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To cite this article: S Darius Gnanaraj *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **906** 012020

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Materials for lightweight electric motors – a review

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Abstract. Electric motors are widely used in automobiles and large electric vehicles would be introduced in market in the near future to reduce global warming. Reduction in electric motor weight also reduces the overall weight of automobiles. The use of fiber-reinforced polymer materials reduces the weight of electric motors. Lightweight electric motors promote energy savings owing to the reduction of self-weight. Researchers all over the World are trying to make all parts of electric motors using lightweight materials. This review paper presents the outcome of research carried out by researchers from Germany and UK. Fiber reinforced plastics (FRP) reduce weight and increase mechanical and electrical properties. Phenolic composite materials gave promising results due to its electrical insulation properties and corrosion resistance. Thermosets do not swell when they are exposed to chemicals unlike thermoplastics. Aluminium matrix composites (AMC) are used to improve the motor efficiency resulting in a considerable weight reduction. Electric motors have 90 percent or above, which means that a high mechanical energy is derived from electrical energy. The remaining electrical energy is converted into heat. To prevent overheating, the heat is conducted through housing to a cooling jacket having cold water. Researchers have replaced the circular wire by rectangular flat wire that can be coiled tightly on the stator. Newer cooling concepts are developed for making housings using polymer materials. Carbon fiber reinforced materials with metal pins are used for reducing weight and to increase thermal conductivity. Use of high modulus fibers increase damping properties and reduce noise produced by electric motors. Comparisons between electric motors made of lightweight materials and traditional metals in terms of weight, efficiency, cooling rate are presented.

Keywords: Lightweight materials, electric motors, Fiber reinforced plastics, Aluminium matrix composites, cooling concepts.

1. Introduction

To reduce the effects of global warming, many countries are replacing traditional vehicles by electric vehicles. Many researchers are working to design energy efficient electric vehicles by reducing overall weight of the vehicles using composite materials. Attempts are being made to reduce the weight and cost of all parts of automobiles including the power source, electric motor. We require lightweight materials with a higher strength to weight ratio, composites with high power to weight ratio and materials with high thermal resistance. Some parts of the electric motor should have high thermal conductivity or electrical conductivity whereas other parts require electrical insulation. It is a difficult task to replace conventional materials with modern materials and achieve high energy



efficiency. 10 Lakhs electric motors are produced in the World every year [1]. Eco-friendly materials are preferred for easy recycling of materials after the life of the product is over. Composites help designers to combine many properties required by different parts of the electric motor into different composites. This paper reviews the progress made by a few researchers in replacing heavy parts of electric motors by lightweight materials, novel cooling methods incorporated and increase in efficiency.

2. Materials for lightweight electric motors

Fiber reinforced plastics (FRP) provide opportunities to replace parts of electric motors to reduce the overall weight. FRP materials increase the mechanical properties and electrical conductivity. Thermosetting FRP materials offer high resistance to heat and corrosion due to chemicals. Soft magnetic composites (SMC) are used for achieving high power to weight ratio at reduced manufacturing costs. Phenolic composite materials (PCM) are useful to replace many metallic parts by a single integrated part. Assembly time may decrease and maintenance also can be carried out on a faster rate. Polymer housings are easier to manufacture than housings made of aluminium. Figure 1 shows the distribution of weight of an electric motor [2].

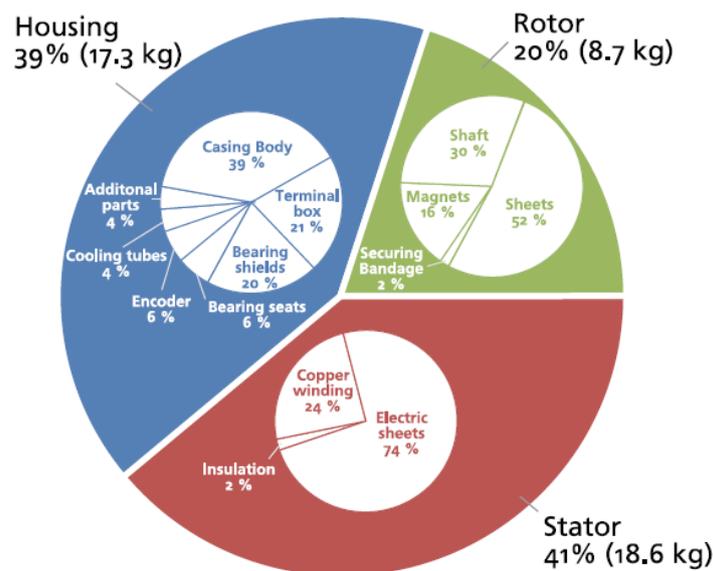


Figure 1. Distribution of weight of an electric motor [2]

