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Effect of Boron Addition on Magnetostrictive Properties of Terfenol-D Alloys

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ABSTRACT: A comparative study of the room-temperature magnetostrictive properties of polycrystalline Terfenol-D ($Tb_{0.27}Dy_{0.73}Fe_2$) and its Boron-substituted alloys is presented. All the alloys are found to be ferromagnetic at room temperature with low coercivity values. X-ray diffraction analysis confirms that Boron addition ($B = 2$ to 6 at.%) does not alter the primary cubic Laves-phase structure but suppresses the secondary $(Tb,Dy)Fe_3$ phase, which disappears for $B = 4$ and 6 at.%. The longitudinal magnetostriction values in terms of strain for the parent alloy saturates nearly at a value of 950 micron in a field of about 0.7 T in agreement with that previously reported for polycrystalline alloy including the commercial ones. The addition of Boron from 2 to 6 at.% is found to reduce the magnetostriction value and no saturation is observed up to the available magnetic fields of 1.2 T.

KEYWORDS: Terfenol-D alloys, Boron substitution, Magnetostriction, Magnetization

I. INTRODUCTION

Magnetostriction (MS) refers to the change in physical dimensions of a material in response to an applied magnetic field. Most ferromagnetic materials exhibit small amounts of magnetostriction, with cobalt showing the highest room-temperature magnetostriction among pure elements. Several rare-earth intermetallic compounds, particularly cubic Laves-phase RT_2 ($R = Dy, Tb, Sm; T = Fe, Co$), exhibit significant magnetostriction at room temperature. Among these, Terfenol-D ($Tb_xDy_{1-x}Fe_2$, $0.2 < x < 0.3$) is widely studied for its large room-temperature magnetostriction in both single-crystal and polycrystalline forms [1,2].

Despite its high magnetostriction, Terfenol-D faces challenges such as brittleness, high cost (due to ~60 wt% heavy rare-earth content), and the requirement of strong magnetic fields (5–10 kOe) to achieve optimal strain [3]. To improve its mechanical and magnetic properties, researchers have explored partial substitution of R with Pr and Fe with Ni, Si, Mn, Co, Al, Be, H, B, and C [4–10,14,16,17]. Among these, Boron and Beryllium substitution has been reported to enhance magnetostriction without significantly lowering the Curie temperature [5,6]. While Chelvane et al. [18] observed that Boron addition led to an increased secondary $(Tb,Dy)Fe_3$ phase, reducing magnetostriction, Wu et al. [4,5] reported that Boron restrained the formation of RFe_3 , resulting in improved properties.

In this study, the room-temperature magnetic and magnetostrictive properties of Boron-substituted Terfenol-D ($Tb_{0.27}Dy_{0.73}Fe_2$) alloys are investigated. The MS measurements were performed using an indigenously designed system developed at the host institution of one of the authors.

II. EXPERIMENTAL DETAILS

A series of Boron-added polycrystalline Terfenol-D, $Tb_{0.27}Dy_{0.73}Fe_{2-x}B_x$ alloys with Boron substitutions of 0 at.%, 2 at.%, 4 at.%, and 6 at.% ($x = 0.0, 0.02, 0.04, \text{ and } 0.06$) were synthesized as ingots by induction melting. The samples are referred to as T0, T2, T4, and T6, based on their Boron content. For structural and magnetic characterization, the samples were powdered for X-ray diffraction (XRD) and magnetization measurements, while solid chunks were cut into slices ($4 \text{ mm} \times 6 \text{ mm} \times 1 \text{ mm}$) for magnetostriction measurements using a Buehler ISOMET Low Speed Saw with diamond blades. XRD measurements were performed at room temperature using a Panalytical X'Pert PRO X-ray diffractometer. Magnetostriction measurements were conducted at room temperature using an indigenously designed four-probe-based system in a magnetic field of 0–1.2 T [12]. This system incorporates a Keithley constant current source and Keithley nanovoltmeter, replacing the traditional Wheatstone bridge. Standard strain gauges were adhered

to the samples along the strain measurement direction using a special adhesive. A data logger software directly recorded the strain in microstrain units. The system demonstrated excellent agreement with literature values for Terfenol-D [11], with a sensitivity of 1 microstrain and a measurement error of 1–5%. Magnetization measurements at room temperature were performed on small quantities of sample using vibrating sample magnetometer (VSM).

III. RESULTS AND DISCUSSION

1. XRD measurements :

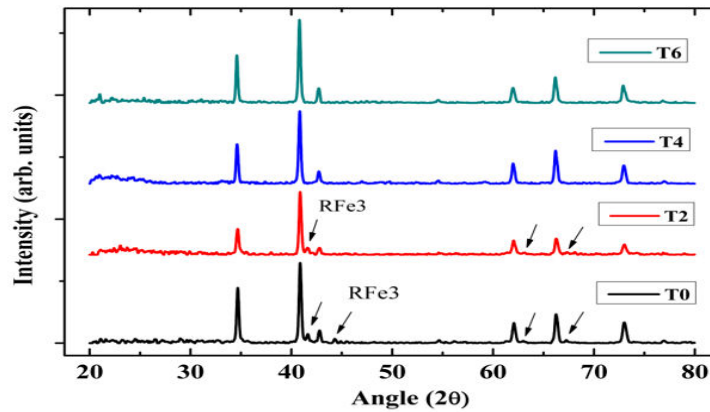


Figure 1 : X-Ray diffraction of $Tb_{0.27}Dy_{0.73}Fe_{2-x}B_x$ alloys (B = 0 at.%, 2 at.%, 4 at.% and 6 at.%)

