The changing shape of magnetostriction

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Magnetostriction was discovered over 150 years ago and magnetostrictive materials were widely used in SONAR devices until about 40 years ago. Recently, new 'giant' magnetostrictive materials, which produce strains up to a hundred times greater than the original materials, have been developed and have opened up a wide range of other applications.

Magnetostriction (pronounced 'mag-neeto-strik-shun') is an effect observed, to differing degrees, in all magnetic (by which we usually mean 'ferromagnetic') materials. The essential nature of the effect is illustrated in figure 1, in which a rod of a magnetic material of length L is shown surrounded by a coil of wire. When an electric current is passed through the wire (figure 1(*b*)) to produce a magnetic field, H, along the rod, the length of the rod increases by a small amount δL. This strain ($\delta L/L$) produced in the rod by the magnetic field is called the Magnetostriction (for which the symbol λ is used). Thus the name 'Magnetostriction' is used both for the effect itself and for the measurable quantity (λ) associated with the effect.

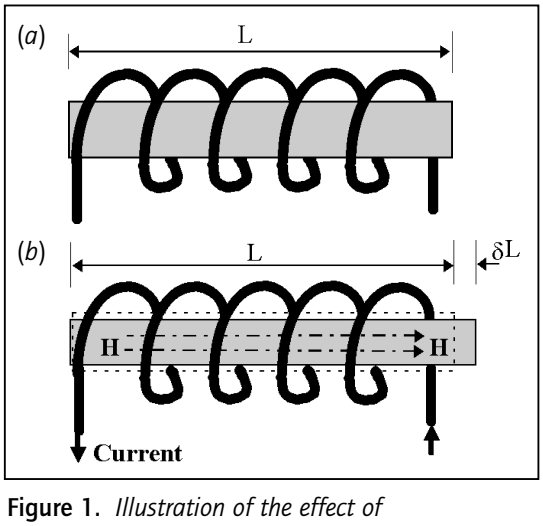

Figure 1. *Illustration of the effect of magnetostriction in a rod. (a) In zero field, (b) in field H.*

Figure 1(*b*) also shows that, in addition to an increase in length in the direction of the field, there is a decrease in the perpendicular direction, and as a result of this the volume of the rod remains essentially constant. What figure 1 does not correctly show is the *magnitude* of λ which is *extremely* small, often only of the order of a few parts in a million (i.e. $\lambda \sim 10^{-6}$). The phenomenon of magnetostriction was first discovered by J P Joule in 1842 and the difficulty of measuring (even now) such a small effect pays testimony to the experimental skill of its discoverer.

The variation of λ with field, H, is illustrated in figure 2, which shows two important features of magnetostriction: firstly, with increasing H, λ eventually reaches a constant 'saturation' value, λ_{sat}, and secondly the sign of λ does *not* reverse when the direction of H is reversed (that is, magnetostriction is a 'second order' effect) Ñthe rod increases in length for both directions of the field.

In figures 1 and 2 the length of the rod was shown to *increase* with increasing magnetic field, and this is termed *positive* magnetostriction. The opposite effect (a decrease in length with increasing field) is

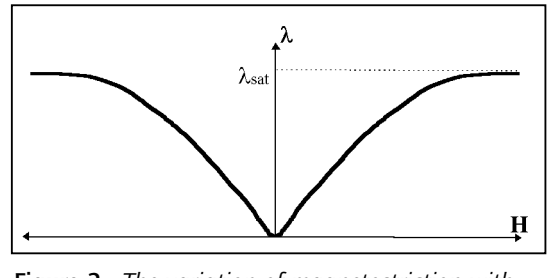

Figure 2. *The variation of magnetostriction with magnetic field.*

termed negative magnetostriction, and both effects are observed in different materials. Nickel, for example, has negative magnetostriction while iron has λ positive in some directions in a single crystal and negative in others. This last observation illustrates the fact that, in common with all magnetic effects, magnetostriction is an *anisotropic* effect, which means it varies with crystallographic direction.

Even though magnetostriction is a very small effect and, in most materials, relatively unimportant in comparison with other magnetic effects, it is of interest to physicists not only because it exists, so that we wish to measure and 'explain' it, but also because it has important practical applications. During and after the Second World War, most SONAR devices, for echo sounding to determine depth and locate other objects, used magnetostrictive elements (made from nickel alloys) to produce their sound. In order to produce sufficient motion, the magnetostrictive material in these devices is made to resonate by driving it with a pulse of magnetic field (by passing a current pulse through a coil wrapped round the material) to give it a 'kick'. This makes the material 'ring', in the same way as any metal rod rings when hit with a hammer, and produces the characteristic 'ping' of the SONAR signal.

The nickel-based materials used in those original SONAR devices have saturation magnetostriction values of only about 50×10^{-6} and, from about the mid-1950s, they were gradually superseded by piezoelectric ceramic materials which are more efficient. There are, however, materials based on the Rare Earth metals such as terbium (Tb) and dysprosium (Dy) which have much greater values of λ_{sat}, as shown in table 1.

