Trends and Challenges of Induction Heating Analyses

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Abstract :
Simple characteristics such as a dense mesh and large scale analysis models are required to handle phenomena caused by eddy currents on the heated bodies in induction heating analyses. An analysis environment is finally available because of the higher performance machines that are offered in recent years. However, work preparing analyses, such as measuring the material properties and current value of the heating coil, is necessary to run the analysis. Furthermore, many users have said they are unsure how to evaluate results when comparing the analysis results and actual results. This presentation proposes a flow for modeling and evaluating induction heating from qualitative to quantitative evaluation.

Trends and Challenges of Induction Heating Analyses

- Handling Motion and Evaluating Results of Heated Bodies -

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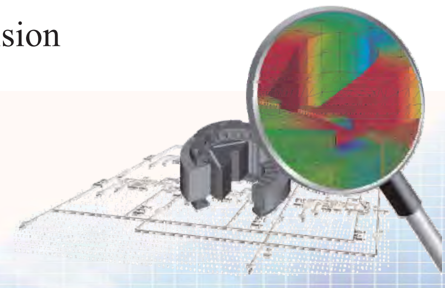

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1. Preface

- In recent years, analyses in fields requiring large scale models, such as induction heating, are being used more as the speed of calculation machines increase. Furthermore, the evaluation of results is also moving from qualitative evaluation to accurate evaluation. Therefore, this year's users conference introduces the effects of magnetic characteristics on analysis accuracy.
- While the demand for higher accuracy and more complicated models grow, the scale of a model that can be used is still limited by the same constraints of the calculation machine as before.
- Cases which the final results are difficult to obtain only occur now occasionally because, even if a large scale model is created inadvertently, the analysis time simply increases.
- This session introduces the present trends and challenges of analyzing heating with motion in JMAG. The combination of accuracy and calculation time can be considered as guidelines. Furthermore, information about how to evaluate results will be provided.

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1.1 Applied Field of Induction Heating

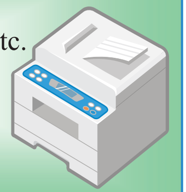
JMAG can be used in a variety of fields from product development to design.

High-frequency induction heating

Induction Hardening
・Harder surfaces for metal parts
Uniform heating of metal sheets

Printer

Fast, uniform heating of fusers, etc.

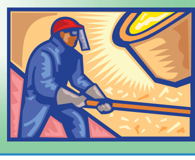


IH Cookers

Heating coil design of cooking devices, etc

Induction Furnaces

Magnetic circuit design of induction furnaces
Leakage magnetic field, etc.



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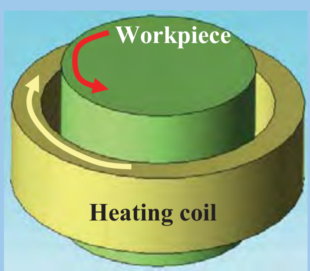
1.2 Structure of Induction Heating Analysis

Magnetic Field Analysis

Magnetic properties (HB-curve)
Electric conductivity



Physical properties change by rising temperatures

- The coil is excited
- Maxwell's equations
- Magnetic flux is produced
- Eddy currents obscuring the magnetic flux are produced
- Joule loss occurs where the eddy currents are produced

- Joule loss acts as the heat source
- Heat conduction equation
- Temperature rises at the center of heating

Displacement of workpiece

Thermal Analysis

Specific heat
Thermal conductivity
Density

1.Correctly model the flow/expansion of magnetic flux
2.Correctly handle areas eddy currents are produced

1.Correctly model the flow/ dissipation of heat
2.Correctly handle variations in temperature distribution

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1.2 Evaluation Items for Induction Heating Analyses

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The fundamental characteristics and temperature distribution of induction heating can be evaluated.