It is seen that the weight of stator is 41%, housing 39% and rotor 20%. There are two types of masses: stator and housing do not rotate but only translate and rotor rotates and translates. Rotational inertia reduction is aimed for saving weight. Better dynamic behavior can be obtained by lowering the rotational inertia. While accelerating or decelerating, higher efficiency of the motor is obtained by lowering the rotational inertia [2]. Injection molded magnetic carrier and magnets mounted on a single rotor disc are shown in figure 2. This structure combines two functional requirements: torque transmission and magnetically active part. GFRP (Glass fiber reinforced plastics) is used for transmitting torque and SMC is used for the flow of magnetic field. The length of the magnet carrier was made equal to the length of the magnet. Multiple magnet carriers are assembled to accommodate required number of magnets. Splines are used for easier assembly on the rotor shaft and for a positive torque transmission between the rotor disc and the shaft [3].

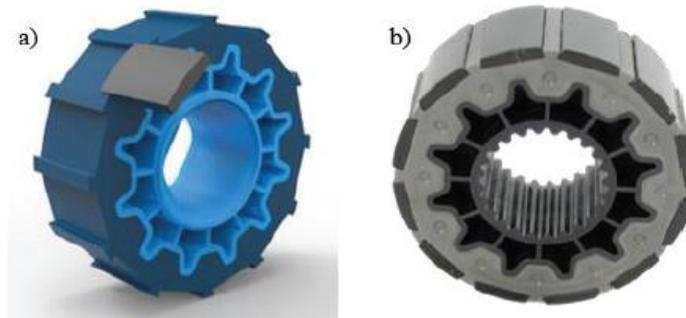


Figure 2. Injection molded magnet carrier a) Soft magnetic composite (inner) and Polyamide (outer)
b) Magnets mounted on single rotor disc [3]

3. Effective cooling in reducing the weight of electric motor built with lightweight materials

Enhancing the efficiency with size, cost and weight of the motor could be succeeded by means of better materials and a better designing process. Design of efficient cooling system is of great importance in electric motors to improve performance and their applicability in various fields such as traction, wind, aviation and transport. The major challenge for designers of an electric motor is to overcome the challenges in the power to weight ratio and to accommodate within the limited available space [4-5].

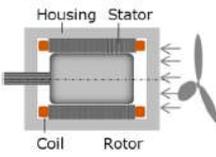
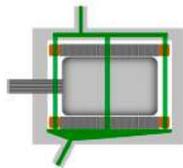
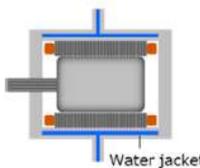
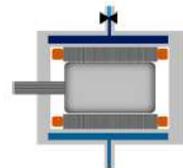
In electric vehicles lighter motors are required and the working temperature of PMSMs is a big challenge to address. Losses in the electric motor reduce the transferred energy and rise the working temperature in all the applications of electric motor. Efficient cooling is paramount for any research related to a high speed and lightweight electric motors. Permanent magnet synchronous motor (PMSM) powers effectively various kinds of electric power vehicles. PMSM has useful features like high torque to weight ratio, simple structure, high power-weight ratio, high efficiency, good reliability, large power density and enormous range of speed. Because of that they are most preferred for aviation applications [6].

Major losses in PMSM are mechanical losses, iron losses and copper losses. Iron losses occur in stator such as eddy current loss and hysteresis loss. Copper losses occur due to high flow of current in armature winding. Windage loss and bearing friction losses cause Mechanical losses. Temperature during the operation of the motor leads to winding insulation failure. This may cause short circuits in the winding. High temperatures developed above critical values in rotor hot spots may demagnetize the permanent magnets in the PMSM. Hence, generated heat in the motor has to be dissipated for the safe operation of the motor [7]. Minimizing the weight of a motor and maximizing the efficiency are the real challenges of a high speed electric motor. Hence, efficient thermal management system through effective cooling influence the weight of electric motor is essential in the design process [8].

Cryogenic cooling with Liquid nitrogen reduces energy loss as resistivity of copper decrease significantly with this method. Hence, less copper utilized to carry copper compared to water cooled or air cooled machines. This improves the power to weight ratio-economically and maximum current density-efficiently, in electric motors [9]. A liquid cooling system has been proved to be good in keeping the insulation temperatures under critical thermal limit. Nitrogen cooling system was designed owing to its compactness and the light weight of the motor. The effective inlet temperatures of fluid cooling systems were higher and hence the size of the heat exchanger also reduced [10].

