Journal of Magnetics 20(2), 155-160 (2015)
ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
http://dx.doi.org/10.4283/JMAG.2015.20.2.155

Efficiency Improvement of an Automotive Alternator by Heat Treatment

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(Received 20 May 2015, Received in final form 8 June 2015, Accepted 9 June 2015)

Recently, CO_2 emission standards and fuel efficiency legislation has been tightened globally. Therefore automotive alternator performance becomes increasingly important to meet the requirements. Many proposed methods have suggested adding magnets or regulation control to increase alternator efficiency and output. However, this creates a significant additional cost. During the stator lamination process, the magnetic property of the stator deteriorates mainly due to stamping and slinky process for an alternator. To maximize the alternator performance, heat treatment of the stator core was performed and magnetic properties were compared to find the optimal condition. Finally, alternator output and efficiency test were performed resulting in significant output and efficiency improvement up to 6.8% and 0.6% respectively.

Keywords : alternators, output, efficiency, heat treatment, slinky, stators

1. Introduction

To meet the mileage regulation and CO_2 restriction, high output and efficiency performance of an alternator for automotive is required by the size constrains. Recent work has proposed solutions but these impose additional cost; for example, adding permanent magnets to reduce the leakage flux [1], using active regulation control scheme [2] and other solutions. However, alternator manufacturers cannot add significant costs since the cost of the alternator itself is low.

During the stator core manufacturing process, electrical steel is stamped and wound by a slinky process. This process maximizes material use since this alternator uses a hot roll for a rotor. In spite of cost benefit of the alternator configuration, magnetic property of stator core deteriorates due to strain and stress during the slinky and stamping process. Although heat treatment (HT) process is well known process for other electric motor applications, HT study for alternator core has still not been performed.

In this paper, HT is proposed to maximize the magnetic property recovering strain and stress due to recrystallization. To find the optimal point, two HT were performed at two different temperatures. This HT study showed that both magnetization and core loss characteristic was greatly improved, which enables us to apply the alternator performance test. Two alternator models were fabricated with a HT stator core and used for a performance test showing 6.8% output increase and 0.6% efficiency improvement. In addition, an audible noise test was performed to verify the deterioration due to HT.

2. Heat Treatment of the Stator Cores

During the slinky and stamping process for the stator core manufacturing, magnetic properties deteriorate due to strain and stress despite its benefits in maximizing the material usage for low cost production. To overcome this deterioration, HT effect study was performed to evaluate the recovery of the magnetic properties in this study. After finding the optimal temperature, alternator prototypes were manufactured with the HT stator core which was prepared by under optimal conditions.

2.1. Stator Core Manufacturing Process

For the alternator stator core manufacturing process, electrical steel or cold rolled sheet is mainly used for the stator core material since this type of material has relatively high permeability and low core loss. In contrast, due to the three dimension configuration, hot rolled sheet is widely used for the rotor material.

The slinky process may help to maximize the material use, which results in cost benefit of the alternator manufacturing. As shown in Fig. 1(a), the material is fed along

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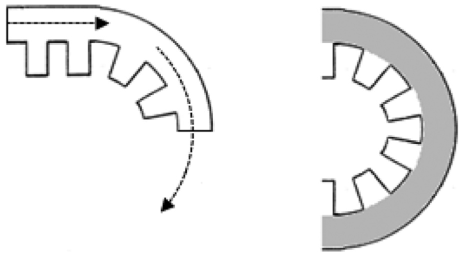

(a) (b)

Fig. 1. Slinky process (a) and deformed area (b).

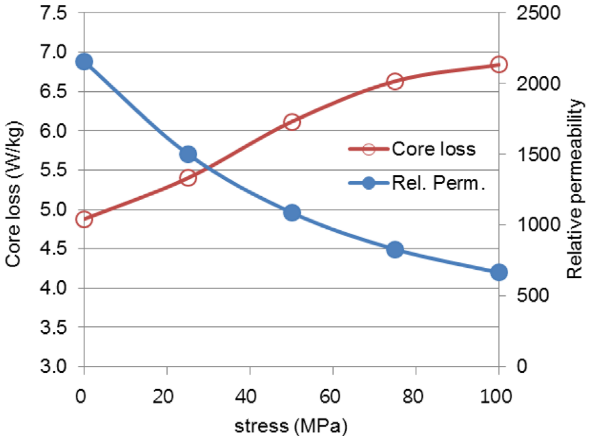


Fig. 2. (Color online) Effect of compressive stress on magnetic properties.