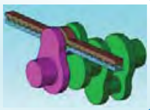
Surface temperature distribution

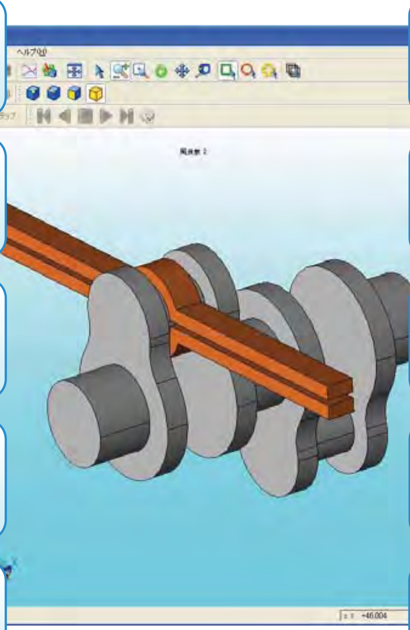
Interior temperature distribution

Speed the temperature rises

Heat generation density

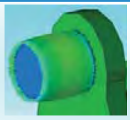
Current density distribution





Leakage magnetic field

Magnetic flux density



Inductance

Efficiency

Electromagnetic force

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2. Handling Motion

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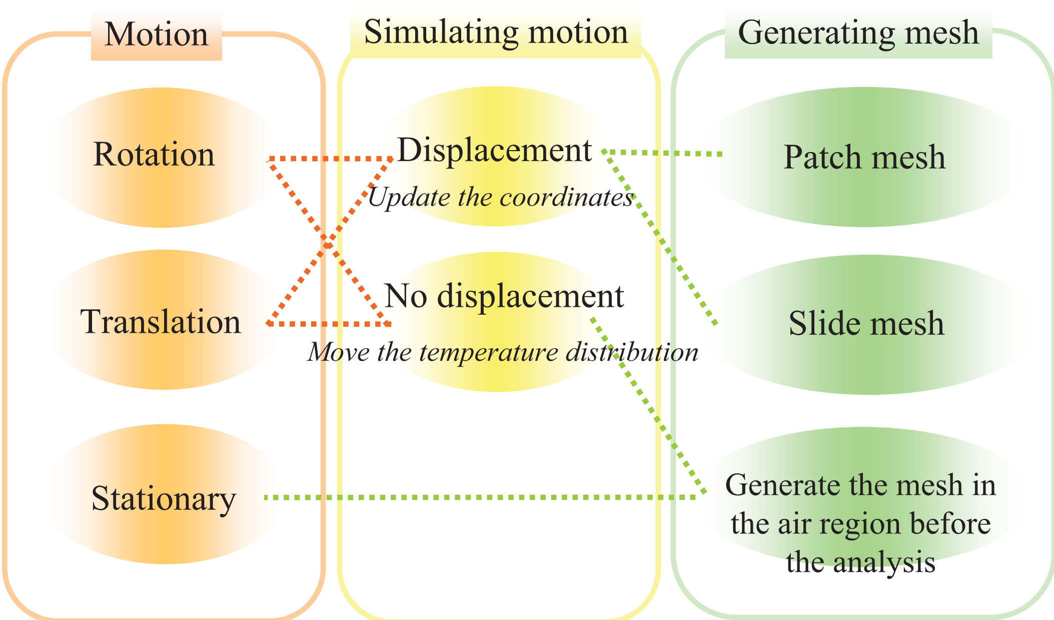
- Presently, motion of heated bodies can be handled as follows:



