

Development of Transverse Flux Motor with Improved Material and Manufacturing Method

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ABSTRACT

Honda has been proposing and developing a Transverse Flux Motor (T.F. motor) in order to shorten axial length of the motor for hybrid electric vehicles (HEVs). In contrast to conventional motors that are composed of a stator core (made from magnetic steel sheet) and winding wires, the T.F. motor is a new type of three-dimensional magnetic circuit motor composed of a soft magnetic composites (SMC) core and a coil. While reducing axial length and achieving a simple stator architecture comprised of just five parts, the new motor raises issues including the need to improve motor efficiency and the development of techniques for the manufacture of rectangular wave-shaped coils.

To improve motor efficiency, we conducted a parameter study of the SMC core material and manufacturing conditions to establish the optimum required specifications for reducing iron loss. In order to successfully manufacture rectangular wave-shaped coils, we developed a coil film that fulfilled the required criteria for both manufacturability and insulation, in addition to developing a new press-forming manufacturing method that bends and reduces the diameter of ring-shaped coils in order to form rectangular wave-shaped coils. We created and tested a prototype of the T.F. motor using the improved SMC core and the rectangular wave-shaped coils produced using the new press-forming method. The average motor efficiency in JC08 mode improved from 79.1% to 83.7%.

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INTRODUCTION

The introduction of electrically driven components into the vehicle power train, as seen in hybrid vehicle, is one method of reducing CO₂ emissions through improved fuel consumption efficiency. Honda's hybrid vehicle system, known as the IMA system (integrated motor assist system)^{[1][2][3][4]} is shown in Fig. 1, with the power train shown in Fig. 2. Fuel consumption efficiency can be improved using a motor to provide additional torque and energy regeneration when braking. As the motor is located between an internal combustion engine and a continuously variable transmission (CVT), the width of the powertrain increases according to the axial length of the motor. Therefore, to use the hybrid vehicle system on various vehicle types with different width requirements, the axial length of the motor needs to be shortened.