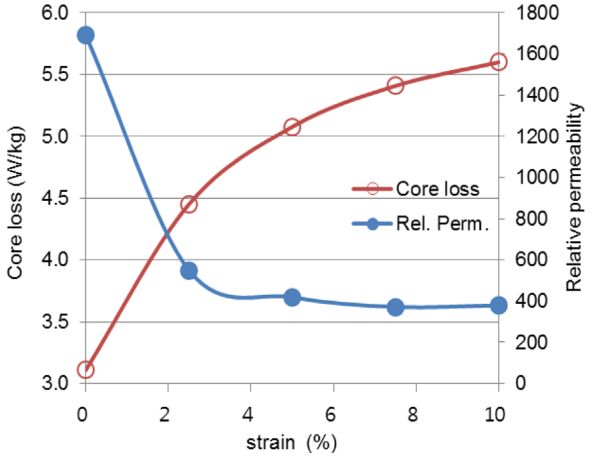


Fig. 3. (Color online) Effect of plastic strain on magnetic properties.

one direction and stamped to make stator slots while the material is being fed. The end of the material is then wound continuously to make a stator core. In this process, the material experiences large deformation which is marked in grey in Fig. 1(b) due to stamping and slinky process. Therefore, this process significantly imposes strain and stress on the overall region of the stator core.

After completing the slinky process, the stator cores are welded so that the laminations are stacked together to meet the stator dimension requirement for the alternator, which results in additional residual thermal stress on the surface of the stator core along with the welding paths.

2.2. Magnetic Properties under Strain and Stress

Electrical steel is widely used for rotating machines since this material is produced to maximize magnetic properties both the magnetizing and the core loss characteristics. During the manufacturing process of electrical steel, Si and Al are added to electrical steel to increase resistivity and the material is rolled to reduce the core loss which is related with the classical eddy current loss, one of main components of core loss. In addition to this process, electrical steel is annealed to get a favorable microstructure as well as to reduce the dislocation and recrystallize after the rolling process. Consequently, the electrical steel sheet material is stress and strain free itself. These properties are exacerbated with strain and stress imposed on the electrical steel material during the alternator manufacturing process. Fig. 2 describes the effect of stress on the magnetic property of electrical steel. For experiment, single sheet test (SST) method with an air actuator that enables compression of the specimen with feedback control by load cell signal was used for the experiment.

Although tensile stress has relatively less negative effect on the magnetic properties, compressive stress was found to reduce the magnetic properties remarkably. As shown in Fig. 2. About 40% core loss increased at 100 MPa compressive stress measured at 50 Hz, 1.5 T. As for the relative permeability, which is related with magnetization, 70% of the relative permeability decreased measured at 50 Hz, 1.5 T. A former study regarding the strain effect on the magnetic properties was performed [3]. According to this study, the relative permeability showed higher dependency on the strain, both the relative permeability and the core loss as shown in Fig. 3. About 80% of the core loss and relative permeability deterioration occurred at 10% strain, measured at 50 Hz and 1.5 T, and even 2% strain may significantly affect the magnetic properties.

2.3. Alternator Specification for the HT Models

Prior to the alternator performance test, the magnetic property test to compare non-HT stator core and HT stator cores were required for verification. In addition to this study, the optimal HT condition study was also required to maximize magnetic property.

To perform the HT study, three alternator models were determined with different materials and output, as shown

Table 1. Alternator model specifications.

Parameters	90A model	120A model	150A model
Voltage (V)	12	12	12
Current (A)	90	120	150
Diameter (mm)	119	120	130
Slot Number	36	36	72
Material	SPCC	50A800	50A800

Table 2. Heat treatment conditions.

Parameters	Value	
Atmosphere	N_2	N_2
Temperature (°C)	740	800
Holding Time (hour)	2	2

in Table 1. The 90A model is made of the cold rolled sheet, while the SPCC and 120A and 150A models are made of the electrical steel, 50A800. Due to the different output, the outer diameter and the slot numbers are also different, and this shows a good combination of different strain and stress levels including material grades.