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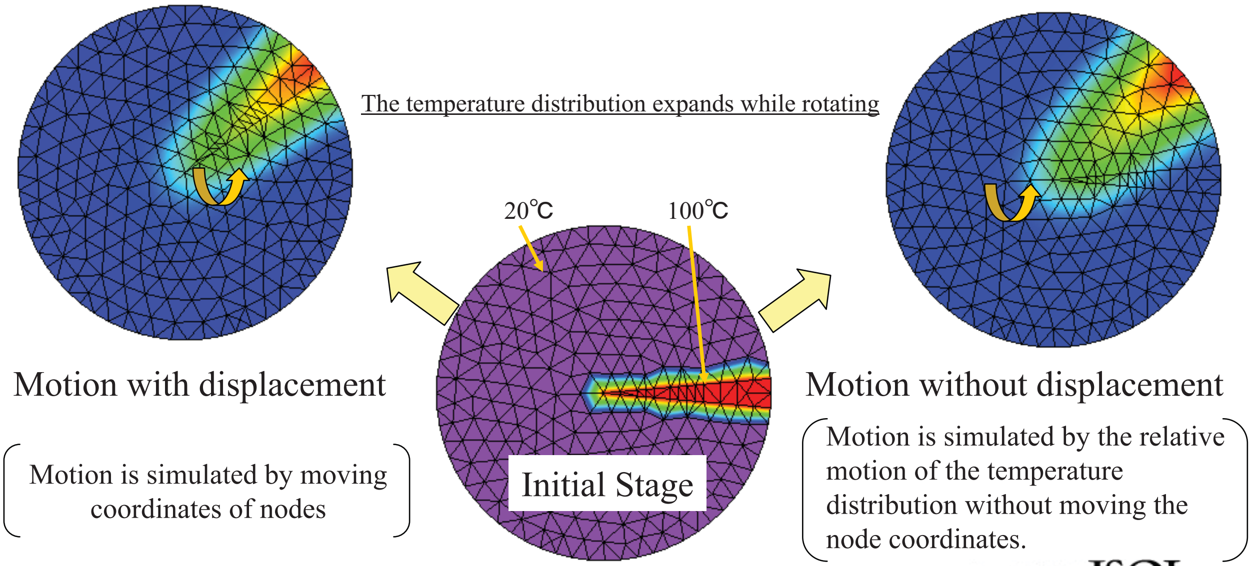
2.1 Motion With and Without Displacement

- Motion with displacement is simulating motion by changing the coordinates of the analysis model.
- Motion without displacement is simulating relative motion by fixing the coordinates and moving the temperature distribution.
  - Motion without displacement can only be used when the cross-section in the displacement direction is uniform.



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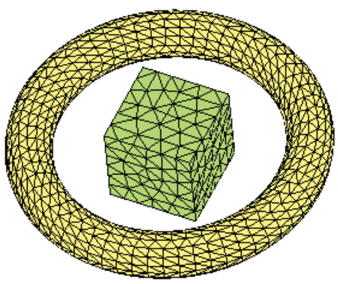
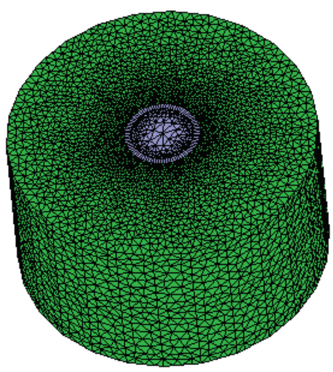
2.2 Patch Mesh and Slide Mesh

- Patch mesh is mesh that is regenerated at each motion position.
- Slide mesh is a mesh generated by equally dividing elements in the rotation motion direction of the gap.
  - Can only be used when the gap is cylindrical for rotation motion
  - Can only used when the gap is horizontal for translation motion



Patch mesh

The mesh in the air region is generated for each step during the analysis.



Slide mesh

The gap and air region around the gap is modeled cylindrically.

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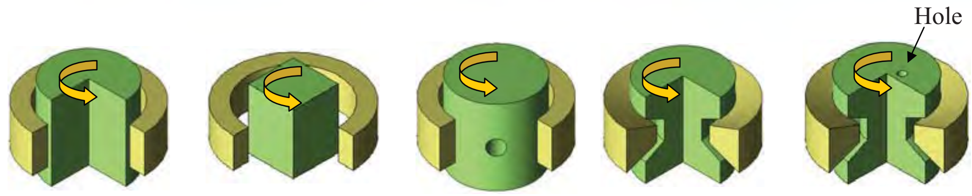
2.3 Rotation Motion



