Fabrication Study of Laminated Stator for an E-bike Axial Flux Electric Machine

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Abstract

The stator core wound from electrical steel strip is one of key components in an axial flux machines. Based on a 250 W e-bike electric machine, wire electric discharge machining (w-EDM), and progressive punch and winding machining (PPW) are performed to evaluate core loss on stator by different machining approach. Comparing with simulation results from finite element model and bearing friction model, the core loss may be raised over 3.7 and 4.3 times higher than ideal condition by w-EDM and PPW, respectively.

Keywords: axial flux machine, core loss, electric discharge machining, punch and winding machining

1 Introduction

Recently, to reduce greenhouse gas emission from burning fossil fuels, electric vehicles have attracted great attention in transportation sector, in which the efficiency of electric machine is more critical than industrial usage because of limited battery capacity. Energy efficiency of electric machine has always been a key issue in electrical industry. Iron losses reduction from machining aspect is one of notable ways to affect the efficiency in previous study [1-2]. Several factors influence property of electrical steel, including grain size, impurities, internal stress, alloy content, and cutting, punching, pressing and welding process [3]. Iron loss models were also compared therein.

Axial flux machine is capable of being installed into narrow space, e.g. direct-drive elevator system without machine room [4], and suitable for slim and compact mobility vehicles [5-7] relying on its unique characteristic of short shaft length. Various designs covered from single to multiple air-gap design of axial flux permanent magnet machine were reviewed [8].

However, different from laminated stator core in radial flux machine, the stator core in axial flux machine is wound from electrical steel strip along rotation direction of the shaft owing to its axial magnetic flux. As a result, machining of tooth grooves becomes more difficult than radial one [9], and iron loss of the stator related to manufacturing process was seldom discussed.

Here, wire-cut electric discharge machining (w-EDM), and progressive punch and winding machining (PPW) were performed and compared based on a 250 W e-bike axial flux permanent magnet machine.

2 Machine design

Structural configuration of the 250 W axial flux permanent magnet machine is shown in Fig. 1. It is a typical single-rotor and single-stator design, and composed of a shaft, a disk magnet, a stator core and several coils. The overall dimension of this machine without machine casing is around...
160 mm in diameter and 22.5 mm in stacking thickness, referred to Tab. 1. The disk magnet is cut from bulk sintered-NdFeB sheet and axially magnetized alone the shaft direction. The coils are wound up to be fan-shaped, and then inserted into the teeth of stator core. The tooth grooves of stator core, referred to Fig. 1, can be formed by either w-EDM or PPW machining. Brief description about machining processes will be presented in following section.

Due to asymmetrical flux in the machine, 3-D finite element model is established to estimate output torque, core loss, efficiency and other electrical characteristics of this machine. According to simulation result of flux density, magnetic flux is easily concentrated to make electrical steel saturated at tooth top nearby the shaft in this axial flux design, as shown in Fig. 2. This may cause obvious influence of iron loss models because of the non-linear behavior of flux density variation.

3 Stator fabrication

The w-EDM is commonly used for fabricating the stator of axial flux machine as well as radial flux machine. High precision, short preparation time and relative low cost are benefits of this approach for small amount of prototypes. In contrast, the PPW is only for the stator of axial flux machines, and regarded as high throughput and low overall cost in mass production. To evaluate the core loss influenced by these two machining processes, two stator cores are fabricated without any additional annealing or finishing process.

3.1 W-EDM approach

Electric discharge machining is a method to shape workpiece into desired geometry by using electrical sparks between tool-electrode and workpiece, where is applied a series of recurring current on them. W-EDM uses tensioned rolling wire as the tool-electrode to avoid erosion of the electrode [10], and is suitable to fabricate 2.5-D geometries.