2.4. Stator Core Heat Treatment Test

There are a number of parameters to be determined for HT: atmosphere type for example, N_2, N_2+H_2 and CO, heat treatment time, and temperature. However, we set N_2 atmosphere and 2 hours for holding time, which is a typical HT condition, and this may reduce the number of HT experiments. In addition, this study was not intended to find the optimal points of HT itself so this is beyond the scope of this study. Therefore, two different temperatures: 740 °C and 800 °C were set for the controlled parameters. The temperature was selected since it is normally acceptable to perform HT at 780 °C for typical stress relief annealing heat treatment but we presumed that this slinky core might need higher temperature than the recommend temperature for better recovery.

However, a temperature higher than 800 °C might not be acceptable since this condition might burn out all insulation coating material on the surface of the electrical steel resulting in excessive core loss. A temperature of 740 °C was also selected since we thought it worthy to see the magnetic improvement at lower than normal annealing temperature. The final HT conditions to be performed are summarized in Table 2.

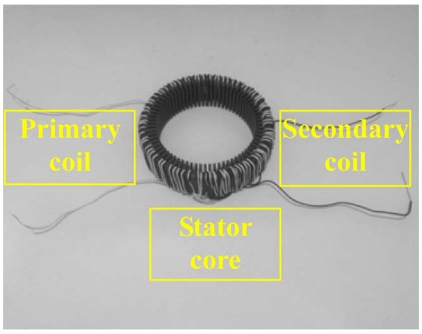
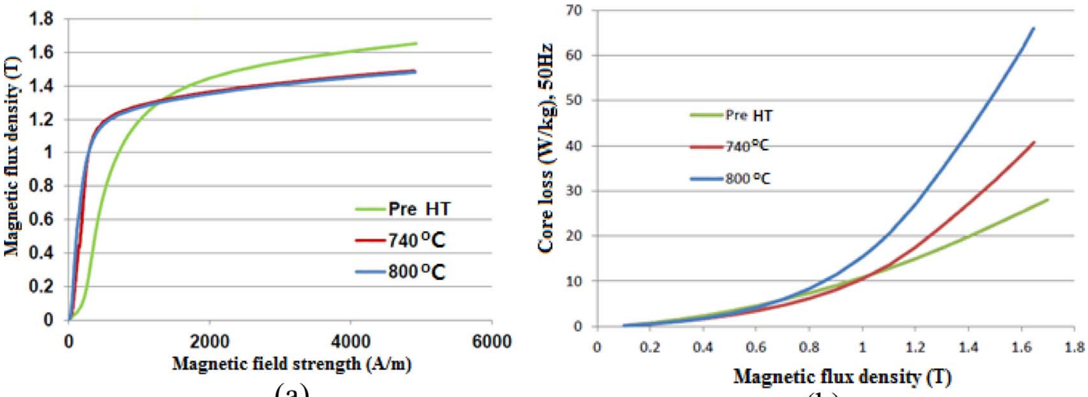


Fig. 4. (Color online) Stator core windings for magnetic property test.

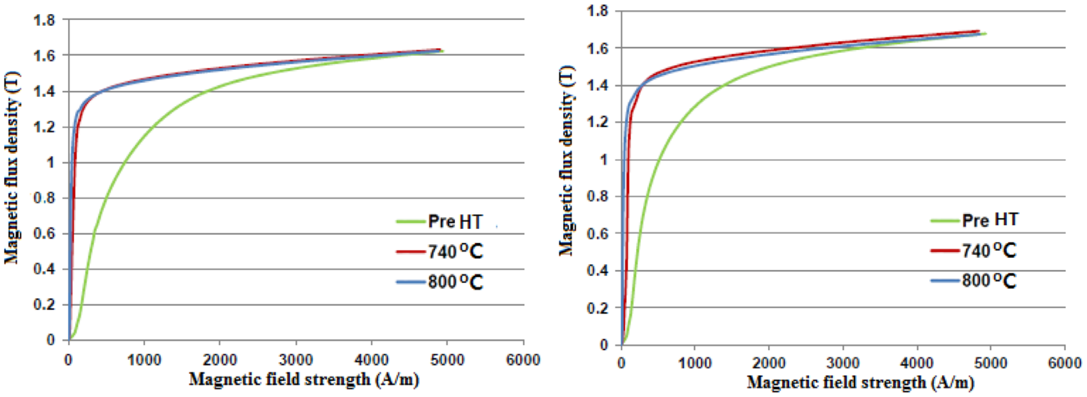
Under the HT condition, three types of stator cores were annealed. After HT, magnetic properties were measured after stator core winding as shown in Fig. 4. For the magnetic property measurement, we assumed that the specimens were ring-shaped having outer and inner diameter. Although the stator teeth were not considered, we can compare the magnetic properties with both non-HT and HT specimens. The magnetic property measurement was performed in accordance with IEC 60404-4 [4].