A novel air ventilation duct was provided as a part of cooling structure in an air cooling system without an additional fan and cooling tubes-for liquid cooling system. The rotation of the electric motor itself would provide the power to enable this method of cooling system. The enhanced convection heat transfer rate method of this cooling had brought down the weight of the motor [11]. A refrigerant cooling method was usual compared to water cooling method with respect to weight of the coolant. Refrigerant cooling method was investigated and proved to be better compared to water cooling. Refrigerant cooling method provides 60% higher torque with less weight and also, at maximum torques the motor operation time was extended by 34%. Electric motor research always aims at effective cooling and bringing down the size of the motor, to enhance the torque and power [12]. Table 1 compares the cooling methods available in literature.

Table 1. Comparison of cooling methods

	Air Cooling	Oil Cooling	Water Cooling	Refrigerant Cooling
Schematic Illustration				
	Heat exchange by wind	Heat exchange by oil directly flowing into heat source	Heat exchange by flowing water in a water jacket	Heat exchange by flowing refrigerant and vaporization heat
Cooling Performance	Low	High	Average	High
Cooling Uniformity	Uniform	Non-uniform	Uniform	Uniform
Weight Component	High	Average	High	Low

Indirect liquid cooling method was investigated to be applicable and appropriate for aviation purposes. Indirect cooling method was a reliable method of removing large amounts of heat with light weight [13]. In oil cooling method high output power to volume ratio was achieved using oil circulation system to cool the electric motor and its shaft bearing. Here the circulated oil is cooled by the water externally. This method of cooling is far better compared to water cooling with respect to weight of the cooling agent [14]. Zadeh et al. investigated the performance of indirect cooling method by means of advanced nano-fluids as coolants to remove the heat generated by electric motor. Aluminum-oxide nano particles are added into the base fluid to enhance the heat transfer rate. Results proved that increased flow rate and increased fraction of the nano particles to 4%, raised the heat transfer rate upto 40%, which is a phenominal improvement in performance [15].

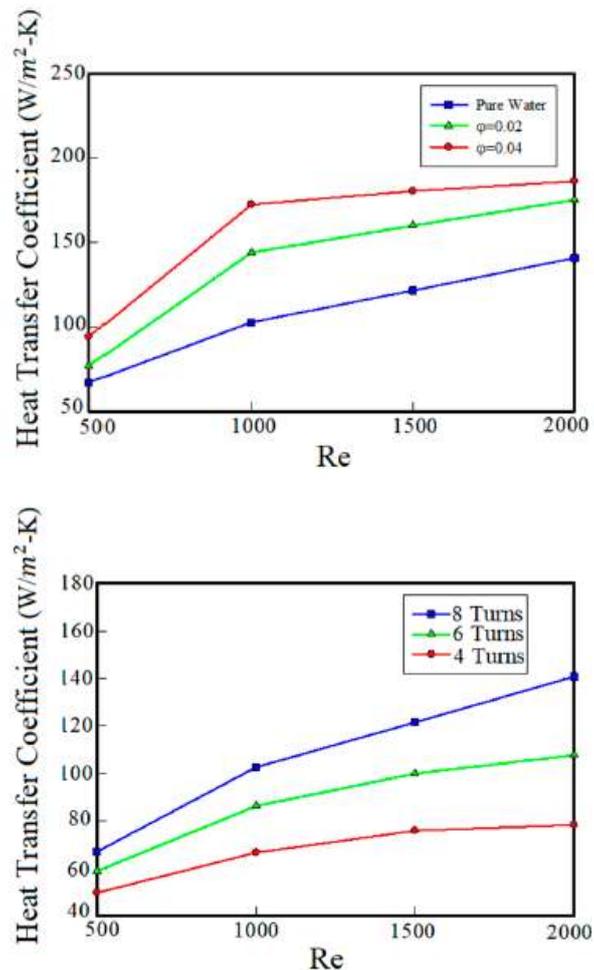


Figure 3. Effect of heat transfer with and without Aluminum-Oxide nano-particles [15]

Prius 2010 motor with V-shaped Nd magnets has cavities in the rotor is shown in figure 4. These cavities not only enhance the air flow and but also increases the effectiveness of the cooling, and reduced weight and inertia [16].