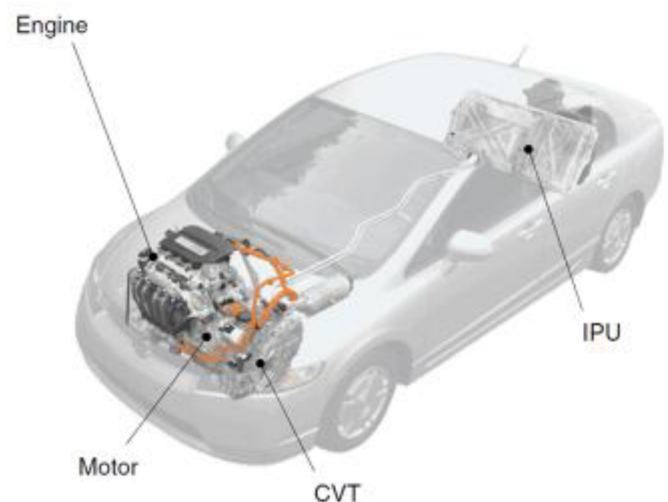


Figure 1. IMA System

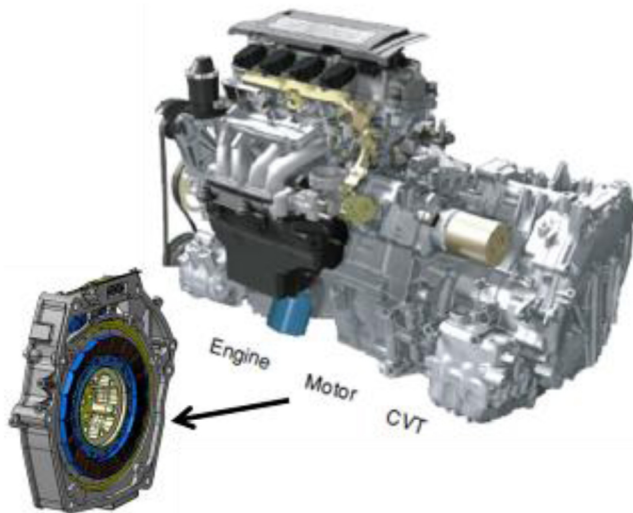


Figure 2. IMA powertrain

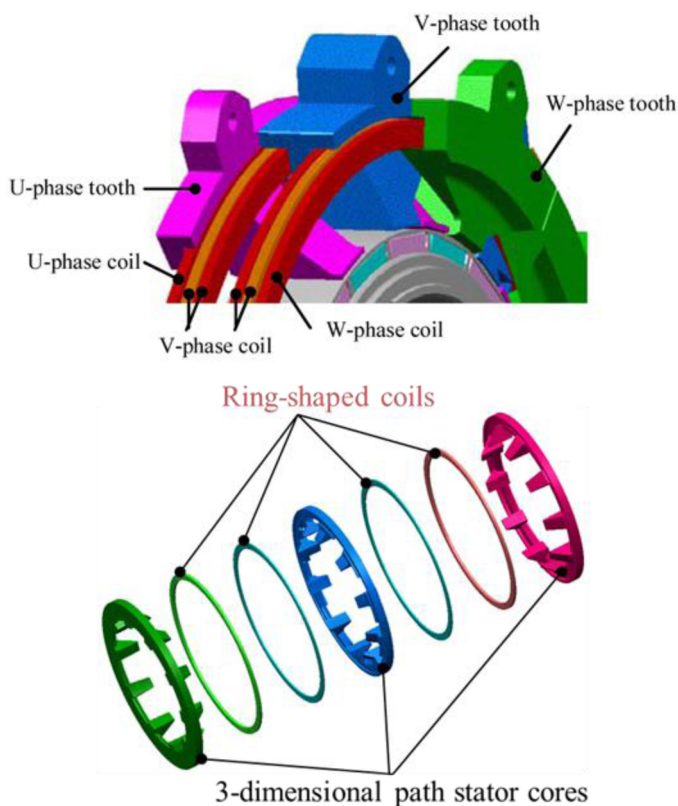


Figure 3. Structure of original T.F. motor

To shorten the axial length of the motor, the authors focused on eliminating the coil end, which does not contribute to the generation of torque, by proposing a transverse flux motor^[5] (henceforth “T.F. motor”) with internal ring-shaped coils and new type of flux path as shown in Fig.3. The design was later improved to counter magnetic saturation and magnetic “short circuits” as shown in Fig.4^[6]. A prototype was constructed to confirm that, in comparison

with the conventional salient-pole concentrated winding motor, the same torque could be generated with a 32% shorter axial length. While the stator of a salient-pole concentrated winding motor, where each tooth is a separate part, is composed of 110 parts, the T.F. motor uses a simple stator made by stacking the three 3-dimensional stator cores and two rectangular wave-shaped coils. However, the authors had to resolve issues, including the improvement of motor efficiency (which drops due to iron loss characteristics of the soft magnetic composites(SMC) used to make the stator), while also developing and manufacturing methods for producing rectangular wave-shaped coils from ring-shaped coils. In this paper, the authors describe methods for reducing iron loss, the development of a method for manufacturing rectangular wave-shaped coils, and the creation and testing of a prototype T.F. motor that incorporates these elements.

