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REVIEW PAPER

Advanced Magnetostrictive Materials for Sonar Applications

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ABSTRACT

Piezoelectric or magnetostrictive materials can be utilised as active materials for electro-acoustic underwater transducers. Piezoceramic materials gained edge over the conventional magnetostrictive materials during 1940s due to their unique electro-acoustic properties. At present, inspite of passive sonars there is a need of low-frequency high-power active sonars for the Navy. This led to research for new active materials with competing characteristics to that of the existing piezo transducers. The discovery of a giant magnetostrictive material, commercially known as Terfenol-D, led to a breakthrough in the development of a new generation of sonar transducers. Now, the materials (including composites) as well as sensors are commercially available. A new generation of transducers have emerged in ocean-related areas like acoustic tomography, long-range underwater communication, geophysical exploration, oil well exploration, etc.

Indian Institute of Technology Madras, Chennai, has also developed the basic material technology a few years back. At present, in India, National Institute of Ocean Technology, Chennai, is developing underwater transducers utilising giant magnetostrictive materials as well as piezoelectric materials for marine applications like sub-bottom profiling (seafloor mapping) and long-range underwater communications. A prototype of a portable, low-frequency medium power transmitter operating over a wide-frequency range has been developed. The main advantage of this transducer is its simplicity in design. In this paper, the recent developments in material processes, importance of device-oriented material characterisation, and transducer design aspects have been emphasised. Some results on the underwater performance of a wide-band transducer have also been presented. These materials also have ultrasonic applications, capable of revolutionising the processing industry.

Keywords: New sonar materials, magnetostrictive sonars, Terfenol-D sensors, actuators, magnetostrictive materials, piezoelectric materials, sonar transducers, acoustic transducer, PZTs, underwater transducers

1. INTRODUCTION

The giant magnetostrictive materials based on $Tb_x Dy_{1-x} Fe_2$ compound, which belong to the cubic laves phase, have attracted much attention due to its exceptionally good material properties as a transducer material suitable for various applications. The research for making a material with optimised characteristics[1,2] started in 1970. Though the composition of the compound $Tb_{0.27} Dy_{0.73} Fe_2$ was already discovered by that time, yet the reports from various research groups could not show identical results. This was an anisotropy-compensated composition near room temperature making the use of negative magneto-crystalline anisotropy of terbium (*Tb*) and positive anisotropy of dysprosium (*Dy*). Since the cost of

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the raw material was very high, the next attempt by all the groups working worldwide on these materials was to obtain the optimum characteristics by the substitution of other rare earth materials as well as transition metals. One of the drawbacks of the original alloy was its brittleness. The material characteristics were also based on the method of preparation. Another major problem was to retain the properties using low-grade starting materials and reliability in bulk production for commercial use.

At the international level, several countries have already started commercial production[3] and several potential applications have been advanced. Dhilsha[1] and Rama Rao at IIT, Madras, Chennai were associated with the indigenous technology development of this material. The addition of cobalt, vanadium, titanium as well as manganese in place of iron has a profound effect on the mechanical, magnetic, magnetostrictive, and the electrical properties of the basic composition. A brief review of the work carried out in the material development, device-oriented characterisation aspects as well as the transducer development based on these materials has been presented.

2. MATERIAL TECHNOLOGY

2.1 International Scenario

Though the main criterion was to obtain an anisotropy-compensated composition near the room temperature in these compounds, it was found that the method of preparation affects the material characteristics. It was analysed that the material composition should vary from one application to another. The tailor-made compositions and device-oriented characterisation were essential for obtaining the unique properties of this so-called smart material. The magnetostriction in this material was found to be anisotropic in nature, and thus, some sort of directional solidification was essential to obtain the maximum magnetostrictive properties.

