Core Loss Analysis in Laminated Core of Electric Motor according to Welding Condition

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1. Background

◆ Electric motor

- **Trend of motor**: High efficiency & Downsizing
  - Less loss, Higher efficiency
  - Less loss, Smaller motor size
  → **LOSS REDUCTION** is significant goal of motor design

- **Unpredicted loss during manufacturing**
  → Decrease of efficiency compared with target efficiency by additional loss

Analyses of additional loss caused by welding in laminated core
2. Losses in Electric Motor

◆ Power flow of electric motor

**Electrical input power**

\[ P_{in} = mV_a I_a \cos \theta \]

**Mechanical loss**

\[ P_{mech} = P_{windage} + P_{bearing} \]

**Core loss**

\[ P_{core} = k_h f B^2 + k_e f^2 B^2 + k_a f^{1.5} B^{1.5} \]

**Copper loss**

\[ P_{copper} = m I_a^2 R_a \]

**PM eddy current loss**

**Mechanical output power**

\[ P_{out} = T \cdot \omega_m \]

**Symbols and Equations**

- \( P_{mech} \): Mechanical loss per unit mass (W/kg)
- \( k_h \): Hysteresis loss coefficient
- \( k_e \): Eddy current loss coefficient
- \( k_a \): Abnormal loss coefficient
- \( P_{core} \): Core loss per unit mass (W/kg)
- \( B \): Magnetic flux density (T)
- \( V_a \): Phase voltage (V_{rms})
- \( I_a \): Phase current (A_{rms})
- \( T \): Torque (Nm)
- \( \omega_m \): Rotational speed (rad/s)
- \( R_a \): Phase resistance (Ω)
- \( P_{windage} \): Windage loss per unit mass (W/kg)
- \( P_{bearing} \): Bearing loss per unit mass (W/kg)
- \( m \): Phase number
- \( f \): Frequency (Hz)
◆ Losses in electric motor

- Mechanical loss
  
  $P_{mech} = P_{windage} + P_{bearing}$
  
  : Loss caused by friction in bearing, windage (Air resistance)

- Core loss (Hysteresis loss, Eddy current loss)
  
  $P_{core} = k_h f B^2 + k_e f^2 B^2 + k_a f^{1.5} B^{1.5}$
  
  : Loss caused by variation of magnetic flux in core

- Copper loss
  
  $P_{copper} = m I_a^2 R_a$
  
  : Loss in winding of electric motor

Mechanical output power = Electrical input power – Loss

Loss is important in efficiency of electric motor.
3. Core loss in Electric Motor

How to reduce ‘Core loss’ in electric motor?

- Steinmetz’s equation:

\[ P_{\text{core}} = k_h B^2 f + k_e B^2 f^2 + k_a B^{1.5} f^{1.5} \text{ (W/kg)} \]

- Eddy current loss
- Hysteresis loss

Reduce hysteresis loss

Electrical steel

- Use soft magnetic materials (Ferromagnetics)
- High permeability (Low reluctance)
- Narrow magnetic hysteresis loop

\[ P_{\text{hysteresis}} \propto \text{Area of hysteresis loop} \]

→ Use electrical steel in core
◆ How to reduce ‘Core loss’ in electric motor?

● Steinmetz’s equation: \( P_{\text{core}} = k_h B^2 f + k_e B^2 f^2 + k_a B^{1.5} f^{1.5} \) (W/kg)

- Eddy current loss
- Hysteresis loss

Reduce eddy current loss

\( P_{\text{eddy}} \propto c^2 \) (c: Thickness of (laminated) core)

→ Use laminated core in electric motor
### How to assemble laminated core

<table>
<thead>
<tr>
<th>Method</th>
<th>Explanation</th>
<th>Method</th>
<th>Explanation</th>
</tr>
</thead>
</table>
| Interlocking | - Using ‘tongue & groove’ system  
- Low freedom of position  
- Mechanical weakness at outer parts | Bonding   | - Full-face-bonded  
- No need for interlock or weld point  
- Dimensional accuracy  
- High manufacturing cost |
| Clamping | - Using ‘clamp’  
- Structural constraints | Welding  | - Easy to manufacture  
- Mechanical stability  
- Low manufacturing cost  
→ Widely used |
◆ **Welding on laminated core**

→ Welding bead and electrical steel plates can make closed-loop
→ Eddy current is caused by induced voltage (Faraday’s Law)
→ **Additional eddy current loss** occurs

![Diagram showing welding bead, eddy current, and magnetic flux](image)

