosities aggravate the strength of the magnets and restrict their usage in magneto-hydrodynamic bearings [14-16], high rpm and low clearance electric motors, and structural elements. Any improvident use of the magnets in such precarious conditions may cause the breakage of magnets. Therefore, it is important to enhance the mechanical strength of magnets.

Improvements in bending, fracture, and uniaxial tensile strengths of NdFeB using sintering process, have been reported [19]. Rowlinson et al [20] reported the enhancement of fracture strength of bonded magnets made by rotary-forging using melt-spun ribbon material. They tried mixing of soft metal such as Al, Zn, Sn, and Cu. They concluded Al-bonded magnet exhibit high mechanical strength. But that mechanical improvement had been achieved at the loss of magnetic properties. Garell et al [21] studied the mechanical properties of PPS bonded and Nylon bonded magnets. They could increase the ultimate strength by decreasing volume fraction of NdFeB powder. As per Li et al. [22], maximum energy product $(BH)_{max}$ can be expressed by,

$$(BH)_{max} = \left[(1 - V_{non}) \frac{d}{d_m} B_r(p) \right] \qquad (1)$$

Where V_{non} is the volume fraction of non-magnetic phase; dm is the theoretical density of ideal bonded NdFeB magnet; Br(p) is remanence magnetization of the powders. As per Eq. (1) magnetic properties can be increased by increasing the density of magnet. In other words decreasing porosity will enhance the magnetic properties.

The present research aims to improve the mechanical properties (i.e. compression strength, density and hardness) of epoxy bonded NdFeB magnets without reducing the magnetic properties of magnet so that application of magnetic material in different application can be increased. In authors' views solid lubricant MoS_2 may increase the flow ability of magnetic particles during compaction and reduces the porosities by filling up the spaces between NdFeB particles. Easy sliding due to MoS_2 will enhance the toughness of magnet. Therefore, molybdenum disulphide (MoS_2), is explored to improve compression strength, density and compression strain of NdFeB magnets.

II. EXPERIMENTAL PROCEDURE

Readily available NdFeB magnetic powder, having $(BH)_{max}$ 8.96 MGoe and particles sizes ranging from 80 micrometers to 300 micrometers, was used to make the bonded magnets. For each sample 3 gm of NdFeB powder was used. For preparing samples 0.0, 15.0, 30.0, 45.0 and 60.0 milligrams of Molybdenum Disulphide (MoS_2) was added. Loctite 210213 Hysol, equal to forty percent volume of NdFeB+MoS_2, was selected as a binding agent.

Samples Preparation

1. Mix NdFeB and MoS2 powders.
2. Liquefy binding agent by diluting it in acetone.
3. Mix powder in liquid binding agent.
4. Daub die and punch with zinc stearate.
5. Use hydraulic press (50 tons) to compact the powder.
6. Cure green compact sample at a temperature of 120^oC for 30 minutes in argon gas atmosphere.

Magnetic Properties Measurement

To check the effect of MoS_2 on magnetic properties, VSM (Model-6500 made by Quantum Design) test was done on all the five samples. The field of 9 Tesla was applied at room temperature to get the magnetic properties like saturation magnetization (M_s), remanence magnetization (M_r), and coercivity. To get these parameters, the first and second quadrant of M-H loop was used due to its symmetrical nature in shape as shown in Fig.1.