(Comparison with the conventional motor)

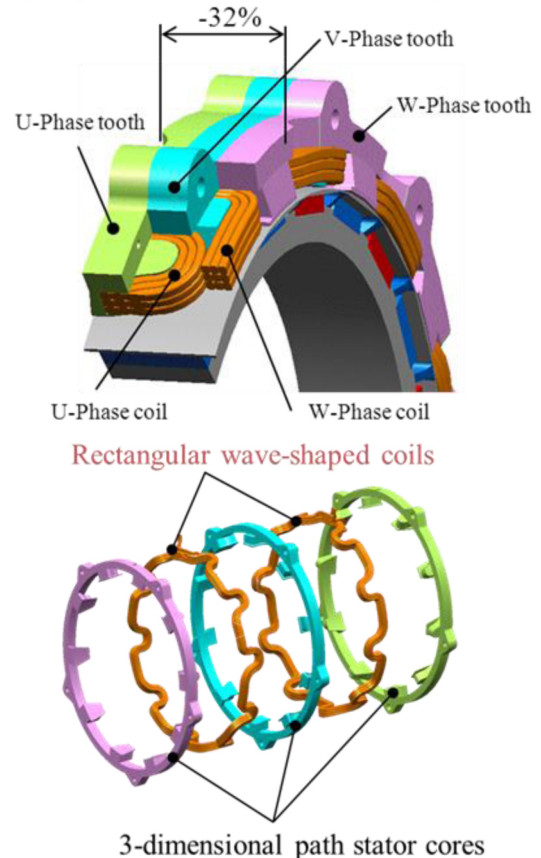


Figure 4. Parts of the improved T.F. motor (5 parts in total)

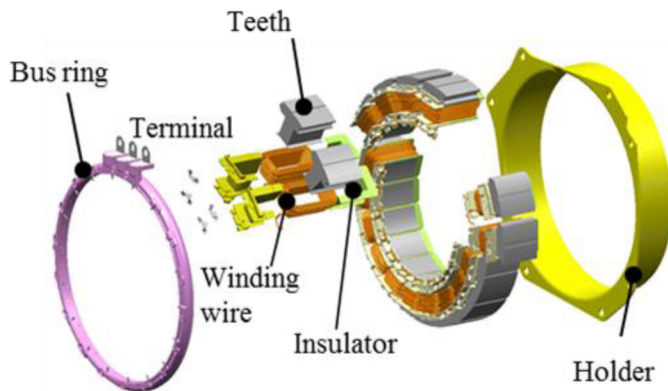


Figure 5. Parts of the salient-pole concentrated winding motor (110 parts)

COUNTERMEASURES FOR REDUCING IRON LOSS

Figure 6 shows the non-load loss for the improved T.F. motor shown in Fig.4 before countermeasures for reducing iron loss were introduced. The vertical axis shows no-load loss divided by the angular speed of the motor revolutions (=no-load torque). The y-axis intersection shows the hysteresis loss, while the gradient shows the eddy current loss. Both the hysteresis loss and the eddy current loss must be reduced in order to bring the T.F. motor iron loss close to the target loss. SMC is produced by compacting iron powder coated with a thin insulator and then heat-treating the greens, as shown by the schematic in Fig.7. A reduced coercivity is required to reduce the hysteresis loss of the SMC. To reduce the eddy current loss, measures must be taken to prevent the destruction of the insulator during the compacting and heat treatment process. In the section below, concrete measures for reducing the above losses of the SMC are described in detail.

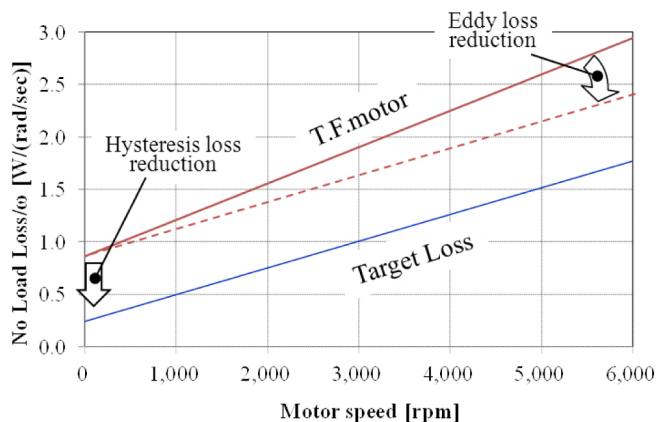


Figure 6. Actual and target no-load loss for T.F. motor before additional countermeasures