**Additional eddy current loss by welding**

**Welding in laminated core causes additional eddy current loss.**
4. Analysis of Loss according to Welding condition

◆ Overview of additional loss analysis

  ● Purpose of analysis: Expectation of loss according to welding condition

  ● Analysis method: No load loss measurement by experiment
    - Comparing no load loss to find out effect of welding
    - Evaluate the additional loss by no load loss, simply

  ● Welding condition
    - Welding position
    - Number of welding

\[ T \times \omega = W_{\text{no load loss}} = W_{\text{no load mech loss}} + W_{\text{no load core loss}} + W_{\text{additional loss}} \]
**Assumption of experiment**

<table>
<thead>
<tr>
<th>Welding in stator core</th>
<th>Wire on stator core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed-loop by welding bead</td>
<td>Closed-loop by wire</td>
</tr>
<tr>
<td>Additional eddy current loss</td>
<td>Additional copper loss</td>
</tr>
</tbody>
</table>

- Difficult to realize closed-loop by welding bead
- Difficult to analyze or expect eddy current

Analyze copper loss in wire instead of eddy current loss by welding bead
◆ Analysis motor: 4 poles 6 slots IPMSM
Experiment set

\[ T \times \omega = W_{\text{no load loss}} \]
\[ = W_{\text{no load mech loss}} + W_{\text{no load core loss}} + W_{\text{additional loss}} \]

Analysis Motor → Torque Sensor → Drive Motor

- Tachometer
- Insulating tape
- Copper wire
- Torque sensor
- Drive motor
- Analysis motor

Wires on laminated core
## Welding conditions of experiment

<table>
<thead>
<tr>
<th>Position of welding</th>
<th>Around the stator teeth</th>
<th>Around the stator yoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of welding</td>
<td>6 times</td>
<td>3 times</td>
</tr>
</tbody>
</table>

![Diagram of welding positions](chart.png)
◆ Result of experiment

- Welding around the stator teeth

<table>
<thead>
<tr>
<th>Welding Condition (position &amp; number)</th>
<th>No load loss (W)</th>
<th>Loss by welding (W)</th>
<th>Loss per 1 welding (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500(rpm)</td>
<td>1000(rpm)</td>
<td>1500(rpm)</td>
</tr>
<tr>
<td>Base model</td>
<td>0.523</td>
<td>2.094</td>
<td>4.712</td>
</tr>
<tr>
<td>Around the teeth</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Loss by welding around the stator teeth
- Proportional to the number of welding
- Proportional to (speed)$^2$, approximately
### Welding around the stator yoke

<table>
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<th>Welding Condition (position &amp; number)</th>
<th>No load loss (W)</th>
<th>Loss by welding (W)</th>
<th>Loss per 1 welding (W)</th>
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</tr>
<tr>
<td>-----------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base model</td>
<td>0.523</td>
<td>2.094</td>
<td>4.712</td>
</tr>
<tr>
<td>Around the yoke</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.513</td>
<td>7.330</td>
<td>14.137</td>
</tr>
<tr>
<td>3</td>
<td>1.570</td>
<td>4.712</td>
<td>9.424</td>
</tr>
<tr>
<td>2</td>
<td>1.047</td>
<td>3.665</td>
<td>7.539</td>
</tr>
</tbody>
</table>

### Loss by welding around the stator yoke

- Proportional to the number of welding
- Proportional to \((\text{speed})^2\), approximately

\[
T \times \omega = W_{\text{no load loss}} + W_{\text{base model no load loss}} + W_{\text{additional eddy current loss}}
\]
Comparison of loss according to welding position (around the stator teeth and yoke)

- Additional loss proportional to \((\frac{d\Phi}{dt})^2\)
- Magnetic flux
  - Stator teeth > Stator yoke
- Additional eddy current loss
  - Stator teeth > Stator yoke

Loss by welding around the stator teeth

Loss by welding around the stator yoke
**How to weld laminated core?**

- Avoid critical position of welding such as stator teeth
- Weld few times as possible

- New type of welding in laminated core: ‘zigzag’ shape of welding
  - Less possibility of closed-loop
  - Make lower additional eddy current loss
5. Conclusion

◆ Analyze additional copper loss in wires instead of additional eddy current loss by welding.
  
  ● Welding condition
    - Position of welding: around the stator teeth & around the stator yoke
    - Number of welding: 6 times & 3 times & 2 times (over 6 slots)

Loss by welding is proportional to the number of welding.

Welding, especially around the stator teeth, affects significantly core loss.

Welding should be done in few times as possible, avoiding around the teeth.