The maximum strain was measured along the <111> oriented crystals along the growth direction. But normally, the grain-oriented crystals were grown along the <112> direction, which is the crystallographic direction near the room temperature. Hence, the major variation in the material characteristics, as explained and reported by various research groups all over the world was due to the relative orientation of this crystallographic direction in polycrystalline samples wrt the measurement of magnetostriction. The variation in the magnetostrictive properties without the application of pressure, as a function of the rate of cooling used in the directional solidification, is shown in Fig. 1. The methodology procedure adopted for the material preparation[2] is shown in the flow chart (Fig. 2). The material composition was varied from $Tb_{0.27\text{-}0.5}Dy_{0.73\text{-}0.5}\ Fe_{1\text{-}x}Z_x$.

It has been established that the automated material processing is essential for the manufacture of the material in bulk quantities for ensuring reliability and quality assurance. Internationally, these materials are available in various sizes and shapes like discs, annular rings, tubes, rods, size varying from 1-70 mm diameter and a length of 10-250 mm, depending on the type of application. To synthesise materials in different shapes and sizes, powder metallurgy techniques have also been successfully developed in the recent years, especially in Japan. A comparison of the material properties of Terfenol-D with that of other active materials, is given in Table 1.

The static magnetostriction value of ~2000 x 10^{-6} is the largest value known to date for any material. This value is attainable only when the material is subjected to an applied pre-stress along the direction of measurement. The magnetostriction

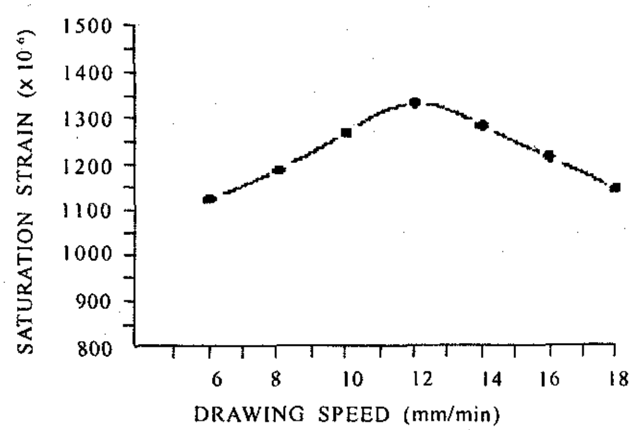

Figure 1. Variation in magnetostriction values versus rate of cooling.