It was found that HT result with the 90A stator (SPCC) deteriorated the magnetic properties for both magnetization and core loss characteristic as shown in Fig. 5. In



(a) (b)

Fig. 5. (Color online) Effect of HT (SPCC): (a) Magnetization, (b) Core loss.



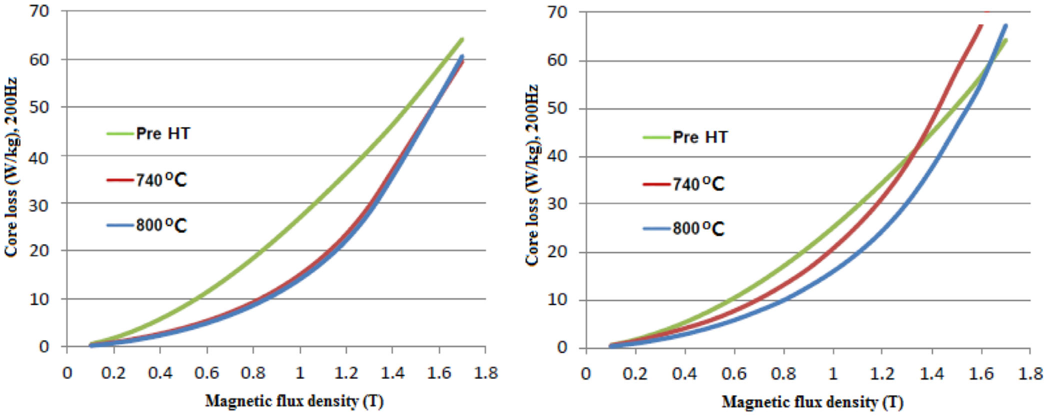
(a) (b)

Fig. 6. (Color online) Effect of HT (50A800) on magnetization: (a) 120A, (b) 150A model.

addition, HT at 800 °C increased the core loss further showing no benefit of HT with SPCC core. To find this reason, core loss components were separated mathematically [5] and as result, there was excessive eddy current loss which increased the overall core loss, even including the hysteresis reduction due to the HT process. This result is reasonable since SPCC does not have insulation coating so that HT process deteriorates surface insulation resistivity of SPCC. Consequently, we excluded the HT SPCC core for the alternator performance test. Regarding the 120A and 150A stator cores (50A800), we found significant magnetic property improvement, especially magnetization over both low and middle field excitation, as shown in Fig. 6. As expected, there was no magnetization improvement in the saturation region since this property is dependent on the chemical components of the material, which is invariant due to the HT process. As for the temperature effect, both 740 °C and 800 °C showed similar magnetization improvement as the 120A and 150A models. In contrast, 800 °C showed effective core loss improvement. Fig. 7 shows core loss at 200 Hz for both the 120A and 150A models. Accordingly, 800 °C showed a better HT effect for both the magnetization and core loss characteristic, which made us to determine 800 °C HT stator cores for the alternator performance test.

3. Effect of Heat Treatment on Alternator performance

To verify the performance improvement, HT alternator prototypes were manufactured and an efficiency and output test was performed. According to the test result, 0.6% efficiency was improved and 6% output currents were increased after HT. In addition, an acoustic noise test was performed to check the difference by according to the HT effect.



(a) (b)

Fig. 7. (Color online) Effect of HT (50A800) on core loss: (a) 120A, (b) 150A model.

