Manufacturing Processes of Soft Magnetic Composite Cores for Permanent Magnet Machines

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***Abstract*—By using the low mass density compaction, the electrical machine with soft magnetic composite (SMC) cores has shown its great advantage of the low manufacturing cost over that with silicon steels, especially in the mass production. For the laboratory prototype, wire cutting method is widely used to build the SMC cores for electrical machine. However, cutting the SMC preform block can destroy the magnetic properties of the SMC material, making that the electrical machine made in the laboratory cannot have the same performance as that in the mass production. To minimize the gap between the laboratory prototype and the mass production, the SMC cores should be made by the die compaction. However, to achieve high mass density, the compact pressure must be high and the productivity is low. On the other hand, low mass density compaction would greatly increase the productivity, but the core performance may deteriorate, which can be dealt with careful design and optimization of electrical machine. This paper presents our recent investigation on the manufacturing process of soft magnetic cores. The details of designing the die tools and building the SMC cores by using these tools are described.**

***Index Terms*—Die compaction, soft magnetic composite (SMC) material, low manufacturing cost, mass production, laboratory prototype.**

I. Introduction

RECENTLY, the soft magnetic composite (SMC) material has shown its advantages over the traditional silicon steel in designing electrical machines [1]-[4]. The advantages of the SMC material can be summarized as, 1) magnetic and thermal isotropy, 2) short eddy current path, 3) relatively high saturation flux density, 4) net shape of compacted core, 5) easy to be manufactured with the complex structures, and 6) low manufacturing cost especially in the mass production. However, it also has the following disadvantages, 1) low permeability, 2) high hysteresis loss, and 3) low mechanical strength [5], [6]. For the general occasion, it is very difficult to design an electrical machine with the SMC cores with better performance than that with high grade silicon steels, when the traditional electrical machine topologies are applied such as the radial flux machine [1]. To design a good electrical machine with SMC cores, the following design guidelines should be obeyed. Firstly, it should be designed with the permanent magnet (PM) excitation to minimize its demerit of low permeability. Secondly, it should be designed to operate with relatively high electric frequency, for example over than 300 Hz. Thirdly, it should be designed with 3D magnetic flux paths to utilize the magnetic isotropy property. Fourthly, it should be designed with simple structure for die compaction to lower the manufacturing fees [5]-[11].

Electrical machines are generally composed of the stator core, rotor core, windings, shaft, bearings and machine frame. From the viewpoint of manufacturing, the main difference between the electrical machine with SMC cores and that with silicon steels are the stator cores and rotor cores. The manufacturing process of the winding is determined by the machine topology [12].

The main manufacturing processes of the silicon steel cores include the lamination cutting and lamination stacking, as well as the lamination surface insulation, annealing, heat treatment. Lamination cutting can be completed by two ways, one is the stamping machine cutting (mass production) and the other is laser beam cutting. To keep the magnetic, thermal and mechanical properties of the silicon stamped or laser cut laminations, the lamination annealing is also needed. Lamination stacking is always made by compressing the laminations with high pressure for obtaining the rigidity of the silicon cores; they can be bonded using either adhesives or pins [10]. Thus, there are some disadvantages of the manufacturing process of the silicon steel cores, 1) material wastes, and 2) many manufacture steps which increase the manufacturing cost.

The main manufacturing processes of the SMC cores include three aspects, 1) powder production, 2) powder compaction, and 3) heat treatment, as shown in Fig. 1 [13]. This kind of manufacturing method belongs to the powder metallurgy technology. The SMC powder is made by the powder metallurgy technology, each particle is composed of the pure iron particle enclosed by the inorganic insulation layer, and the average diameter of the iron particle is 0.1 mm, as shown in Fig. 2. The SMC powder is provided by the material companies. The machine manufacturers only need to do the rest two steps (powder compaction and heat treatment). In the powder metallurgy technology, the main methods to build the iron core include the die compaction, powder injection molding, and iso-static compaction. The powder injection molding is not suitable for the SMC particle due to its large size and that it is hard to obtain high mass density. Compared with the die compaction, the productivity of iso-static compaction is much lower. Therefore, for the mass production, die compaction is chosen.