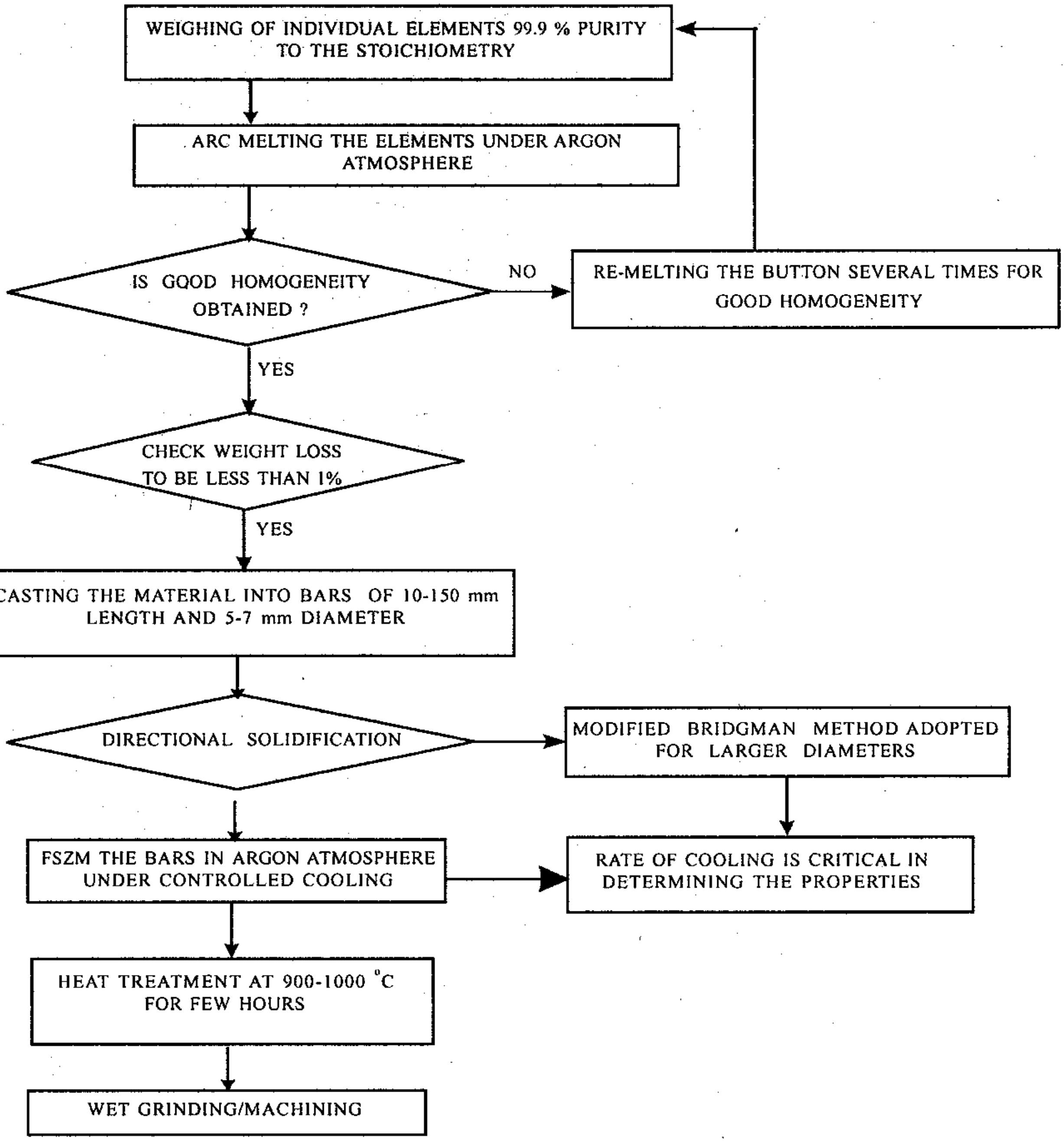

Figure 2. Flow chart for material preparation

values reach a maximum under the application of an optimum pre-stress as well as an optimum dc magnetic field[4]. However, higher dynamic strain values have been reported for the same material under device-oriented measurement conditions. The addition of cobalt or vanadium has found to increase the Curie temperature to about 50 °C for smaller additions of cobalt or vanadium. The strength of the material is also significantly improved by the careful addition of these elements.

The higher strain capability and very low-sound velocity of this material, compared to that of the existing piezoelectric material, PZT, allows a transducer designer to realise the dream of low-frequency high-power sonar transducers with a

Table 1. Comparison of properties of Terfenol-D with other active materials

Property	Terfenol-D	PZT
Saturation strain (x 10^{-6})	1500-2000	100
Coupling coefficient	0.7-0.8	0.65
Density (kg/m^3)	9100-9250	7600
Sound velocity (m/s)	1395-2444	3500
Energy density (J/m^3)	5000-25000	670
Frequency range	dc to kHz	kHz- MHz
T_c (°C)	357	300-370

considerable reduction in size and a higher figure of merit. The larger energy density makes the possibility of generating larger forces with an unimaginable control. The fast response time (< 3 ms) of this material makes it attractive for its use as a hydraulic valve and for micro-control applications. In addition to all these benefits, the reliability of this material has been established even after several trillion cycles of operation.

