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Electric vehicle traction motors without rare earth magnets

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ABSTRACT

Since the Hybrid Electric Vehicle (HEV) became main-stream with the launch of the Toyota Prius in 1997, the use of rare earth magnets in vehicle traction motors has become common. In particular the rare earth based, hard magnetic material Neodymium Iron Boron (NdFeB) has offered significant performance benefits, not possible with other technologies, enabling the development of compact, torque- and power-dense electric traction motors. This trend has continued as mass market Battery Electric Vehicles (BEV) such as the Nissan Leaf, have come to market. However in 2011–2012 the price of these materials rose significantly, owing to geopolitical concerns relating to security of supply. Whilst the price has recovered more recently closer to historical levels, concern still remains in the minds of governments and many manufacturers of hybrid and electric vehicles. Reports have also raised questions over the environmental sustainability of these materials and this has further encouraged users to consider alternatives. This paper therefore examines why these magnetic materials have been so successful in traction motor applications. It also explores the alternatives, including those which are ready for market and those which are in the process of being developed.

1. Introduction

1.1. Neodymium Iron Boron magnets and electric traction motors

The sintered Neodymium Iron Boron (NdFeB) hard magnetic material was patented by Sumitomo Special Metals in 1983 [1] (Fig. 1) and brought about a step change in terms of electric motor performance. Neodymium is a member of the family of materials known as Light Rare Earth Elements (LREE), along with others including for example Lanthanum (used in optics) and Samarium (also used in magnetic materials).

These magnets offer such high levels of performance owing to their very high Maximum Energy Product compared to other magnetic materials (Fig. 2). The Maximum Energy Product is the measure of the magnetic energy which can be stored, per unit volume, by a magnetic material; it is calculated as the maximum product of a material's residual magnetic flux density (degree of magnetisation) and its coercivity (the ability to resist demagnetisation once magnetised). Equally, if each of these constituent properties, the remnant flux density and coercivity, is taken separately then in NdFeB they are in their own right significantly higher than for other magnetic materials (Fig. 3) [2–4].

It is also important to recognise that a key ingredient in allowing NdFeB magnets to operate at high ambient temperatures is Dysprosium; this Heavy Rare Earth Element (HRE) is added to NdFeB in order to increase the high temperature coercivity (ability to withstand demagnetisation) of the magnets above circa 100 °C [5]. This has been essential in making it possible to use these magnets in high power density applications, such as vehicle traction.

In an electric traction motor, NdFeB magnets allow a very strong magnetic field to be generated in a very small volume. The alternative would be to use electromagnets, where a magnetic field is generated by passing current through a conducting coil. It can be shown that a 3 mm thick piece of NdFeB magnet produces the equivalent magnetic field to passing 13 A (being the rating of a UK home electrical socket) through a coil with 220 turns of copper wire. In terms of space, if a current density of 10 A/mm^2 is assumed in the conductor (which is typical for normal operation of a traction motor), then an equivalent electromagnetic coil might have five times the cross sectional area of the NdFeB magnet (Fig. 4). At the same time the coil would produce losses in the windings of 50 W or more per metre length of the coil, arising due to the electrical resistance of the conductor. To put this in perspective, in a representative 80 kW traction motor the optimum use of NdFeB magnets would theoretically be equivalent to saving perhaps 20% in total

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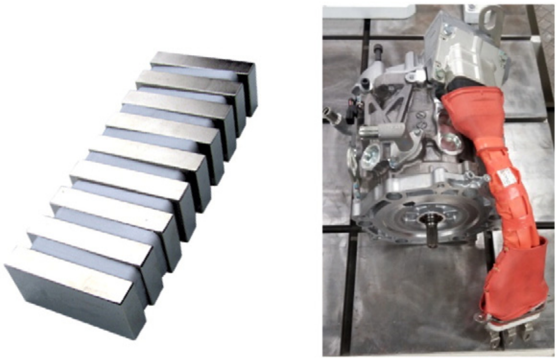

Fig. 1. (Left) An example of a sintered NdFeB magnet and (right) a vehicle traction motor, the 80 kW interior permanent magnet motor from the Nissan Leaf, in which such magnets are used.

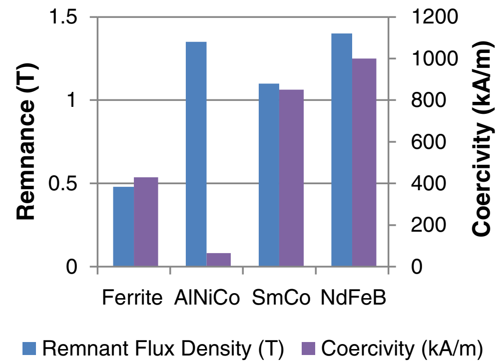

Fig. 3. Comparing remnant flux density (magnetic strength) and coercivity (resistance to demagnetisation) for different hard magnetic materials.

motor volume and, conservatively, in the order of 300 W of winding loss.