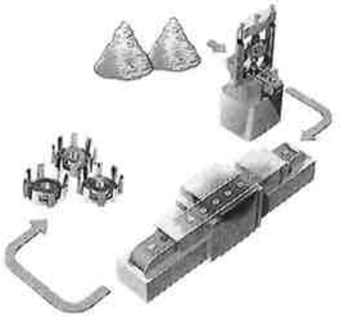

Fig. 1. Main manufacturing process of SMC cores [13]

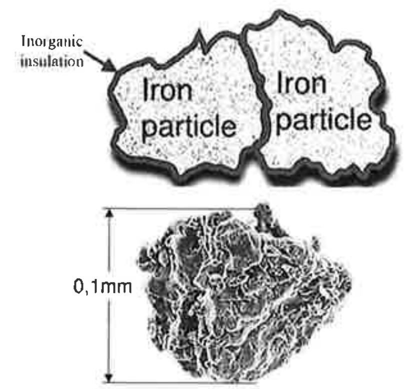

Fig. 2. Diagram of SMC particles [13]

Through the comparison of the manufacturing process of the silicon steel core and SMC core, it can be concluded that the SMC core has the following advantages. 1) Less manufacturing steps, less manufacturing machining, higher productivity and lower manufacture cost. 2) Less material wastes (about 95% usage). 3) Net shape and no need for further machining. In conclusion, the SMC material has the great potential for designing the low cost electrical machine.

II. Manufacturing Process of SMC Core in the Laboratory

For the mass production of SMC cores, the die compaction method is widely used as the advantage of low manufacturing cost. However, it is difficult to use this method to prototype the SMC core in the laboratory since it is expensive to build a set of this kind of die tools. Nowadays, the wire cutting method is widely utilized to build the SMC cores in the laboratory.

A. Wire Cutting Method for the Production of SMC Core

Through cutting the SMC pre-forms provided by the material company, the wanted SMC core can be obtained. To improve the performance of SMC core, the heat treatment is also needed after the SMC core is obtained from the pre-form. Using this method, the prototyping is quite easy and cheap. On the other hand, there are some disadvantages of the SMC core made by this method. Firstly, all the SMC blocks need to be obtained from the material company; the prototyped core will based on determined mass density. From our previous work, it can be found that the performance of the SMC motor can be optimized with the different mass density, when the manufacturing cost is considered [16]. As shown in Fig. 3 and Fig. 4, the mass density of the SMC core determined by the compaction method and the magnetization curve is determined by the mass density. Thus, the mass density of the SMC core should be controlled by the designers themselves. Secondly, the SMC cores with different sizes and shapes may need different kind of heat treatment process. As shown in Fig. 5, the heat treatment process really affects the magnetic properties of SMC core. For the SMC core, the optimized heat treatment process is necessary to be obtained, which will be considered in our future work. Thirdly, cutting the SMC block will destroy the magnetic properties of the SMC material. As shown in Table I, the maximum permeability of one kind of SMC material is 565, while after cutting; its maximum permeability becomes 359. As well as the cutting process will make the SMC material have higher core losses for the insulation layer of the SMC is destroyed [14]. Thus, using the wire cutting method to build the SMC cores has several drawbacks, and a new manufacturing method for building the SMC core in the laboratory should be proposed.

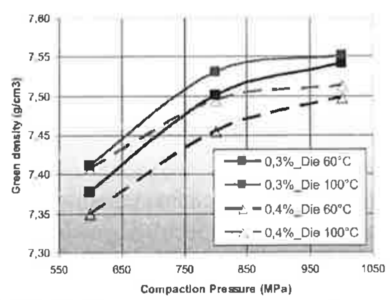

Fig. 3. Density of the SMC cores with different compaction pressures and methods [14]

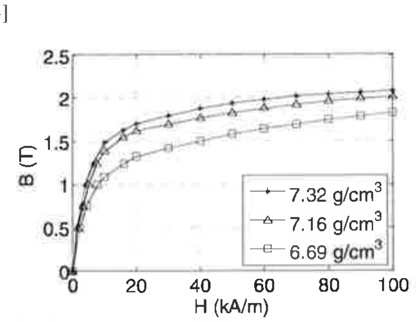

Fig. 4. Magnetization curve of the SMC cores with different mass density

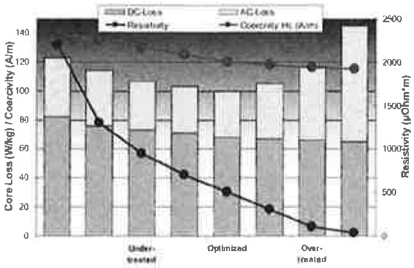

Fig. 5. Influence of the heat treatment to the electromagnetic properties of SMC cores [14]