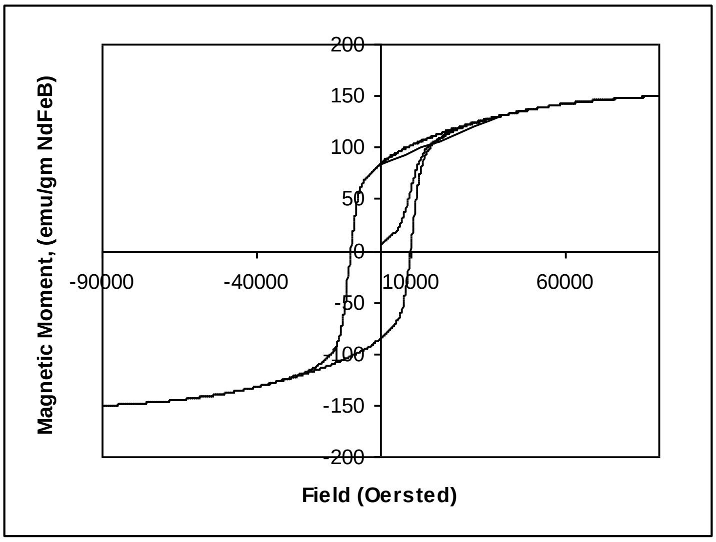

Fig. 1 Complete M-H plot of a NdFeB sample

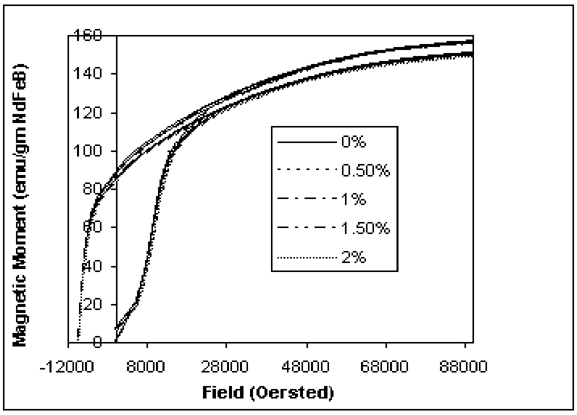

Fig. 2. M-H Plot

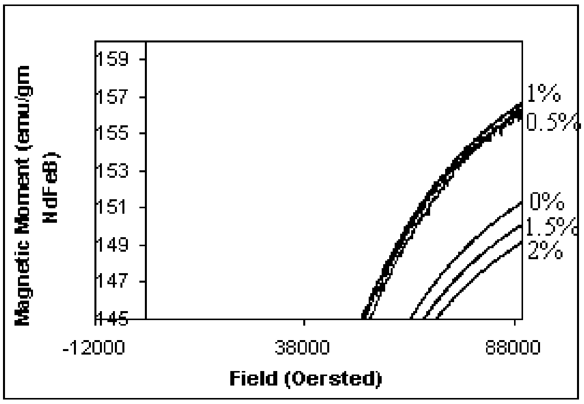

Fig.3. Zooming of saturation magnetization portion of M-H plot

The results have been shown in Figs. 2 and 3. The Fig.3 shows the zoom out portion of saturation magnetization of different samples. The values M_s, M_r and H_{ci} are listed in the Table-1. From the Table-1 and Figs. 2-3, it is seen that the values of M_s and M_r increase with increasing of MoS_2 percentage from zero to one percentage. From 0% to 0.5 % the value of M_s is increased by 3.3% and from 0.5% to 1% the further increment is 0.64%. Again, the increment of M_r due to increasing of MoS_2 from 0% to 0.5 % is 2.68% and M_r further increases to 1.88% due to increase of MoS_2 from 0.5% to 1%. After that, both the value of M_s and M_r decrease with further increase of MoS_2. The coercivity remains same at the value of 9.71 kOe.

Table-1 Magnetic Properties of NdFeB Bonded Magnet

% of MoS_2	M_s (emu/gm NdFeB)	M_r (emu/gm NdFeB)	H_{ci} (kOe)
0	151.33	84.97	9.71
0.5	156.34	87.25	9.71
1	156.70	88.89	9.71
1.5	150.13	84.69	9.71
2	149.17	83.86	9.71

The cause of increment in Ms value is due to lubrication properties of MoS_2. In un-magnetization state random placement of magnet domains provides zero magnetic field. However, on the application of field, magnetic moments in domains are aligned with direction of applied field by domain rotation and domain wall motion [23]. With addition of MoS_2 friction between particles decrease and easy particle alignment in the directions of magnetic field occurs. When the amount of lubricant increases beyond certain limit (as experiment results shows above 1% of the magnetic powder), the magnetostatic energy of the inclusion is high and form the spike domain to reduce its energy.