1.2. Concerns with rare earth magnets

Although the performance benefits are undisputed, the use of rare earth materials, such as NdFeB, has raised concerns in a number of areas. In 2011 and 2012, China reportedly threatened to cut off international supplies of these materials [6]. Concern over the availability of these materials then led to dramatic, though short-term, increases in the price of many rare earth materials, with Neodymium and Dysprosium prices both increasing by an order of magnitude (Fig. 5). Prices have since recovered to nearer their early 2011 levels, however in the case of Dysprosium, they have not yet returned to their previously low levels. It is reported that as a result of this price spike, a number of organisations are seeking to open new mines. However these have focused on light rare earth oxide extraction (for example, Neodymium) [7]. It appears that heavy rare earth oxide mining remains focussed on extraction from ionic absorption clays found in southern China. This suggests that light rare earths (Neodymium) will remain at relatively low costs whilst heavy rare earths (Dysprosium) may remain in relatively short supply.

Whatever the price of rare earth magnets, it is generally recognised that their elimination from electrical machines will lead to a reduction in costs. [8] reported that traction motors without NdFeB materials would have significantly lower materials costs (Fig. 6). However caution must be taken in this respect; it is possible that the use of other motor technologies may result in increased costs in other elements of the electric vehicle drivetrain (power electronics or batteries). If not carefully managed this could offset or even exceed any cost benefits linked to the removal of rare earth magnets from the electrical machine.

It has also been widely reported that the extraction and refinement of rare earth oxides is a potentially environmentally damaging process [9,10]. This aligns with research by the automotive industry (see Fig. 7) which suggests that NdFeB magnets may be, per unit mass, more damaging than other materials commonly used in electrical machines. If the breakdown of materials is estimated for a representative rare earth permanent magnet electric traction motor, it can be calculated that the NdFeB magnets may be responsible for perhaps 25% of the material related greenhouse gas emissions, despite being less than 5% of the motor by mass.

Whilst this analysis has the potential to exaggerate the environmental impact of NdFeB magnets when considered as part of the overall electric vehicle system, it is perhaps still true that their elimination could reduce the environmental footprint of traction motor manufacture, reducing that of electric vehicle manufacture in turn.

1.3. Other considerations with rare earth permanent magnet motors

Other important considerations relate to specific limitations in the performance of electrical machines which use these materials.

Rare earth magnets (along with other types of permanent magnet) are always ‘on’, whether the electrical machine where they are used is operational or not. This means that when a rare earth magnet (or other magnet based motor) is rotating, even with no electrical current applied, magnetic flux will still be present within the machine. This leads to a number of undesirable effects.

One consequence will be high, magnetically induced voltages at motor terminals if the motor's electrical terminals are open-circuit or, alternatively, high currents through motor windings if the motor terminals are short-circuited. The motor will also produce losses; these will be due to so-called iron losses, induced in the motor's core by the rotating magnet fields, and to resistive losses in motor windings, where the motor terminals are short-circuited.

Permanent magnet based motors will also ‘cog’ when not on load. Cogging is the term used to describe the way in which the motors,

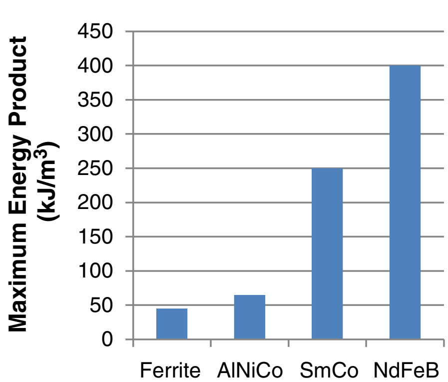

Fig. 2. Comparison between the Maximum Energy Product of differing hard magnetic materials.

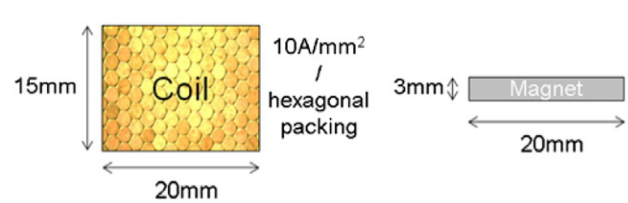

Fig. 4. A simple comparison between the area of electromagnet coil and NdFeB magnet required to produce the same magnetic field.