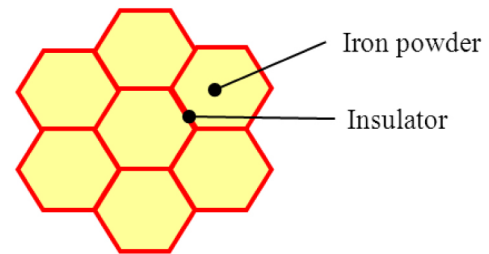


Figure 7. Schematic showing structure of soft magnetic composites

Countermeasures for Hysteresis Loss

To reduce the coercivity of the iron powder, which is required to reduce hysteresis loss, obstacles preventing the movement of flux must be removed. The principal factors are the grain boundary of the iron powder and the strain of the iron powder during the compacting process. Therefore, in this section we investigate means of increasing the grain size through annealing of the iron powder, as well as means of preventing strain by increasing the heat treatment temperature after compaction. The experimental results for each condition and test piece are shown below.

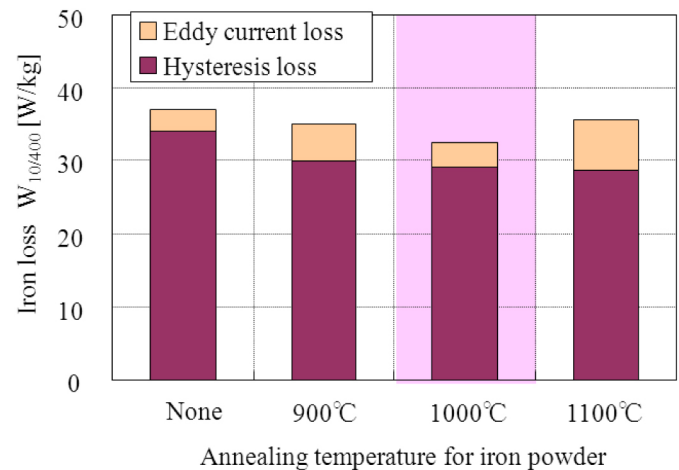


Figure 8. Actual relationship between Annealing of iron powder and the results of iron loss

Figure 8 shows the iron loss as a function of the temperature at which the powder was annealed, while Fig. 9 shows micrographs displaying the corresponding structure. Annealing is conducted in a hydrogen atmosphere. As apparent from the photographs of the structure shown in Fig. 9, grain size increases through annealing of the powder. As shown in Fig. 8, this increase in grain size reduces hysteresis loss. Figure 10 shows the relationship between the temperature at which the powder was subject to annealing and the iron powder size. When annealed at 1100°C, the iron powder is sintered, thereby increasing in size of iron powder and increasing the eddy current loss inside the iron powder, resulting in an increase in overall iron loss as shown in Fig. 8.

Therefore, the optimum temperature of the annealing of the iron powder is 1000°C, where the maximum reduction in iron loss is obtained.

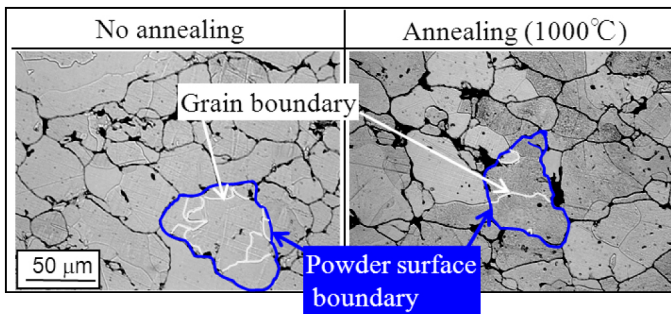


Figure 9. Optical microscope section image of grain size

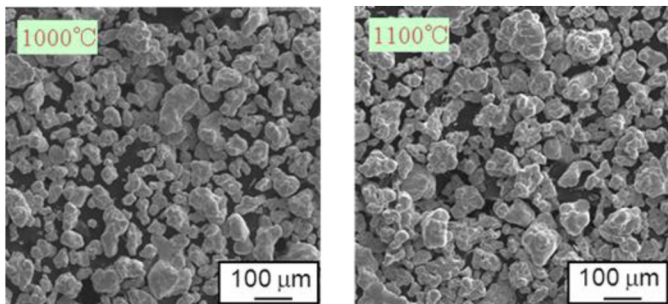


Figure 10. Scanning electron microscope image of relationship between annealing temperature and powder size