Unfortunately, from the point of view of making use of these rare earth metals in their elemental form, their magnetic properties only exist at low temperatures, as shown (in table 1) by their Curie temperature (T_C), which is the temperature above which the material becomes non-magnetic. However, this temperature limitation can be overcome by combining the rare earth metals with iron in intermetallic compounds. Such compounds are formed from two metallic elements (say, A and B) in certain simple, fixed ratios, giving a compound (AB or AB_2, for example) which has a crystal structure different from either of its components. In particular, the RFe_2 compounds (where R is a rare earth element) retain their magnetic properties above room temperature and also have saturation magnetostriction, as shown in table 2, many times greater than the 'conventional' materials based on Fe and Ni. As a consequence they have become known as 'Giant Magnetostrictive' materials.

Table 1. Saturation magnetostriction (λ_{sat}) and Curie temperature (T_C) for various elements.

Element	$\lambda_{sat}/10^{-6}$	$T_C/^{o}C$
Fe	20	+770
Ni	40	+358
Tb	8000*	−43
Dy	7500*	−188

*These values are measured at very low temperatures.

Table 2. Saturation magnetostriction (λ_{sat}) and Curie temperature (T_C) for various giant magnetostrictive materials.

Material	$\lambda_{sat}/10^{-6}$	$T_C/^{o}C$
$TbFe_2$	+1750	+430
$DyFe_2$	+430	+360
$SmFe_2$	−1560	+400
$Tb_{0.27}Dy_{0.73}Fe_2$	+1100	+380

When these RFe_2 materials were first developed in the 1960s, they were found to have another major limitation to their practical application because very large magnetic fields are required to develop the magnetostriction due to their enormous 'magnetocrystalline anisotropy' energies. This property is measured by a constant K_1 which characterizes the energy required to change the direction of the magnetic moments in a single crystal of the material (remember the anisotropy in magnetic properties mentioned earlier). Hence the larger the value of K_1 is, the greater is the field required to produce any change in magnetic property; unfortunately, K_1 for $TbFe_2$ is the largest known for any cubic material, at room temperature. It seemed that Nature had conspired to provide giant magnetostriction, but at the price of requiring unreasonably large magnetic fields to achieve the effect.

The solution to this problem was provided, in 1974, by Art Clark and his co-workers at the Naval Ordinance Laboratory (NOL) in Maryland, USA. They realized that by combining $DyFe_2$ (which has positive K_1) and $TbFe_2$ (which has negative K_1), in the appropriate ratio, a material of composition $Tb_xDy_{1-x}Fe_2$ could be obtained for which K_1 would be reduced to near zero, but the magnetostriction (which is positive for both components) would remain large. It turned out that the appropriate composition was that with $x = 0.27$ (that is 27% $TbFe_2$ and 73% $DyFe_2$) and the resulting material $Tb_{0.27}Dy_{0.73}Fe_2$ was given the name 'Terfenol-D', which was obtained from the letters TER (from terbium) + FE (from iron) + NOL (from their laboratory) with the D from dysprosium.

The saturation magnetostriction for $Tb_{0.27}Dy_{0.73}Fe_2$, given in table 2, is truly giant (compared with the Fe and Ni alloys) but, more importantly, the magnetostriction can be produced with sufficiently small magnetic fields, due to the reduced anisotropy. This is illustrated schematically in figure 3 where a peak in $\delta\lambda/\delta H$ (which is the change in strain with change in applied field) is shown at $x = 0.27$, the Terfenol composition.

Since the initial development of Terfenol-D much further research has been carried out, around the world, to optimize methods of production, to characterize its properties and their dependence on temperature, frequency and pre-stress, to investigate related compositions and to develop possible applications. There is space to mention only a selection of these topics.

The 'best' properties are produced in material that is grain-oriented by float-zoning. In this technique, a rod of the material (produced by arc-melting the required proportions of Tb, Dy and Fe) is held vertically in a vacuum chamber and a narrow zone across the rod is melted, by induction heating from radio-frequency coils around the outside of the chamber, and then this zone is moved down the length of the rod. This process is similar to the 'zone refining' that is used to purify semiconductor crystals but the result in this case is that the metal grains grow with a particular crystal direction along the axis of the rod. Fortuitously, this crystal direction is one in which the magnetostriction is large. It is much simpler and less expensive to make the material just by arc-melting, but then there is no preferred orientation and some grains have low-magnetostriction directions aligned with the rod axis and the overall (average) magnetostriction is reduced.

