Research of Thermal Loads in Plate Forming Coil during Repeated Electromagnetic Forming Process

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Background

After decades of research and development, electromagnetic forming (EMF) has gradually become a high-speed and efficient forming method that can be put into industrial production. However, more research on coil service life should be done before large-scale application of EMF, especially during repeated discharging, which is necessary in industrialization. The Joule heat generated by large discharging current accumulates in the coil and lead to notable temperature rise. Long-term high temperatures will have a huge impact on coil life.

Objectives

- Simulate the thermal load of forming coil using COMSOL Multiphysics;
- Measure the real-time temperature of forming coil using fluorescence fiber measurement, and verify the feasibility of the method;
- Analyze the influence of coil structure, discharging interval, discharging energy and crowbar circuit to the balance temperature of forming coil in repeated EMF process;
- Study the temperature distribution of forming coil.

Conclusion

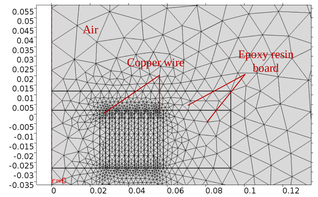
- Fluorescence fiber measurement is suitable for the temperature measurement of electromagnetic forming coil, which requires direct contact with strong current;
- Increasing the cross section area (height) can effectively reduce the coil equilibrium temperature when the discharging current remains invariant. In comparison, increasing the spacing of the wires is less effective at reducing the balance temperature;
- Increasing interval time can reduce the balance temperature of the forming coil in a certain extent. However, the effect will not be obvious when the discharge interval is already long, and increasing interval time will lead to reduced efficiency at the same time;
- For the same load, the temperature rise of the coil is proportional to the square of the discharge voltage. The coil temperature rise of high voltage repeated discharge can be estimated by processing the result of low voltage repeated discharge;
- The crowbar circuit is effective in reducing the temperature rise in repeated EMF process, especially when the oscillation is strong;
- The temperature distribution maintains invariant under different discharge conditions.

Simulation

Simulation Parameters

Symbol	Description	Value
Copper		
ρ_{Cu}	Density	8700 kg/m^3
k_{Cu}	Thermal conductivity	390 W/(m·K)
C_{pCu}	Heat capacity	385 J/(kg·K)
ρ_{Cu}	Resistivity	1.72×10^{-8} Ω·m
α_{Cu}	Temperature coefficient	0.00391 /K
Epoxy resin board		
ρ_e	Density	2000 kg/m^3
k_e	Thermal conductivity	0.13 W/(m·K)
C_{pe}	Heat capacity	737 J/(kg·K)
Air		
ρ_{air}	Density	1.28 kg/m^3
k_{air}	Thermal conductivity	0.023 W/(m·K)
C_{pair}	Heat capacity	1003 J/(kg·K)

Simulation Model



A 2-d axial symmetry finite element model is established to study the thermal load distribution in the repeated discharging process of the plate forming coil, based on COMSOL Multiphysics multi-physics modeling and simulation software.

- The geometric model is set up using the dimension of the two coils in experiment.
- The capacitance value, initial discharge voltage of the capacitor in the simulation model are set according to the actual requirements, and the parameters of discharging circuit is in agreement with actual experiment system.
- Temperature rise ΔT before and after each period is calculated. It is considered to come to a balance temperature or stable temperature when ΔT<0.05℃.

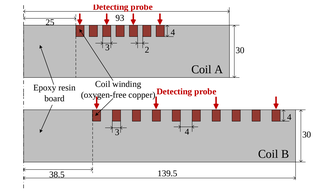
Experiment

Experiment Parameters

Symbol	Description	Value
Discharging circuit		
R_c	Line resistance	0.195 Ω
R_d	Crowbar resistance	0.2 Ω
L_c	Line inductance	450 μH
C_1	Capacitance	3.2 mF
Coils (under 200Hz)		
R_{coilA}	Resistance of coil A	2.58 mΩ
L_{coilA}	Inductance of coil A	4.91 μH
R_{coilB}	Resistance of coil B	7.11 mΩ
L_{coilB}	Inductance of coil B	16.13 μH