Heated body	Cylindrical	Not cylindrical	Not cylindrical	Not cylindrical	Not cylindrical
Cross-section in circumferential direction	Uniform	Not uniform	Not uniform	Uniform	Not uniform
Gap geometry	Cylindrical	Cylindrical	Cylindrical	Complex	Complex
1. Axisymmetric analysis	◎	×	×	◎	×
2. No displacement	O	×	×	O	×
3. Slide mesh *1	O	O	O	×	×
4. Patch mesh *2	O	O	O	O	O

*1) Slide mesh is a feature to generate uniform mesh in the gap before the calculation.
*2) Patch mesh is a feature to regenerate mesh at each position of displacement during the analysis. Patch mesh is specified by selecting the [Subdivide Automatically] check box. Induction heating analyses use the Semi Auto Mesh feature.
Note) The features indicated are for JMAG-Designer Ver. 10.3

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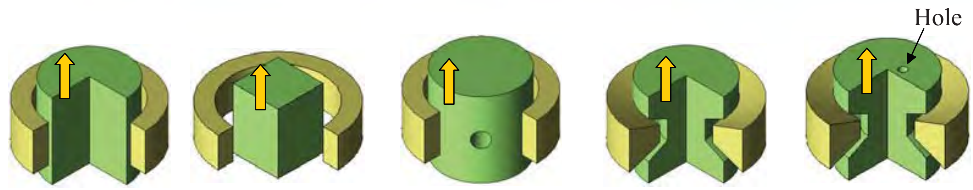
2.4 Translation Motion



Heated body	Cylindrical	Not cylindrical	Not cylindrical	Not cylindrical	Not cylindrical
Cross-section in circumferential direction	Uniform	Not uniform	Not uniform	Uniform	Not uniform
Cross-section in axial direction	Uniform	Uniform	Not uniform	Not uniform	Not uniform
Gap geometry	Cylindrical	Cylindrical	Cylindrical	Complex	Complex
1. Axisymmetric analysis	◎	×	×	◎	×
2. No displacement	O	O	×	×	×
3. Slide mesh	×	×	×	×	×
4. Patch mesh	O	O	O	O	O

Note) Translation slide mesh currently only supports a horizontal gap with a single mover.
Note) The features indicated are for JMAG-Designer Ver. 10.3

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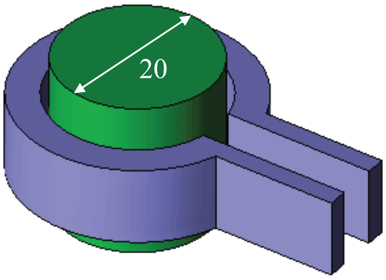
2.5 Model Scale and Analysis Time

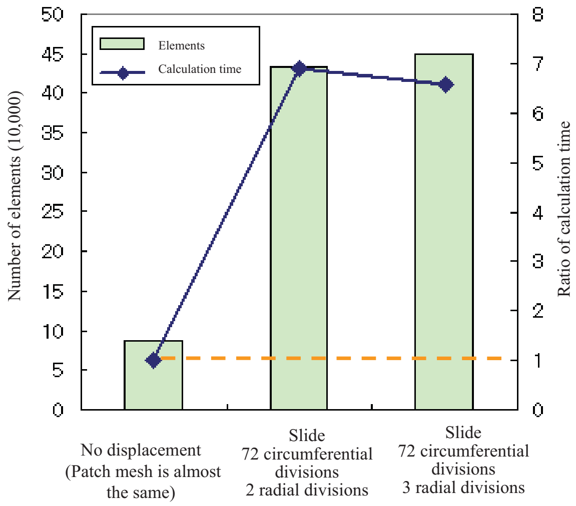
- Caution should be used when creating a model that has almost the same calculation accuracy (heat generation) because the number of elements in the gap increases if the slide mesh option is used.
- The slide mesh option is difficult to use in induction heating problems from a calculation time perspective.