The remanence (Mr) increases due to the effect of increasing the density of magnet rather than the diminishing effect of increasing the non-magnetic phase at the initial stage of increment of MoS_2. As the amount of lubricant increases above 1%, remanence decreases due to increasing the non-magnetic secondary phase [21]. The value of coercivity remains same, as it does not change much when the magnetic powder is incorporated into an organic matrix [24].

From above results, it is clear that usage of MoS_2 greater than 1% is detrimental on the magnetic properties. Since the target of the authors is to enhance the mechanical properties without affecting the magnetic properties, therefore for mechanical (density, compression strength and hardness) tests, only three samples with 0%, 0.5% and 1.0% MoS_2 were considered.

Mechanical Properties Measurements

Green density of each sample was checked after compaction. Vicker Test machine (Maker: Future Tech, Model-FV700) was used to measure the hardness of sample. Ultimate compression strength (UCS) was measured using 50 kN UTM machine (Maker: LLOYD Instrument, UK).

Density Measurement

The density of each sample was calculated by weighing the sample after compaction and measuring the height of sample after compaction made in die. The density values have been listed in the Table-2.

Compression Strength Test

The compression strength test has been performed according to ASTM (American Society of Test Methods) standards E9-89a [24]. According to the ASTM standard, the size of short specimen for cylindrical sample is taken as 0.8 lengths to diameter ratio. The tests have been conducted in a 50 kN UTM machine (Maker: LLOYD Instrument, UK). The crosshead speed was controlled at a speed of 1 mm/min with an accuracy of 0.2%@ 100 mm/min. Data was collected from load cell to PC through NI (National Instrument) DAQ card 57600 BAUD, 8 Bit, no party, 1 stop bit. Load was applied until the breakage of the sample. The load Vs. Displacement plot has been depicted at Fig. 4. The values of compression strength are listed in the Table 2. The compression strain, which is defined by change of length per unit length of the specimen before fracture, has also been tabulated.

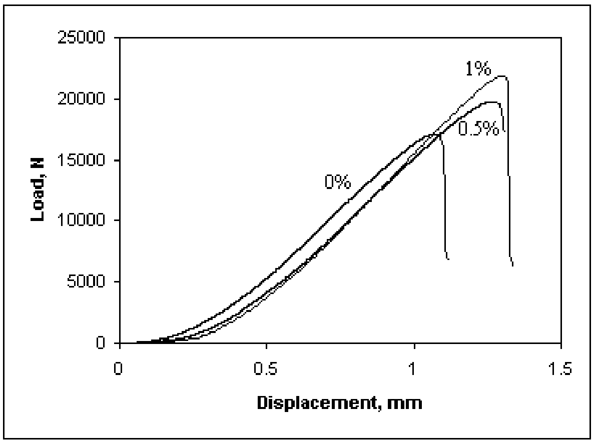

Fig 4. Compression Load vs. Displacement Curve

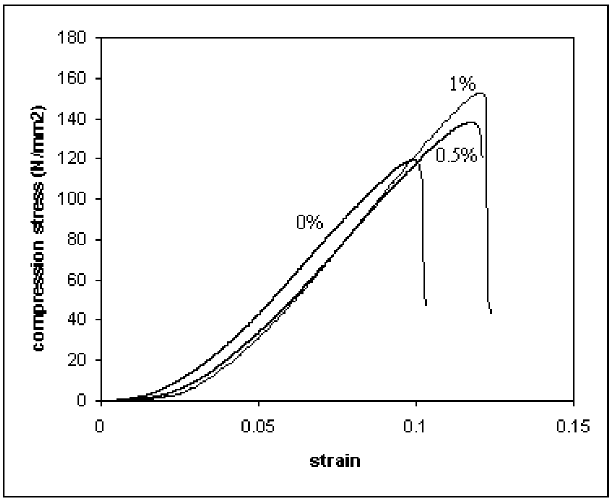

Fig 5 Compressive Stress vs. Strain

Table-2 Mechanical Properties

Sample Properties	0% MoS2	0.5% MoS_2	1% MoS_2
Green Density, g/cc	5.83	6.17	6.25
Compression Strength (N/mm^2)	119.39	137.92	152.58
Compression Strain	0.099	0.12	0.117
Hardness (HV)	88	87	85

