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TITLE: Manufacturing Condition and Variations of Soft Magnetic Composite Cores for Application in PM Motors Based on Taguchi Method
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ABSTRACT BODY:
Digest Body: Soft magnetic composite (SMC) material has been investigated for the development of cores for permanent magnet (PM) motors in recent years. Compared with the cores made of traditional silicon steel sheet, there are several special properties of SMC cores, including (1) the isotropic performance in electromagnetic and thermal properties due to the powder nature of SMC, making it ideal for the PM motors with 3D flux path, such as transverse flux machine (TFM) and claw pole motor (CPM); (2) the lower eddy current loss and magnetic permeability because of the isolation coat of the particles, (3) the easier manufacturing ability of stator/rotor cores by using molding technology [1]-[3].

On the other hand, there are two main challenges for the manufacturing and application of SMC cores in PM motors. First, heat treatment is a crucial process in the manufacturing of SMC cores. There are several control parameters in this step such as the burn-off and curing temperatures and times. They will determine the core loss and magnetic permeability of the manufactured SMC cores. Therefore, optimal manufacturing factors should be investigated to obtain the best magnetic properties of the cores. Second, there are some manufacturing variations of the SMC cores like core densities and dimension, which will lead variations of the motor performances, such as output power and efficiency. Thus, the quality of the manufactured SMC cores will affect the quality of the SMC motors. To gain the best performances and good quality of the SMC cores and motors, manufacturing uncertainty analysis should be investigated for both SMC cores and motors. This work will consider these two challenges by using the Taguchi method.

The Taguchi method is a robust design method with consideration of manufacturing variations and other noise factors in the manufacturing and usage of a product like motor. It is a structured approach for determining the best combination of inputs to produce a product or service, based on the orthogonal design technology and quality loss functions (or S/N ratio). It is one of the most powerful methods available to reduce product cost, improve quality, and simultaneously reduce development interval [4]-[6].

In this work, this method will first be used for the determination of the best parameters for the heat treatment of SMC cores, and some manufacturing variations will be discussed. Then, to decrease the effects of manufacturing variations of SMC cores on the motor performances, this method will be investigated again to find out the best dimension of a 3D TFM to increase the manufacturing quality of the motor.

1. Determination of the best heat treatment parameters of SMC cores
Fig. 1 illustrates several manufacturing facilities and samples for a 3D TFM with SMC cores. The hydraulic compact machine (Fig.1(c)) uses the die tools (Figs.1(a) &(b)) to compact the SMC powders to produce the raw SMC core (Fig.1(e)), then the high-temperature furnace will cook the raw core with a controlled heat treatment plan as shown in Fig. 1(g) to obtain a cooked core (Fig.1(f)).

As shown in Fig.1(g), there are five main parameters for the heat treatment of the SMC cores. They are Te1, Te2, Te3, Ti1 and Ti2. Te1 is the initial temperature of the furnace. The basic effect of temperature Te2 is to ensure the mechanical strength of the compacted SMC core. The effect of temperature Te3 is to eliminate the stress and improve the magnetic performance. Ti1 and Ti2 are the cooking times. To determine the best parameters of them, an orthogonal design is adopted with three levels for each factor. Table 1 lists the details of the orthogonal array. As shown, there are 18 experiments. For each experiment, the relative permeability and the core loss are measured for the cooked core. The measured results are shown in the table as well. Based on the analysis of Taguchi method, it is found that the best levels for those five heat treatment parameters are [200 °C, 480 °C, 60 mins, 500 °C, and 30 mins]. The obtained relative permeability is 267 and core loss is 4.48 W/kg.

2. Determination of the best dimension of a SMC motor

Based on the experimental results, it is found that there are some manufacturing variations for the cooked SMC cores. The most important one is the relative permeability, which will affect the electromagnetic analysis and performances of the designed motor. However, it is hard to decrease these variations in the core manufacturing step (high cost will be required to upgrade the equipment like the high-temperature furnace). Therefore, the dimension of the motor is optimized to decrease the sensitivity of these variations by using the Taguchi method. In the implementation, seven parameters including PM dimension and air gap are selected as the control parameters and the relative permeability is regarded as noise factor. With a similar analysis to the heat treatment part, an optimal design is obtained. This design can increase the motor reliability from around 76% to 98% by using the proposed method.

In conclusion, Taguchi method benefits the manufacturing of good quality SMC cores and PM-SMC motors.

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KEYWORDS: Soft Magnetic Composite, Manufacturing Variations, Taguchi Method.