2.2 National Scenario

The Magnetism and Magnetic Materials Laboratory of the Indian Institute of Technology (IIT) Madras, Chennai, has indigenously developed the basic material technology, on a laboratory scale, in the form of small rods of ~6-8 mm diameter and 50-60 mm length. Instead of free stand free zone melting, a contained zone-melting technique has been developed[2,3]. Costwise, this works out to be cheaper, but there exists a limit in the realisation of larger and longer diameter rods with consistent material properties. This was found to be mainly due to the reaction of the container material (quartz tubes) with that of the rare earth material. The zone-melting cooling rates have been optimised with a particular composition of the compound. The effect of cobalt substitution on the basic compound has also been studied extensively using magnetic, magneto-mechanical, and electrical studies. Typical optical micrographs of the arc-cast material as well as that of a directionally-solidified, cobalt-substituted material are shown in Figs 3 and 4. A better orientation has been achieved for other cobalt compositions. The microhardness of the material also found to increase with the addition of cobalt. The typical microhardness of these compounds is ~780 (Vicker's hardness). The grain sizes were larger and typically of the order of 50 μ. It has also been reported that the magnetostrictive and magneto-mechanical properties enhance when the materials were annealed in the presence of an applied magnetic field. Attempts were also made to prepare these material by the unidirectional solidification method in the presence of an applied magnetic field.

3. DEVICE-ORIENTED CHARACTERISATION OF MATERIALS

It has been found that the performance characteristics of the material improves by the application of pre-stress under optimum dc bias conditions. It is essential to have a dc bias applied along the direction of expansion of the material for achieving a linear operation. A pre stress application (mechanical bias) is also required since the material is basically brittle in nature. The enhancement in strain as well as in the coupling factor by the application of an optimum stress is due to mismatch of about a few degrees in the alignment of the highly magnetostrictive <112> oriented crystals wrt the direction of application of the field[2,4]. A rotation of the domains as well as the crystallographic axes is possible in the twinned crystals. So, the method of preparation of high quality material depends not only on the composition but also on the metallurgical

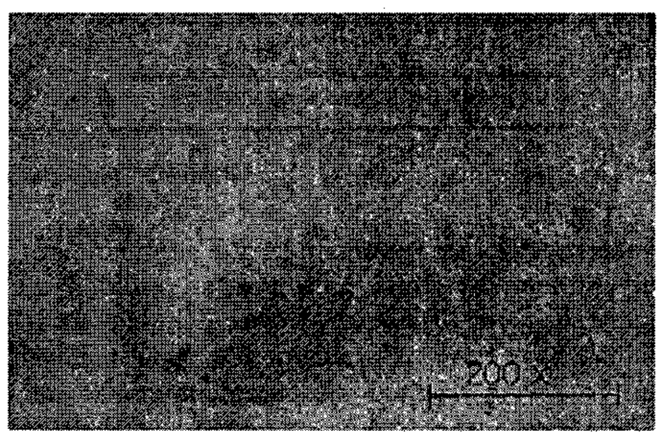

Figure 3. Optical micrograph of arc-cast annealed $Tb_{0.3}Dy_{0.7}Fe_{1.93}$.

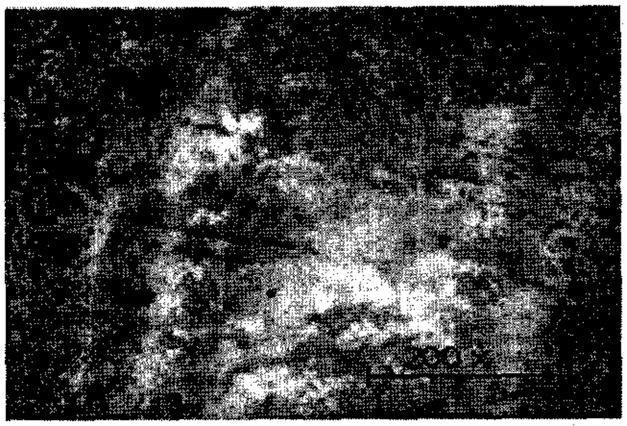

Figure 4. Optical micrograph of directionally solidified annealed $Tb_{0.27}Dy_{0.73}Fe_{0.8}Co_{1.2}$.