Vickers Hardness Test

Vickers hardness test was conducted according to the ASTM standards E92-82[25]. Load of 5 kg was applied to avoid the load dependency of hardness [25]. First, the surface of the sample was polished with emery paper of grade 1000 and then polished by cloth with alumina solution to have mirror finish. After that, surface was cleaned with acetone and dried. Tests were performed done on Vickers Hardness Tester (model FV700). The hardness values of different samples are provided in the Table-2. The Vickers hardness values show that the hardness decreases with increasing the MoS_2 percentages.

III. RESULTS AND DISCUSSION

From the Table-2, it is seen that the green density of the samples is increased with increasing the MoS_2. Addition of the MoS_2 increases the flow ability of magnetic particles during compacting and reduces the friction between particles [26]. It also reduces the porosities by filling up the spaces between comparatively bigger sizes particles of NdFeB magnetic powder.

Figure 4 shows compressive load versus displacement curve and Fig 5 is the stress-strain version of the same curve. It is seen from both the plots that with increase in the percentage of MoS_2 ductility of NdFeB increases, the crushing of the material occurs at higher load. From individual quantitative assessment of each curve it is seen that the compression strength has increased by 15.52% due to adding 0.5% MoS_2 with the magnetic powder. Increase in the compression strength reaches to about 27.8% due to 1% increment of MoS_2. The high compression strength may be due to the lower porosities and high density in the MoS_2 mixed samples [26].

The strength of the magnetic material against brittle and shear fracture may be described by two characteristics, the resistance to separation and the resistance to sliding [27]. In compression test, there is a lateral expansion of the material due to compression load. From Fig. 5, it is indicated that the sample with higher MoS_2 contained slide more laterally than the sample with lower MoS_2 before failure. It is seen that strain value has increased 18.18% due to addition of 0.5% lubricant and the value increases up to 21.21% on 1% addition of MoS_2. Therefore one can concludes that the resistance to sliding of the sample with higher MoS_2 contained is lower than the resistance to separation (i.e. overcoming the cohesive force of particles). This reduction in the resistance to sliding reduces the brittleness of magnetic materials.

IV. CONCLUSIONS

The trend of increasing the values of properties of NdFeB magnets reveals the favorable effects of MoS_2 on NdFeB bonded magnet. Addition of MoS_2 up to 1% increases the saturation magnetic moment and remanence value. Beyond 1%, it diminishes the magnetic properties. On the other hand, mechanical properties like density and compression strength increase. The hardness value decreases.

Acknowledgement

This research was supported by Council of Scientific and Industrial Research, New Delhi, India, Grant No. 70(0073)/2013/EMR-II.

REFERENCES

[1]. O. Wouter, P.D. Baets, and W.D. Waele, Failure of a large ball bearing of a dockside crane, *Engineering Failure Analysis, 11(3)*, 2004, 335-353

[2]. H. Hirani H, Root cause failure analysis of outer ring fracture of four row cylindrical roller bearing, *Tribology Transactions, 52(2)*, 2009, 180-190.

[3]. H. Hirani, Multiobjective Optimization of a journal bearing using the Pareto optimal concept, *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, 218(4)*, 2004, 323-336

[4]. H. Hirani, and N.P. Suh, Journal bearing design using multiobjective genetic algorithm and axiomatic design approaches, *Tribol Int,38*, 2005, 481–491.

[5]. H. Hirani, K. Athre and S. Biswas, Lubricant Shear Thinning Analysis of Engine Journal Bearings, *STLE, Journal of Tribology Transaction, 44 (1)*, 2001, 125-131

[6]. S.M. Muzzakir, 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, Vol 229(2)*, 2015, 178-195.