Figure 1 presents the XRD patterns of Boron-substituted polycrystalline Terfenol-D samples, $Tb_{0.27}Dy_{0.73}Fe_{2-x}B_x$ ($x = 0.0, 0.02, 0.04, 0.06$), which are consistent with those reported for the parent alloy. It is observed that Boron addition ($B = 2 - 6$ at.%) does not change the crystal structure of the alloys. The as-cast polycrystalline Terfenol-D ($Tb_{0.27}Dy_{0.73}Fe_2$) alloy shows two prominent phases: the cubic Laves phase ($MgCu_2$ -type) $(Tb,Dy)Fe_2$ and the $(Tb,Dy)Fe_3$ phase. The presence of the secondary RFe_3 phase depends on the Boron concentration. In our study, this secondary phase disappears completely in the samples with $B = 4$ at.% and 6 at.%, whereas previous reports observed its reduction for B concentrations exceeding 5 at.% [4,5].

2. Magnetization Measurements:

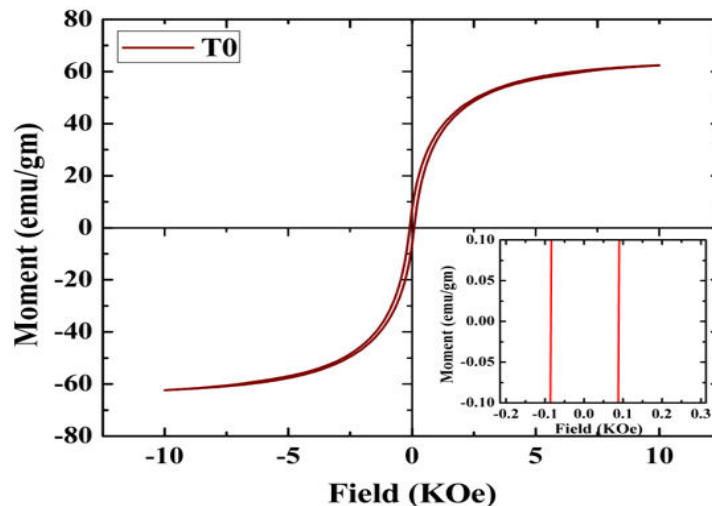


Figure 2: Room temperature M-H curve of $(Tb_{0.27}Dy_{0.73})Fe_2$ alloy.

Figure 2 shows M-H plot for the parent T0 sample measured at room temperature, illustrating the characteristic magnetic behaviour of the alloys. The inset shows the corresponding coercive field. All the samples exhibit ferromagnetic behaviour, with saturation magnetization (M_s) ranging from 55-70 emu/g and coercivity (H_c) between 85 and 115 Oe. Boron addition is seen to have increased the coercivity of the alloys, suggesting Boron addition affects the grain size distribution and secondary phase formation, which can act as pinning sites for magnetic domain walls.

3. Magnetostriction Measurements:

The plot of variation of the longitudinal magnetostriction ($\lambda_{||}$) measured in microstrain as a function of the applied magnetic field of the samples is shown in figure 3. The T0 sample shows saturation in strain in fields between 0.6-0.7 T, reaching a value of 990 micron at 1.2 T, which agrees with the reported value of polycrystalline Terfenol-D alloys. With the addition of Boron, it is observed that the magnetostriction strain does not saturate up to the highest achievable field of 1.2T and the magnetostriction values decrease with increasing B concentration. It is also observed that the brittleness of the alloys decreases with increasing B concentration. The effect of B addition does bring about a change in the magnetovolume effect as observed from the magnetostriction measurements.

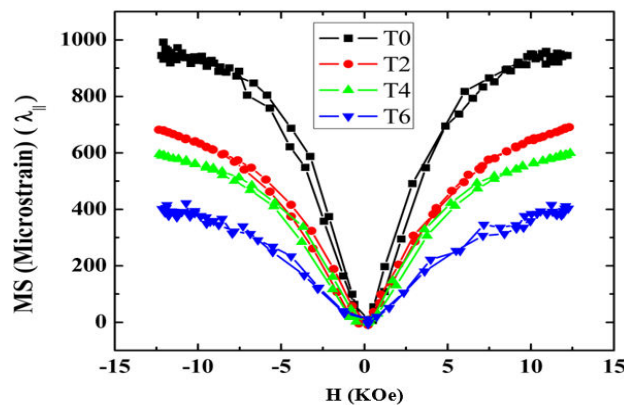


Figure 3: Longitudinal MS values vs applied magnetic field at room temperature of $Tb_{0.27}Dy_{0.73}Fe_{2-x}B_x$ alloy (B = 0 at.%, 2 at.%, 4 at.% and 6 at.%).

IV. CONCLUSION

The magnetization and magnetostriction measurements at room temperature have been carried out on a series of Boron-added polycrystalline Terfenol-D, $Tb_{0.27}Dy_{0.73}Fe_2$ alloys with Boron substitutions of 0 at.%, 2 at.%, 4 at.%, and 6 at.%. The alloys showed soft ferromagnetic magnetic properties. The longitudinal magnetostrictive strain reached a value of 990 micron at 1.2 T for the parent alloy while the Boron substituted ones showed a comparative decrease in magnetostrictive strain and did not saturate up to experimentally available fields of 1.2 T. The parent samples are observed to be brittle and the brittleness is observed to decrease with increasing Boron concentration. Boron addition is seen to reduce the secondary RFe_3 phase and it disappears for $B \geq 4$ at.% concentration. Further systematic studies based on these variations in higher applied fields is expected to throw light on the use of these materials in piezomagnetic devices.

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