B. Manual Die Compaction of SMC Core

To ensure that the performance of the electrical machine prototyped in the laboratory can have the similar performance as that in the mass production, the die compaction of the SMC core is necessary. To reduce the prototyping cost, manual die compaction may be used. Similar to the SMC core in mass production, the SMC core made by the manual die compaction has three steps as well: 1) the premix of the SMC powder, 2) powder compaction, and 3) heat treatment. The main differences between the manufacturing process in industry and laboratory are the tool quality and the compaction process. To better explain the compaction process of SMC core by using the manual die, it is necessary to explain the principle of the compaction process of SMC core in the mass production firstly.

Table I
Effect of machining process to the compacted SMC core

Sample	Machined	Compacted
Density (g/cm3)	7.46	7.5
Resistivity (μΩm)	1356	1179
Flux density (at 4kA/m) (T)	1.09	1.32
Flux density (at 10kA/m) (T)	1.47	1.58
Maximum relative permeability	359	565
Core loss (at 1T, 400Hz) (W/kg)	53	45
Core loss (at 1T, 1kHz)(W/kg)	158	134
Core loss (at 1.5T, 200Hz) (W/kg)	49	43

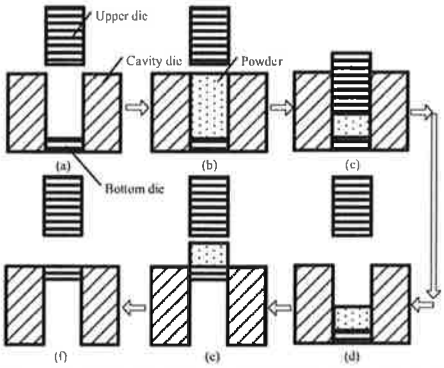

Fig. 6. Main process of the compaction of SMC core in mass production

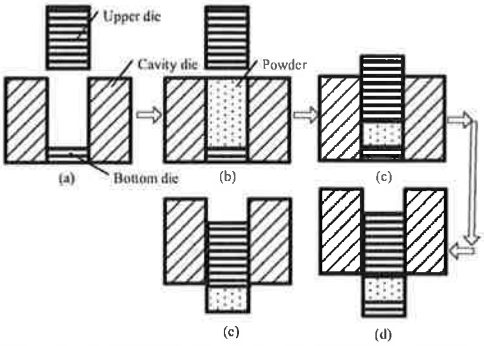

Fig. 7. Main process of the manual compaction of SMC core in laboratory

Fig. 6 shows the main compaction process of SMC core in the mass production. It can be seen that the die tools are composed of three parts, 1) upper die, 2) bottom die, and cavity die. Before pouring the powder, the bottom die and cavity die are assembled as shown in Fig. 6(a). The height between the upper surface of the bottom die and the cavity die is determined by the wanted core density and powder density. After the powder is poured into the cavity die, the upper die is pressed to compact the powder to the wanted core, shown in Fig. 6(c). Then, the upper die is pulled out from the cavity die, and the bottom is pushed upward to remove the compacted core from the cavity die. The key to the die compaction in the mass production is that both the upper die and bottom die can be controlled to either the upward or downward direction by the pressing machine, and thus the compacted core can be released from the die tools easily.

The main difference between the die compaction of SMC core in mass production and in laboratory is how to release the SMC core. For the laboratory compaction, the pressing machine is only controlled to press downward, while the productivity is not crucial. Releasing the compacted SMC core from the upper die is the last step, and specific steps to release the SMC core can be always changed and they depend on the specific design. In this paper, some examples will be given to show how to release the SMC core from the upper die.