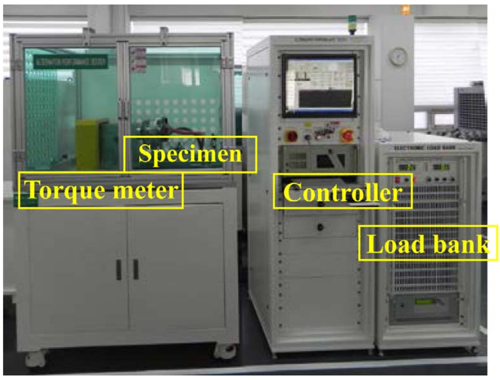


Fig. 8. (Color online) Alternator performance test.

3.1. Alternator Prototype Manufacture

After the heat treatment of stator core at 800 °C for the 120A and 150A alternators, three alternator prototypes were manufactured for each type. Also, to compare the performance improvement, three non-HT alternator production samples were prepared for each model. Before the manufacturing the stator assembly, the HT stator core dimensions were checked to verify the dimensional deviation. It was found that there was no dimensional difference due to HT, which can be acceptable for manufacturing.

3.2. Test Procedure

To validate HT, an alternator performance test was performed, as shown in Fig. 8. In this test, the test specimen was coupled to a torque meter that can control speed and measure the torque at the specific load. With the measured value of the torque, speed, current, and voltage, the alternator efficiency is defined as follows [6]:

$$\eta = \frac{UI}{T\omega} \tag{1}$$

where:

η : Efficiency [%]
U : Alternator Voltage [V]
I : Alternator Current [A]
T : Alternator Torque [Nm]
ω : Alternator Speed [rad/s]

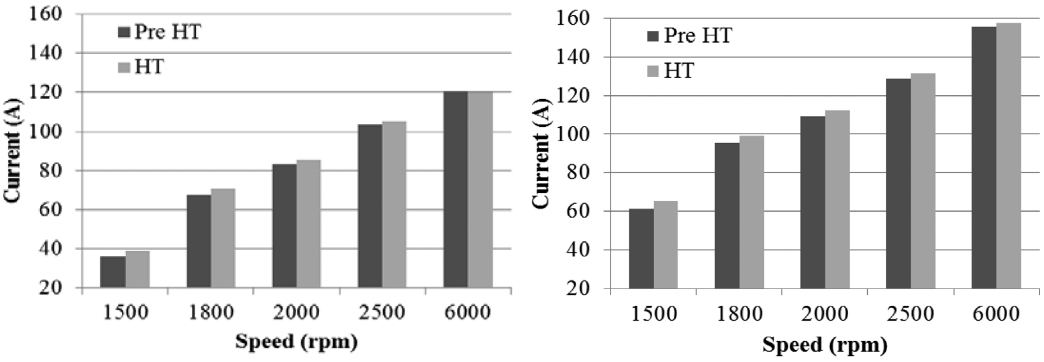
Since the alternator efficiency depends on the speed and load, it is common practice that the alternator performance test is performed in accordance with the German automotive industry or VDA standard. The VDA efficiency is measured under the condition that half of the rated output current is to be charged by controlling the load resistance at different speeds: 1800 rpm, 2000 rpm, 8000 rpm, and 10000 rpm. The weighting factors are then multiplied with the measured efficiency and summed as follows:

$$\eta_{VDA} = 0.25\cdot\eta_{1800} + 0.40\cdot\eta_{3000} + 0.25\cdot\eta_{6000} + 0.10\cdot\eta_{10000} \tag{2}$$