aspects like the formation of additional phases other than RFe_2 phases, during the manufacture. The formation of needle like structures in the metallographic studies confirmed the presence of such phases which affect the material quality. It was also found that the addition of cobalt in smaller quantities gives rise to a better phase formation in addition to an enhancement in the Curie temperature. The strain as well as other magneto-mechanical properties need an optimum applied stress along with the application of an optimum applied dc bias. There are two ways of providing dc bias. One way is to provide bias by two coils separately for dc as well as for ac excitation currents. Another way is to use a single coil with a dc-ac isolation circuit[5,6]. An alternate method is to provide the magnetic dc bias via permanent magnets. But the latter method needs extreme care while designing, since any leakage in the flux may result in a low-magnetic closed-circuit situation. When this happens, there is a possibility of the material being subjected to nonlinear stress over its length, which causes breakage of the active materials under high-power drive levels. Extreme care is essential in this aspect while designing the devices without the availability of material data under stressed conditions. Techniques for the material characterisation for such applications have also been developed.

4. DEVICE DEVELOPMENT/APPLICATION

The technology demonstration of a transducer working around 3 kHz has also been carried out using these materials[5]. The underwater performance studies showed encouraging results. At present, National Institute of Ocean Technology (NIOT), Chennai, is engaged in the development of underwater transducers for oceanographic applications, such as sub-bottom profiling and long-range underwater communication utilising Terfenol-D as well as PZT-based materials. A portable medium power, low-frequency transducer, working over a wide-frequency range as well as a liquid-level sensor has also been developed. The fundamental design of the transducer has been described by Dhilsha[5], *et al.* In the present design, the dc magnetic bias is applied through two *NdFeB* permanent magnets of diameter 25 mm and thickness 20 mm at the two ends of the Terfenol-D rod. A single Terfenol-D rod was used in this case and was obtained from the Etrema Inc, USA. It was 100 mm long and 12 mm in diameter. The mechanical bias was provided by three 4 mm diameter rods of *Be-Cu* utilising Belleville washers. The head-mass to tail mass ratio was approx. 1:2 and the diameter of the head mass was 136 mm and was made of aluminum. The tail mass was made of mild steel and a magnetic closed circuit was provided by high permeability sheets used in the transformer cores. A typical transmitting voltage response of the prototype transducer developed by NIOT is shown in Fig. 5. A maximum transmitting voltage response of 133 dBre1 μPa/V@1m has been measured at 1.13 kHz. The transmitting voltage response could be increased to 146 dBre1μPa/V@1m by