[7]. S.M. Muzakkir, H. Hirani, G.D. Thakre and M.R. Tyagi, Tribological Failure Analysis of Journal Bearings used in Sugar Mill, *Engineering Failure Analysis, 18(8)*, 2011, 2093-2103

[8]. H. Hirani and M. Verma, Tribological study of elastomeric bearings of marine shaft system, *Tribology International, 42 (2)*, 2009, 378-390.

[9]. S. Shankar, Sandeep and H. Hirani, Active Magnetic Bearing, *Indian Journal of Tribology,1*, 2006, pp 15-25.

[10]. K.P. Lijesh, and H. Hirani, Optimization of Eight Pole Radial Active Magnetic Bearing, *ASME, Journal of Tribology, 137(2)*, 2015, (7 pages).

[11]. N.C. Tsai, and C.W. Chiang, Spindle position regulation for wind power generators, *Mech. Syst. Sig. Process, 24*, 2010, 873–889.

[12]. B. Padden, N. Groom, and J. F. Antaki, Design formula for permanent magnet bearings, *J. Mech. Des., 125*, 2003, 734–738.

[13]. K.P. Lijesh, and H. Hirani, Development of Analytical Equations for Design and Optimization of Axially Polarized Radial Passive Magnetic Bearing, *ASME, Journal of Tribology, 137(1)*, 2015, (9 pages).

[14]. P. Samanta and H. Hirani, Magnetic Bearing Configurations: Theoretical and Experimental Studies, *IEEE Transactions on Magnetics, 44 (2)*, 2008, pp. 292-300.

[15]. H Hirani, and P Samanta, Hybrid (Hydrodynamic + Permanent Magnetic) Journal Bearings, *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, 221(8)*, 2007, pp. 881-891.

[16]. K.P. Lijesh and H. Hirani, Stiffness and Damping Coefficients for Rubber mounted Hybrid Bearing, *Lubrication Science, 26(5)*, 2014, 301-314.

[17]. S.M. Muzzakir, K.P. Lijesh and H. Hirani, Tribological Failure Analysis of a Heavily-Loaded Slow Speed Hybrid Journal Bearing, *Engineering Failure Analysis, 40*, 2014, 97–113.

[18]. A. Lawley, and T. F. Murphy, Metallography of powder metallurgy materials, *Materials Characterization, 51(5)*, 2003, 315-327.

[19]. J.A. Horton, J.L. Wright, and J.W. Herchenroeder, Fracture toughness of commercial magnets, *Magnetics, IEEE Transactions on, 32(5)*, 1996, 4374,4376.

[20]. N. Rowlinson, M.M. Ashraf and I.R. harris, New developments in bonded Nd-Fe-B magnets, *J.Magn.Mater, 80*, 1989, 93-96.

[21]. M.G. Garrell, B.M. Ma, A.J. Shih, E.L. Curzio, R.O. Scattergood, Mechanical properties of polyphenylene-sulfide (PPS) bonded Nd–Fe–B permanent magnets, *Materials Science and Engineering: A, 359(1–2)*, 2003, 375-383.

[22]. J.Li, Y. Liu, S.J. Gao, M.Li, Y.Q Wang, M.J.Tu, Effect of process on the magnetic properties of bonded NdFeB magnet, *J.Magn.Mater, 299*, 2000, 195-204.

[23]. P. Samanta and H. Hirani, Magnetic Bearing Configurations: Theoretical and Experimental Studies, *IEEE Transactions on Magnetics, 44 (2)*, 2008, 292-300

[24]. ASTM Standard E 9-89a, *03-01*.

[25]. ASTM Standard E92-82, *03-01*.

[26]. L.-P. Lefebvre, Y. Thomas, B.Whaite, Effects of lubricants and compacting pressure on the processability and properties of aluminum P/M parts, *J.Light metals 2*, 2002, 239-246.

[27]. S.P. Timoshenko, D.H.Young, Elements of strength of material, *5th edition East-West Press Pvt. Ltd*, 1968.