3.3. Alternator Output and Efficiency Test Result

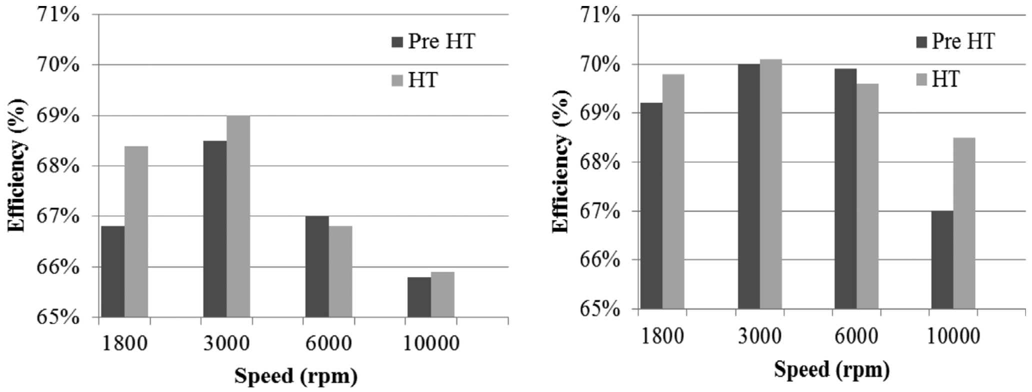
The alternator winding resistance is dependent on the temperature; therefore, the alternator test performance was conducted at various conditions: cold and hot at ambient temperature, 20 °C and 90 °C. Although the output improvement level varied at different temperature conditions, the overall output was improved, especially at low speed, as shown in Fig. 9. As for the 120A model, the output at 1500 rpm improved by 3 A (5%). This improvement can be explained due to the magnetization improvement, which shows agreement as good as the stator HT magnetization test. As for the 150A model, the output improvement was by 4 A (6.8%) at 1500 rpm, as shown in Fig. 9. This data perhaps can be explained due to the higher improvement with relatively highly strained and stressed thinner stator tooth.

At high speed, the current output was similar to the non HT model. Fig. 10 shows the alternator efficiency test result with the 120A and the 150A model. For the 120A



(a) (b)

Fig. 9. Output test result: (a) 120A, (b) 150A model.



(a) (b)

Fig. 10. Efficiency test result: (a) 120A, (b) 150A model.

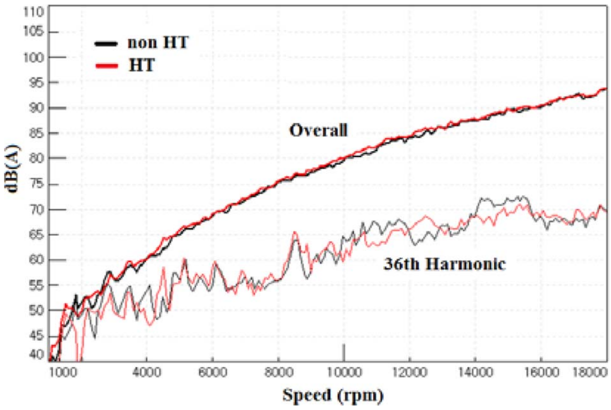


Fig. 11. (Color online) Acoustic noise test result at load condition (120A model).

model, the efficiency improvement was 1.6%, whereas it was 0.6% for the 150A model at 1800 rpm. In addition, at 3000 rpm, which has the highest weighting factor, 0.40 for VDA efficiency, 120A model efficiency improvement was 0.5%, and 0.1% for the 150A model. In contrast, the efficiency improvement was 1.5% at 10000 rpm, which was the same as the 150A model. The VDA efficiency improvement was 0.6% for the 120A model and 0.3% for the 150A model, respectively.

3.4. Alternator Acoustic Noise Test

As for the alternator test, not only the electrical performances such as the output and efficiency but also the acoustic noise are important since noise can affect the passenger's comfort. Therefore, it is necessary to assure the noise performance due to HT. The acoustic noise of the alternator is mainly composed of mechanical noise, aerodynamic noise, and electromagnetic noise [7]: the former comes from the bearing and cooling fan of the alternator, while the latter comes from electromagnetic force on the stator. As for the acoustic noise test, no load and load test were performed to separate aerodynamic noise and electromagnetic noise. In addition, this acoustic noise is combined with the number of poles and stator slots resulting in harmonics proportional to the rotor speed. In this test, the distance between the alternator and the microphone is 1 m, and the noise was measured on four sides: front, rear, right, and left. According to the test result, there was no change at no load condition after HT for both the 120A and 150A model. However, for the 120A model at the load condition below 5000 rpm, there was slight electromagnetic noise increase, as shown Fig. 11. This difference seems mainly due to the increase of the current output, even if this increase level is acceptable.

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