To design the die tools for the manual compaction of SMC core, some attention should be paid to. Firstly, the position tool should be designed appropriately, so the mass density of the SMC core will be uniform for different parts. Secondly, the upper die should be designed capable of pressing the powder evenly. Thirdly, the releasing process should be considered carefully [15]. Generally, there are three kinds of connection relationships between the upper die and the SMC core, as shown in Fig. 8. To ensure that the obtained SMC core is good, when taking the SMC core from the upper die by hand, the relationship between the SMC core and upper die should be the last one (Fig. 8(c)), and avoid the first one (Fig. 8(a)).

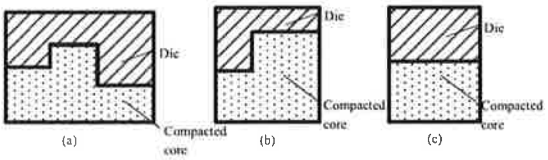

Fig. 8. Three kinds of connection between the upper press and compacted core.

The specific design process of the die tools and how to use these die tools to compact the SMC cores are shown in the following section, with some examples.

III. Compaction of SMC Core for Claw Pole Machine

In this section, the specific process of compaction of the SMC core for a claw pole machine (CPM) is illustrated. Different from the SMC core for the 3D TFFSPMM, the stator core for CPM structure is more complex as it has three different heights and the thickness for the stator yoke and the stator teeth are only 3 mm.

A. Topology of Claw Pole Machine

Fig. 9 shows the topology of the CPM with SMC core, which is the single phase model. The complete machine is composed of three single phase models, which are stacked axially with shifting angle of 120° electric degree to each other. Each phase model consists of two disks with the concentrated global winding in between. The rotor of CPM has 12 magnets, which are surface mounted on the rotor iron core. One housing component is used to hold and protect the stator core [17].

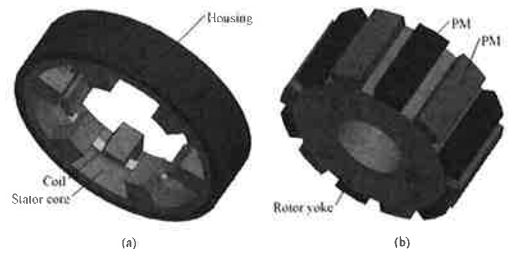

Fig. 9. Topology of claw pole machine.

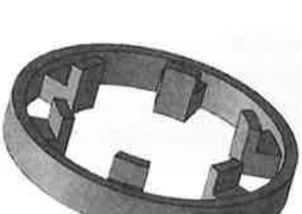

Fig. 10. One piece of stator core for claw pole machine.

To simplify the manufacturing process, the stator core for each phase is divided into two pieces, as shown in Fig. 10. Comparing with the rotor core and stator core for the 3D TFSPMM, it can be found that the structure of stator core for CPM is more complex, which has three different heights for stator yoke, stator wall, and stator teeth.

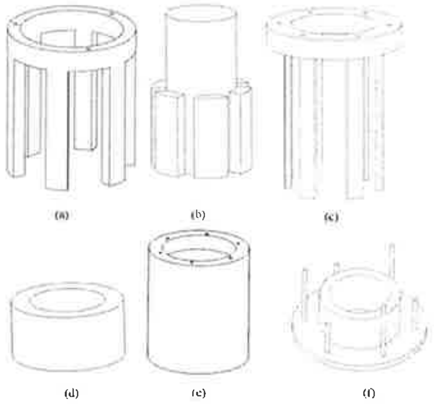

Fig. 11. Die tools for compaction of stator core for claw pole machine.

B. Compaction of Stator Core

For the compaction of stator core for CPM, 6 different die tools are needed. Fig. 11(a) is the upper die for pressing the stator wall. Fig. 11(b) is the inner cavity die for determining the inner shape of the stator core and it also functions to determine at which position the upper die will stop when the stator core is made. Fig. 11(c) is the upper die for pressing the stator teeth. Fig. 11(d) is the cavity die for determining the outer shape of the stator core. Fig. 11(e) is the upper die for pressing the stator yoke. Fig. 11(f) is the position tool to ensure that the die will be poured with appropriate powder for the compaction.