Experimental Procedures

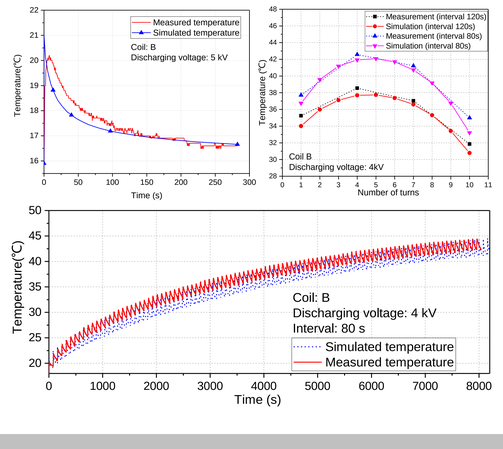
- Two plate forming coils are fabricated.
- A power supply system with maximum energy of 1MJ is applied to discharge the coils.
- A fluorescence fiber thermometer is applied to measure the temperature in different parts of the coil.
- Repeated discharges to the coils and obtain temperature information.



Fluorescence fiber thermometer:
Measuring range: -40℃ to 200℃
Precision: 0.1℃
Sensor: Optical fiber
Advantages: small size and immune to electromagnetic interference

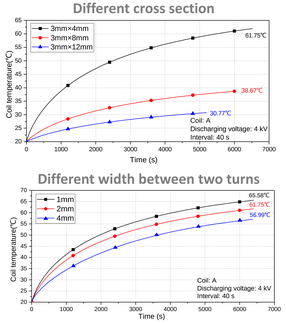
Results

Comparison between Experiment and Simulation Results



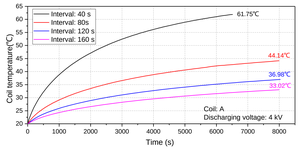
- The comparison shows good agreement on the general trend.
- Temperature balance phenomenon exists in both the simulation result and measuring result.
- Apparent hysteresis exists in the measuring result due to the existence of response time of the detector.
- The measuring results are slightly larger than the simulation results.
- The transient response lag and deviation do not interfere with the measurement of the overall trend. Simulation reliability is verified.

Coil Structure



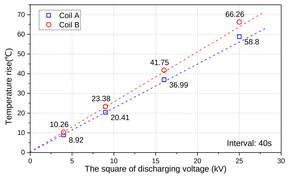
- Altering the cross section (height) of the coil to avoid excessive coil temperature is an advisable method in comparison to adding the width between turns.

Discharging interval



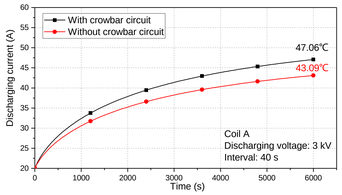
- Increasing interval time from 40 s to 80 s can decrease huge amount of the temperature rise and the balance temperature. When increasing the interval time from 80 s to 120 s or even 160 s, the effect of reducing balance temperature becomes relatively poor.
- In industrial production, increasing interval time can reduce the balance temperature of the forming coil in a certain extent, but Increasing interval time would also lead to great reducing of production efficiency.

Discharging energy



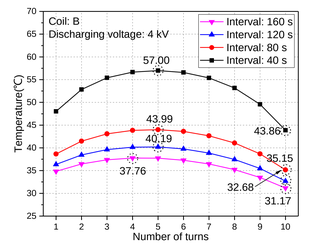
- The Joule heat has linear square relationship with the discharging voltage, ignoring the change of the coil resistive.
- This regulation could be applied to the estimation of coil safety by doing repeated discharge experiment in low voltage and estimating the balance temperature under high voltage repeated discharges.

Crowbar circuit



- The effect of the crowbar circuit is to eliminate the discharge current oscillation, thus reducing the production of joule heat.
- The discharging current amplitudes remains the same in both situation.
- The effect of crowbar circuit is already evidence, although the oscillation of discharging current is not very strong in our experiment system.

Temperature distribution



- The temperature shows obvious distribution pattern because of the different heat dissipation condition.
- In coil design, the temperature of middle turn and its inner part require special attention.

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