Generate uniform mesh every 5 degrees in the circumferential direction. (Element size 0.86 mm)

Set the air region to 5 times the model length

The heat generation he almost the same if the mesh for the heated body is uniform and an adequate size is used for the air region



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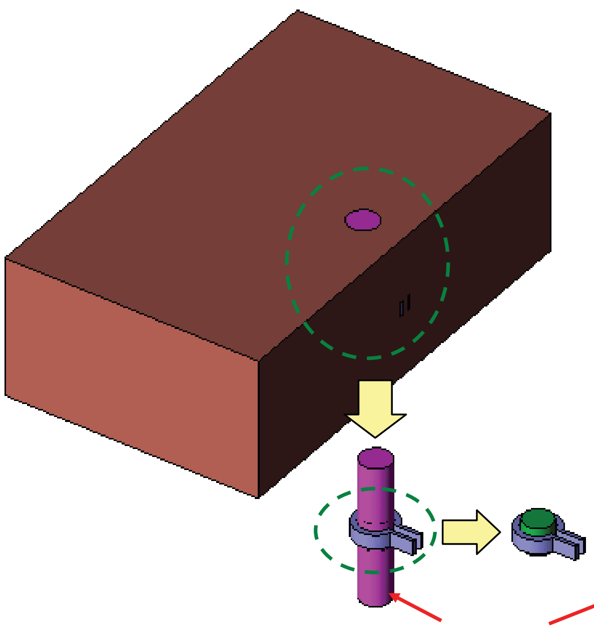
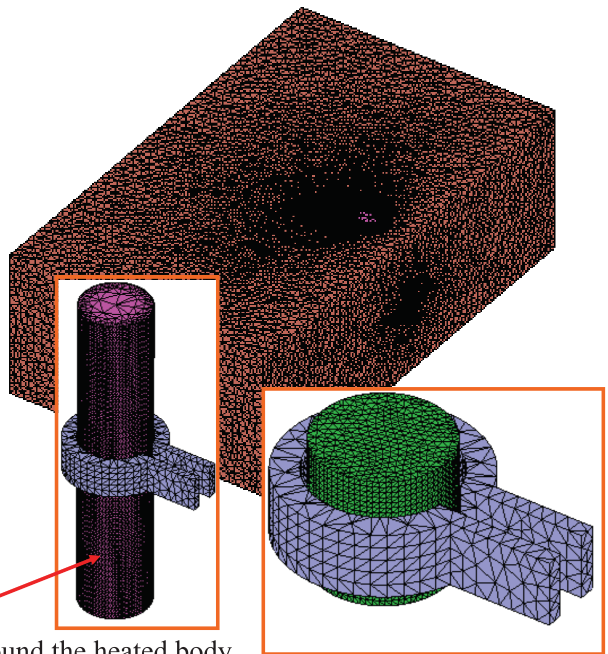
2.5 Example of a Slide Mesh Model

- There are more elements than necessary because the mesh is generated equally in the circumferential direction between the mover and stator when slide mesh is used.