In stator core machining process, electrical steel strip will be tensioned and wound on a circle-shaped mold to be a ring core, and then welded immediately on one lateral side of the core to prevent from loosing after mold release. Next, put the core on index plate to specify the rotation angle. Finally, tooth grooves are formed separately by the wire electrode with an U-shaped path at different rotation angle. The fabrication result is shown in Fig. 3. The tooth surface is flat and smooth because of straight wire as tool-electrode; however, in consequence of electrical spark during machining, the grain size, impurities, internal stress and other material properties might be changed nearby the cutting surface.

3.2 PPW approach

On the other hand, progressive punch and winding machining is to cut electrical steel with progressed pitch to make teeth groove by punch press. Because radius of the core will increase during winding process, the pitch needs to be increased simultaneously.

First, one end of electrical strip is pulled through press die and hooked on a circle-shaped mold at certain tension force. Then, the mold stepwise rolls the electrical steel up after punching. Finally, cut off the strip and weld the rolled core at two ends of electrical strip on bottom side. As can be seen in Fig. 4, slots on the stator are not straight and lateral surface of teeth are slightly zigzag. These issues may come from accumulation of pitch error and fabrication variation, including punch pitch, strip tension and other influences on material and machine. Also, iron loss might be influenced by this punching and pressing process.

4 Experiment and results

To evaluate core loss, a no-load rotation loss test is performed. Although the core loss and mechanical loss will be countered into the result, the core loss can be approximately calculated based on similar structural configuration and friction model of bearing [11].

4.1 Experiment setup

A typical test rig for electric machine is adopted, as shown in Fig. 5. A simplified machine structure is used to diminish variation of wiring and assembly. Only a shaft, a disk magnet and one stator core are assembled into this test machine. In the test, the stator cores fabricated by w-EDM and PPW approach will be swapped in turn into test machine. All other components, including shaft, disk magnet, machine casing and bearings are the same to keep similar conditions. During the test, test machine is driven by the test rig, and its power losses are recorded at condition of twelve speeds from 250 to 3000 rpm.
4.2 Test results

The experiment results of no-load rotation loss test and simulation results of finite element model and bearing friction model are shown in Fig. 6. As can be seem, both experiment and simulation results are very small, approximately 1 to 3 W at 250 rpm. From 500 to 3000 rpm, the experiment results increase rapidly up to over 250 W, and the w-EDM result is higher than PPW one over 30 W at 3000 rpm; however, the trend of core loss from finite element model and bearing loss from friction model are almost the same and slowly rise up to 50 W at 3000 rpm.

Considering the core and friction loss of simulation results, the maximum losses are around 53 W and 58 W, respectively; meanwhile, the difference between experiment results, w-EDM and PPW, and the friction loss are over 200 W and 230 W, respectively. This result shows that core loss may be raised over 3.7 and 4.3 times higher than ideal condition by different machining processes.

5 Conclusion

Here, two machining processes, w-EDM and PPW, are performed to fabricate the stator cores and estimate their influence on core loss by comparing to the simulation results of finite element model and bearing friction model. It shows that machining process will highly affect core loss, which could be raised over 3.7 and 4.3 times than theoretical calculation. Due to this result, machining process should be seriously considered during design stage.

6 Figures, Tables and Equations

6.1 Figures

Figure 1: Axial flux machine structure

Figure 2: Simulation result of flux density at 250 rpm

Figure 3: Stator core fabricated by w-EDM approach

Figure 4: Stator core fabricated by PPW approach
6.2 Tables

Table 1: specification of the axial flux machine

<table>
<thead>
<tr>
<th>Property</th>
<th>3 phase/40 pole</th>
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<tbody>
<tr>
<td>Rotor diameter, mm</td>
<td>160</td>
</tr>
<tr>
<td>Stack length, mm</td>
<td>22.5</td>
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<tr>
<td>Air gap, mm</td>
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<table>
<thead>
<tr>
<th>Dimensions</th>
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<tbody>
<tr>
<td>Rotor/Magnet thickness, mm</td>
</tr>
<tr>
<td>Stator thickness, mm</td>
</tr>
<tr>
<td>Slot width, mm</td>
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<td>Slot depth, mm</td>
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References


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