Figure 4. Prius 2010 electric motor-baseline [16]

In general weight of the motor depends upon the type of the motor. The stator core volume in case of a brushless PM motor is half of the volume of single-phase induction motor (SPIM). The conductors employed in a brushless PM motor are weighing one-third of the weight used by a SPIM [17]. Recently, heat pipes are used as efficient phase changing heat transfer devices. The low cost, light weight and high thermal conductivity heat pipe cooling method is best opted for air-cooled motors. Air cooling motors using heat pipes have good cooling effects and are used in electric vehicles [18]. High Temperature Superconducting (HTS) electric machines field windings employ HTS wires which have less weight, less volume and high power density. Temperature distributions under Axial Magnetic Motive Force (AMMF), with High Temperature Superconducting (HTS) wires of machine components are investigated and the results are shown in figure 5. Temperature distribution in the machines having copper wires and HTS wires are helpful in designing the simpler, less weight and more reliable cryogenic cooling system [19].

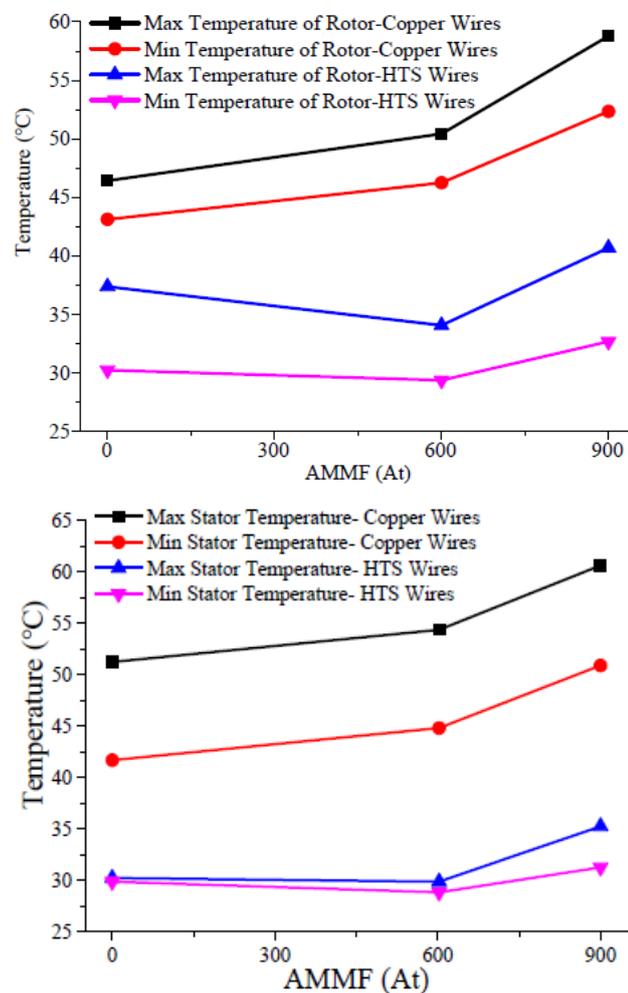


Figure 5. Temperature distribution on Rotor core and Stator core with HTS Copper wires [19]

Metal housing dissipates heat to the jacket having cold water for cooling the electric motor. Recent research replaced the circular wire used for the windings by a rectangular flat wire which could be wound more tightly on the stator, creating room for a cooling jacket adjacent to windings. Generated heat could be transmitted away from the source of heat through a short distance using this method. This motor is lighter and power-to-weight ratio is good in comparison to the existing ones [20].

4. Lightweight materials for improving performance of electric motors

Whether intended for a small or large household appliance, or used for driving hybrid and/or electric cars, or applied in industrial environments, the electric motor continues to confirm an unprecedented trend in global growth. Performance of any electric motor depends upon various factors, for an instance, efficiency is a measure of numerous mechanical and electrical imperfections within the motor. Similarly, the design of electric motors facilitates not just to reduce the cost but also to enhance the performance and the pursuit of the full potential. There are many facets of attaining the maximum performance of an electric motor. The choice of core materials, too, is among them. A task that also includes the components that makes up the core of electrical motors, from magnetic lamination to the stator case [21]. Raw materials with better properties increase the motor's performance. This seems to be doubtless from the view point of material research. Nevertheless, the achievement of the motor performance improvement goal is not adequate with the proper raw material. On a more general standpoint, in the past, magnetic losses and power losses provided the only primary architecture parameter. The losses in electric motor are distributed into various components, in three-phase motors, resistance losses (I^2R losses) in stator windings and rotor bars will result in an output loss of up to 15 percent. In single phase fractional horsepower motors the I^2R losses could be up to 30 percent. Similarly, losses in magnetization in the stator and rotor cores induce an output loss from around 1 percent to 7 percent. Likewise, 0.5 to 1.5 percent of losses may occur due to bearing friction and inefficient cooling fans. Losses in friction and magnetization are related only to the size and design of the motor and not dependent of motor load. The subsequent losses are called as stray load losses, which is around 2 percent of total losses. Partially loaded motors have lower efficiencies because of constant losses such as magnetizing losses, friction losses, and windage losses that will be the larger percentage of total motor power consumption. Figure 6 shows the various components of losses for a 50 hp squirrel cage induction motor as a function of motor load.