Generates a cylindrical air region around the heated body

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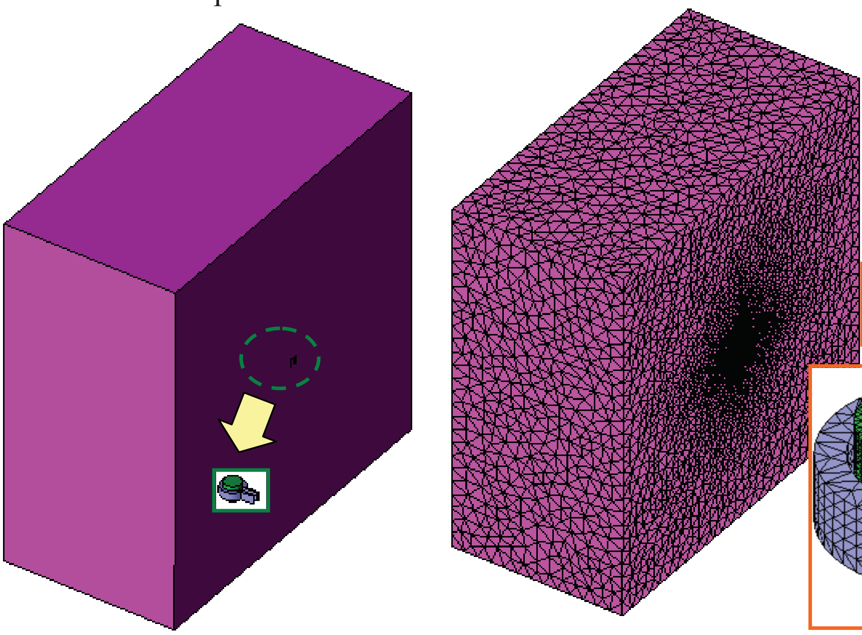
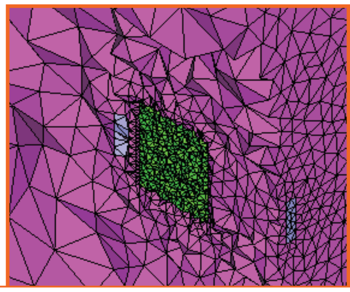
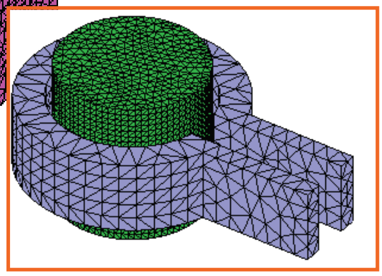
2.5 Example of a Mesh model without Displacement

- The size/element size of the air region set around the heated body and coil should fill in the mesh model without displacement. The number of elements stays within a reasonable range because the equivalent of the analysis model is divided finely differing from the slide mesh option.



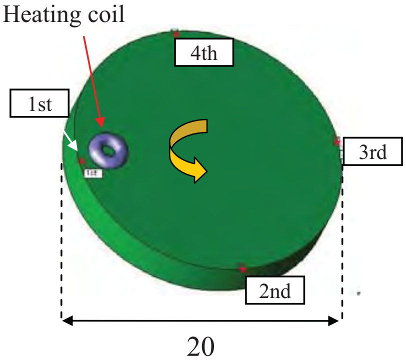


Mesh divisions for the cross-section of the heated body



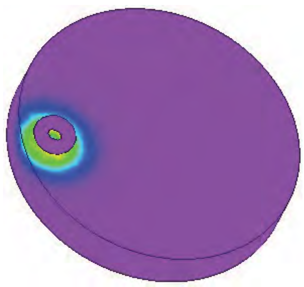
2.6 Motion without displacement

- Investigating the relationship between the rotation angle to specify for each analysis step and the calculation accuracy



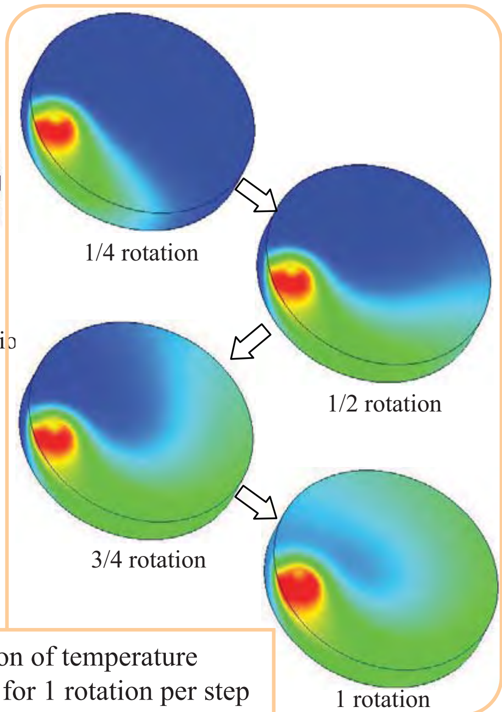
The temperature of the heated body is measured by exciting the heating coil with a 50 kHz current. The rotation speed is set to 1 rps, and then the relationship between the rotation anagle for each step and the analysis accuracy is confirmed.