The authors then investigated how increasing the heat treatment temperature after compaction resulted in reduced strain. When heat treating under a high temperature, the extent of the reduction in iron powder strain was measured and compared when using a coating of phosphate, a standard insulator for SMC, and when using a coating of magnesium oxide (MgO), which has higher heat resistance properties^[7]. Figure 11 shows the relationship between the measured iron loss and heat treatment temperature. The MgO coating has greater heat resistance than the phosphoric acid coating. Therefore, the MgO coating shows greater heat resistance than the phosphoric acid coating even at temperatures where the eddy current loss increases dramatically. Hysteresis loss decreases with higher heat treatment temperature irrespective of coating type. Therefore, the MgO coating should be used during the heat treatment process with an optimum temperature of 650°C.

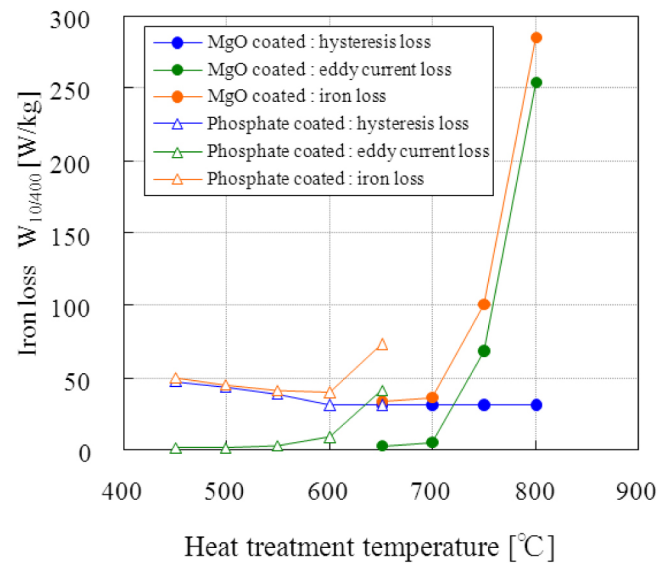


Figure 11. Actual relationship between heat treatment temperature after compaction and measured iron loss

Methods of Reducing Eddy Current Loss

To reduce eddy current loss, the insulation coating of the iron powder must remain intact. It can be destroyed during either the compacting or the heat treatment process, and it must be able to withstand the heat treatment temperature of 650°C. Therefore, in the section below, methods for protecting the insulation coating during the compacting process are discussed.

The compacting process destroys the MgO coating because the membranes split through contact with each other. This can be prevented by reducing the roughness of the iron powder surface and improving its fluidity during compacting. Therefore, this section investigates the benefits, in terms of reduced eddy current loss, that can be achieved firstly by using a centrifugal mill to reduce the iron powder surface roughness, and secondly by increasing the volume of resin binder and using a lubricant to improve iron powder fluidity. The experimental results for each condition and test piece are shown below.

Figure 12 shows micrographs that demonstrate the difference in powder morphology depending on whether a smoothing process is used. A smoothing process reduces the surface roughness of the powder, making the grains rounder. Further, Fig. 13 shows the relationship between smoothing time and iron loss. The longer the smoothing process, the greater the reduction in eddy current loss. However, an extended smoothing process reduces the interaction between iron particles, resulting in reduced compactibility. Based on the compactibility limit for the shape of the stator, the optimal smoothing time is 4 minutes.