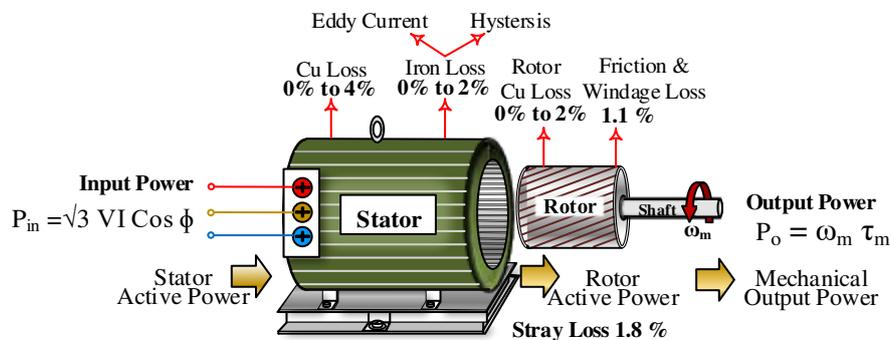


Figure 6. Typical loss component of 37.5 kW three phase squirrel cage induction motor

The overall efficiency of a motor is dictated by the construction materials, mechanical and electrical design. Power sensitive motors use high quality components and use engineered architecture to achieve higher efficiencies. Large copper wire diameter in the stator and more aluminum in the rotor minimize motor resistance losses. Enhanced rotor configuration and optimized air gap between stator and rotor results in stray loss reduction. An optimized design of the cooling fan gives ample motor cooling with a minimum loss of windage. Thinner and higher-quality rotor and stator core steel laminations allow the energy-efficient motor to work with lower magnetization losses. High quality bearings lead to reduced losses of friction [22]. The development and the architecture advancement have led in time to understand a higher importance to the dimension of the magnetic permeability. Magnetic permeability is defined as the ratio of the magnetic induction to the magnetic intensity. It is a scalar quantity and denoted by the symbol μ . Magnetic permeability helps us measure a material's resistance to the magnetic field or measure of the degree to which magnetic field can penetrate

through a material. Realizing that magnetic losses, heating and power losses occur in the core magnetization process, it is also important to assess the required current intensity. Effectiveness in magnetizing the conductive material allows a lower quantity of it to be used optimally. Materials that ensure easy magnetization in isotropic manner in all directions of the lamination plan making up the ferromagnetic core for applications on rotary machines. From the viewpoint of material crystallography, it is necessary to ensure that the (crystallographic) directions of easy magnetization are distributed homogeneously in the plane. Focusing on improved crystalline texture includes maximizing magnetic properties to achieve greater efficiency of application. Magnetic lamination, i.e. the ferromagnetic content inside the core and its behavior, but also the amount of conductive content and the current strength required to produce the desired result. Thus, considering the material resistivity element, it faced the selection of materials that benefited predominantly from silicon but also from aluminum or manganese. With a limit, as the commonly used Silicon rises with values above 3.5 percent, the substance is very brittle, making their industrial development and usage very important. A further strategy then consisted of orienting the research towards improving the quality of the material surface and its cleaning. The new trend then appears to be conducting work into extremely thin materials but we should consider the potential implications right now. From mechanical parts to approaches that incorporate laser technology that are less influenced by the influence of thickness and that result in a slight deterioration of magnetic activity in the blanking / cutting regions. In the meantime, we should imagine producing super-thin laminations with a multi-layer technology that can reduce magnetic loss while facilitating their use.

5. Summary

A review on the progress in research in replacing heavy metal parts by lightweight parts made of plastics and composites are presented. The details of requirements of materials for withstanding the turning moment and their ability to conduct magnetic field are discussed. The intricacies involved with the design of composite parts to satisfy the requirements are shown. Novel cooling methods like, cryogenic cooling with liquid nitrogen, liquid cooling system, indirect cooling by nano-fluids as coolants are presented. Heat transfer rate is found to rise up to 40% while using aluminium oxide nano particles into base fluid water. High temperature superconducting (HTS) wires are found to reduce weight and increase power density. Rectangular flat wires are found to be more efficient compared to round wires in conducting heat. High quality materials and optimized design are used by energy efficient motors for achieving high efficiencies.

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