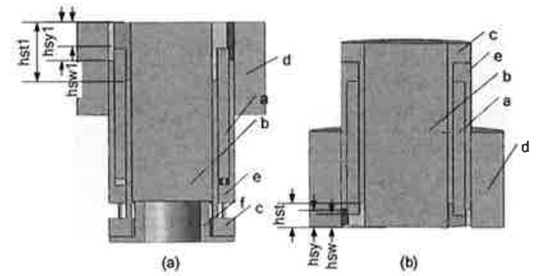

Fig. 12. Two typical assembled status of the die for compaction of stator core for claw pole machine.

To compact the stator core for CPM, three steps are needed. Fig. 12 shows the typical assembled status of the die for compaction of stator core for CPM. Fig. 12 (a) is the status for pouring the SMC powder, and Fig. 12(b) is the status when the stator core is compacted.

Step 1: Pour the powder into the die tools. Before pouring the powder, the die tools are assembled as shown in Fig. 12(a). The tool f is put below all the other tools, and then the tools c, e, a, b, and d. The heights of poured powder for stator teeth, stator wall and stator yoke are hst1, hsw1 and hsy1 respectively, which are several times the heights of stator teeth, stator wall, and stator yoke of the completed stator core.

Step 2: Compaction of the stator core. Put a cylinder steel plate on the top surface of the assembled die tools

(Fig. 12(a)), and then put them upside down and put them on the pressing machine. Use the pressing machine to press the tool f. When f touches tool e, the pressing machine will press the tool e as well. When tools f and e touch tool c, the pressing machine will compact all the upper die tools until the upper surface of tool c reaches the same plane as that of tool b. By using the above method, the stator core can be compacted.

Step 3: Release the stator core from the cavity die. Put two cylinder stator irons below the dies, one is under the tool d and the other is under tool b. Continue to press tool c to make the stator core out from the cavity. Then, fix the position between tool d and tool e, use tool f to press tool a to make the stator core leave from the die tools a and e, and then the stator core can be taken out by hand.

For these tools, the manufacturing requirement for tools a, b, c, e, and f is high, which should be made by the hard tool steels. The other parts can be manufactured by the common steels in the workshop.

IV. Heat Treatment

After the SMC core is compacted, the SMC cores are very fragile and easy to be broken. The heat treatment can improve the mechanical strength of the compact SMC core but also can eliminate the defects in the core resulted by the compact process. However, if the SMC core is over heat treated, the insulation layer could be destroyed by the high temperature and the phase structure of the particle would be changed. Thus, the heat treatment is quite important in the manufacturing of SMC cores. Nowadays, the two step heat treatment method is popular for the heat treatment of SMC core.

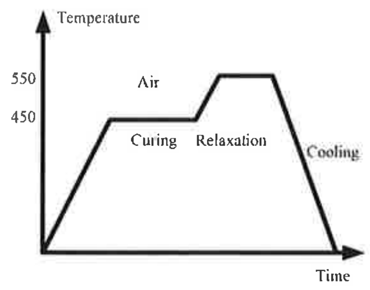

Fig. 13. Heat treatment process of the compact SMC core.

Fig. 13 shows the heat treatment process of the compact SMC core, a general temperature pattern for the SMC cores. The basic effect of first 450 °C is to ensure that compacted SMC core can be a complete part and thus it can have enough mechanical strength. The effect of second 550 °C is to eliminate the stress and improve the magnetic performance. For the different structure and mass density of SMC core, the optimized heat treatment process should be different. It will be investigated in our future work.

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V. Conclusion

Compared with the traditional electrical machine with silicon steels, the electrical machine with SMC cores owns the benefits of low manufacturing cost, and it may dominate in the low cost domestic applications in the near future. For the construction of electrical machine with SMC core in the laboratory, the wire cutting method is quite easy, but this kind of construction method has some constraints. To minimize the gap between the laboratory prototyping and the mass production, the manual die pressing method is quite important. The manual die pressing decreases the manufacturing cost of the SMC core in the laboratory and also has the high flexibility to improve the motor design, for example, the different kind of the mass density of the SMC core with different heat treatment can be chosen. These factors can be investigated in the later design optimization stage by using some optimization methods [19-23]. Then the best motor design scheme can be found in terms of different manufacturing methods and production volumes.

This paper systemically reports the compaction principle, how to design the die tools for the compaction, how to use the designed die tools for the compaction, and how to heat treatment the compacted core. By using a example, the details of manual die pressing are presented.

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