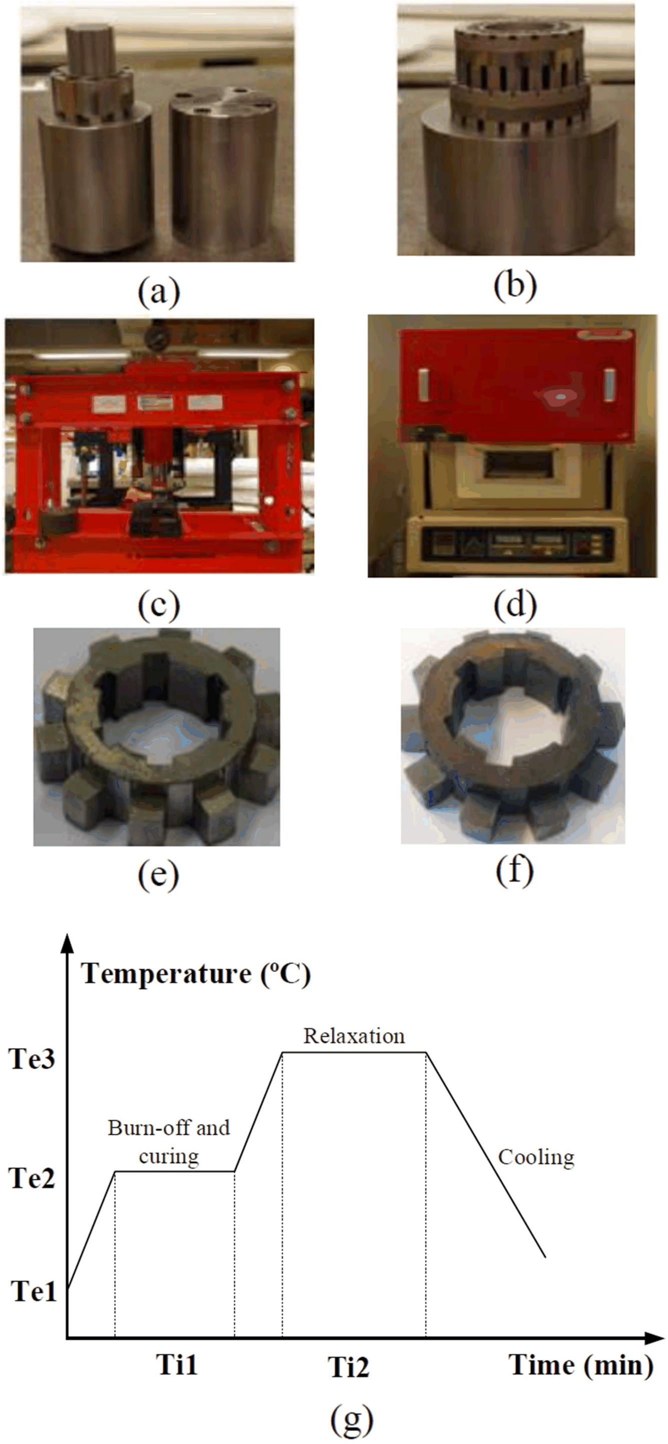

Fig. 1. Manufacturing facilities and SMC cores for the proposed 3D TFM, (a) die tools for compaction of rotor core, (b) die tools for compaction of stator cores, (c) hydraulic compact machine, (d) high-temperature furnace, (e) rotor core before heat treatment, (f) rotor core after heat treatment, (g) heat treatment plan.

No.	X1. Te1 (°C)	X2. Te2 (°C)	X3. Ti1 (min.)	X4.Te3 (°C)	X5. Ti2 (min.)	μ_r	Core loss (W/kg)
1	25	420	30	500	10	210.73	10.87
2	25	450	60	550	30	239.76	14.73
3	25	480	90	600	50	192.1	66.21
4	100	420	30	550	30	243.34	67.48
5	100	450	60	600	50	197.12	70.42
6	100	480	90	500	10	261.68	7.56
7	200	420	60	500	50	249.63	5.71
8	200	450	90	550	10	265.92	14.57
9	200	480	30	600	30	206.15	67.48
10	25	420	90	600	30	222.22	48.72
11	25	450	30	500	50	273.33	7.42
12	25	480	60	550	10	274.41	15.13
13	100	420	60	600	10	202.56	83.4
14	100	450	90	500	30	226.28	5.94
15	100	480	30	550	50	250.75	14.9
16	200	420	90	550	50	271.49	13.59
17	200	450	30	600	10	183.11	74.4
18	200	480	60	500	30	267.1	4.48

Table 1. Orthogonal array and experimental results for heat treatment