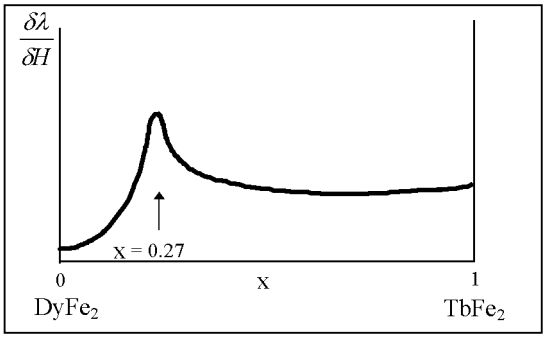

Figure 3. *The variation of magnetostrictive d–coefficent with composition, showing a peak at the Terfenol–D composition.*

The variation of the magnetostrictive strain with applied field and its temperature dependence are very sensitive to the Tb to Dy ratio. For example, the composition $Tb_{0.30}Dy_{0.70}Fe_2$, when given a pre-stress, shows a 'burst effect' in which the strain increases very rapidly at some point as the applied field is increased. This effect, which is illustrated in figure 4, is not observed in $Tb_{0.27}Dy_{0.73}Fe_2$.

A great many practical applications of Terfenol, some exotic and some mundane, have been suggested and investigated. These include SONAR, in which it should be possible to obtain echoes from much greater distances than with conventional materials; linear actuators and motors; active antivibration control; and even a hearing aid in which a small Terfenol element, driven by the amplified signal from a microphone, vibrates the patient's *teeth*!

Linear actuators (devices that exert a force or produce movement in a straight line) using Terfenol have very large power-handling capability and the

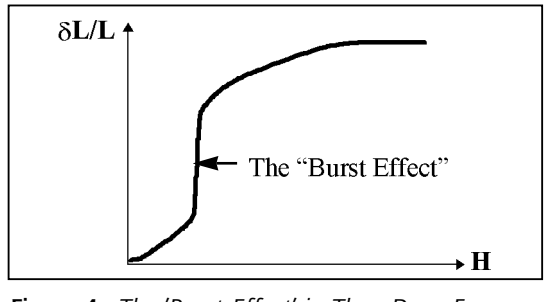

Figure 4. *The 'Burst Effect' in $Tb_{0.30}Dy_{0.70}Fe_2$.*

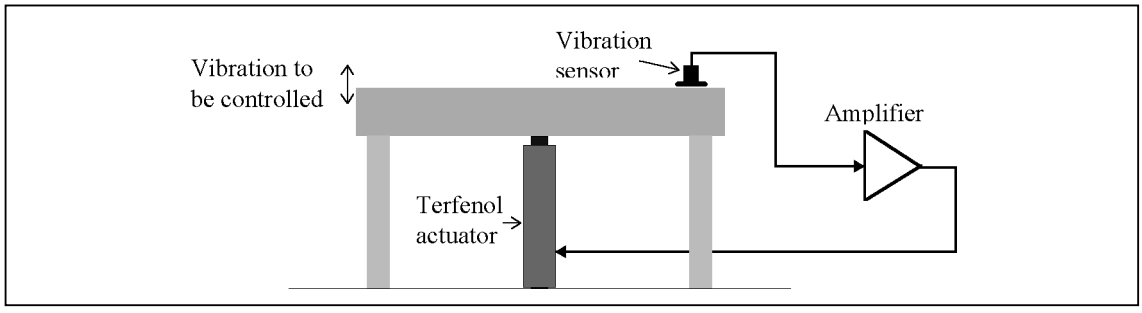

Figure 5. *An active antivibration control system.*

'figure of merit' for their power density is about 10^7 W m^{-3}. This is greater than that for conventional hydraulics and more than ten times greater than for electric motors. In one such application, Magnetostrictive Technology Systems Ltd, a company based in Hull, have manufactured a large actuator which generates 14 kW of power and produces 15 kN force with displacements of about 0.1 mm.

In active antivibration control systems (figure 5) the vibration of the surface to be controlled (a table for example) is sensed. This signal is then amplified and used to drive a Terfenol actuator to produce a motion which is opposite to the original vibration and so cancels it out. Magnetostrictive Technology Systems have shown that vibrations of about 70 μm at frequencies around 5 Hz can be reduced by about 1000 times. Control systems of this sort based on other technologies already exist, but it is suggested that Terfenol-based systems, with their increased power-handling capability, could control whole floors and bridges rather than just table-tops.

For many potential applications, speed of response and operation at high frequencies are important, and Terfenol suffers from the problem of eddy currents that is common to all metallic magnetic materials. Eddy currents, which are electric currents produced in the metal by the effect of the varying magnetic flux (Faraday's Law!), lead to power loss and a limit to the frequency at which the material can operate. The effect of eddy currents in Terfenol is a particularly severe problem because the material is very brittle and therefore difficult to laminate, as is done for example with transformer cores. Recently, this limitation has been addressed by the development of composite materials in which small particles of Terfenol are bonded with a non-conducting polymer binder. There is a loss of magnetostriction as a result of this processing – because some of the material is non-magnetic – but this is compensated by a considerable increase in the high-frequency response. The polymer-bonded material is also easier to fabricate into complicated shapes and can even be injection moulded.

The study of magnetostriction is indeed 'changing shape' and continues to provide fascination and fresh challenges for the physicist, in materials development and characterization, in the development of theoretical models of the physical processes involved and in applications.

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Further reading

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