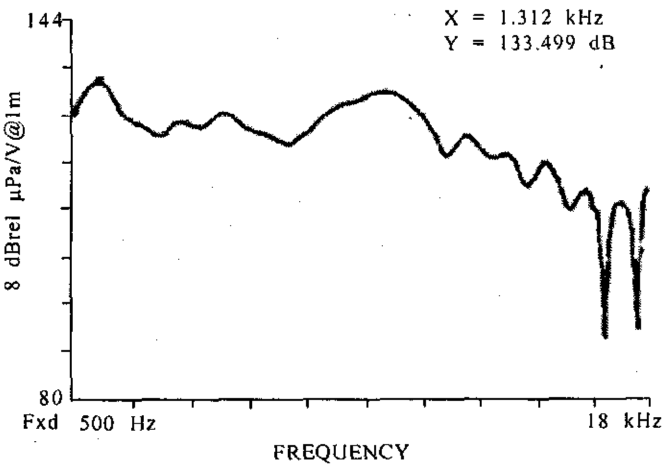

Figure 5. Transmitting voltage response of the transducer

current response of 180 dBre1μPa/1A@1m has been measured. The transducer is operable over a wide-frequency range of 1-12 kHz. At 6.5 kHz, a source level of 194 dBre1μPa@1m was experimentally measured and the power handling capacity of 500 W was achieved with a distortion of ~11 per cent. The decrease in transmitting voltage response values at higher frequencies was due to the eddy current loss, which is an inherent problem when the rod-shaped materials are used without laminations. The thickness of the lamination required is dependent on the frequencies of operation. In this case, an unlaminated rod is used. The photograph of the transducer is shown in Fig. 6. A transducer with a power handling capability of 2 kW is being designed for sub-bottom profiling application, based on the present experimental data.

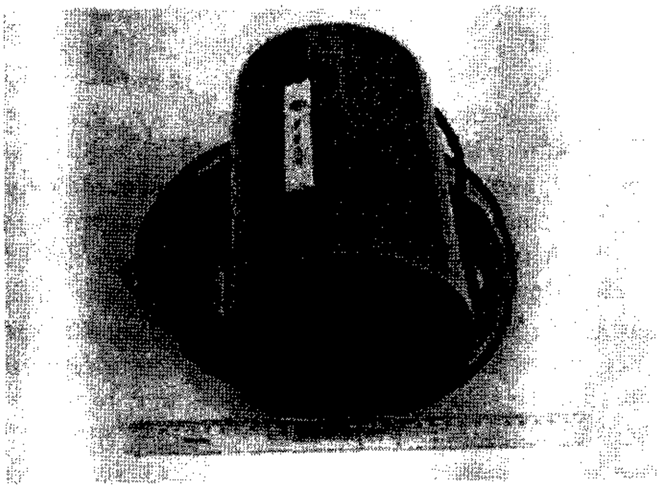

Figure 6. Prototype Terfenol-D transducer

5. CONCLUSION

A lot of technological advancements have been achieved by other countries like France, Sweden, UK, USA, in addition to Japan and China, on the material technological aspects as well as in the development of devices and applications. An overview of the various applications of this material has been presented in the various National seminars[8-10]. The NIOT is at present engaged in the devices and engineering aspects like design, testing as well as optimising the designs for as well as material characterisation techniques are also available. The off-spins of these technological developments can lead to the development of other actuators for commercial applications[7]. Low-frequency wide-band high-power transducers will have applications for the Navy, such as long-range detection active sonars as well as mine-hunting applications. The present tonpilz-type design will have a low-frequency limit of ~ 400 Hz, but this can be overcome by opting for the flextensional designs.

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Contributors

Dr Rajapan Dhilsha obtained his MSc (Physics with Electronics) from the Cochin University of Science and Technology in 1985. He worked as Project Associate and Senior Project Officer on the indigenous development of giant magnetostrictive Indian materials at the Indian Institute of Technology (IIT) Madras, Chennai, from 1986-93.He obtained his PhD in Physics from the IIT Madras in 1993 and won *Prof A.L. Laskar Memorial Prize* for the best PhD thesis awarded to the research scholar with academic distinction. He has established a processing method on the development of materials in addition to the development of instrumentation for their characterisation on his study. He joined National Institute of Ocean Technology (NIOT) as Senior Project Engineer in 1994 and is presently working as Scientist in the area of marine instrumentation with special interest to low and very low-frequency underwater acoustics. His research interests include: Hardware, design, development of low-weight underwater electro-acoustic sensors/transducers over a wide-frequency range for various oceanographic/naval applications and their calibration. He is also guiding graduate and postgraduate-level students. He has several national and international publications to his credit with international citations. The work is also cited in the Handbook of Giant Magnetostrictive Materials, published from the Royal Institute of Technology, Sweden, in 2000. He is a co-inventor on a method of manufacture of a giant magnetostrictive material with IIT Madras where an Indian Patent has been awarded in 2003. He is an associate member of the Acoustic Society of America, and a life member of the Acoustic Society of India, and Magnetic Society of India.