The evaluation points of the temperature progression were measured at the four fixed coordinates above.



Heat generation density distributio

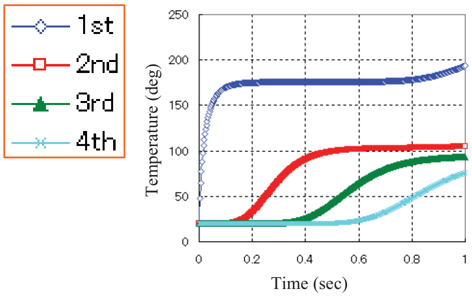
In this analysis, the heat generation density distribution is constant and the [Virtual Movement] check box is selected in the motion condition of the thermal analysis.



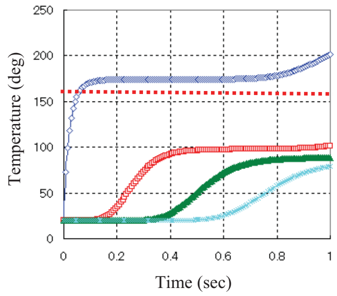
Variation of temperature distribution for 1 rotation per step

2.6 Motion Without Displacement

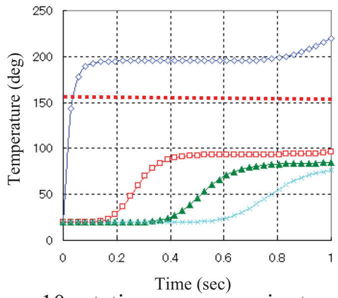
- The calculation accuracy worsens as the amount of rotation increases if 1 rotation per step is positive Approximately 5 rotations are estimated in this example



1 rotation per analysis step



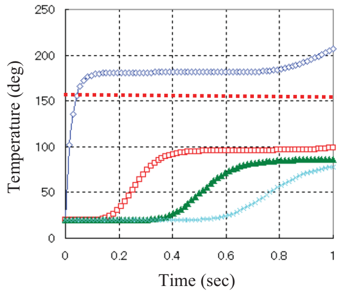
2.5 rotations per analysis step



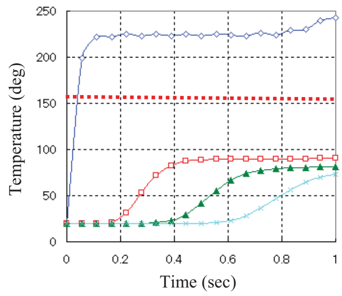
10 rotations per analysis step

An approximate resolution in the direction of motion that can simulate the expanding heat generation and temperature distribution is required if "virtual movement" is used.

Red dotted line indicates the temperature after half a rotation for the 1st evaluation point when rotating 1 rotation per analysis step.



5 rotations per analysis step



20 rotations per analysis step

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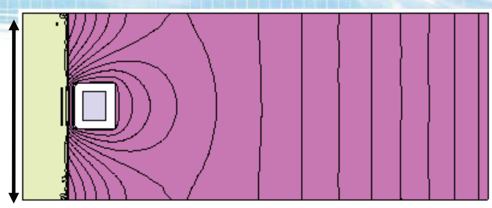
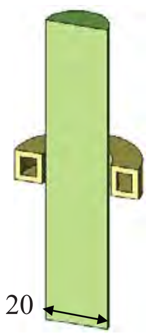
2.7 Translation Motion

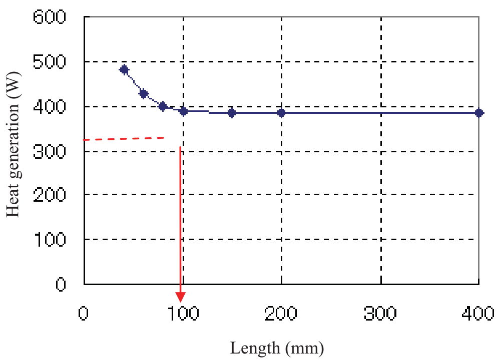
- Determining the analysis space

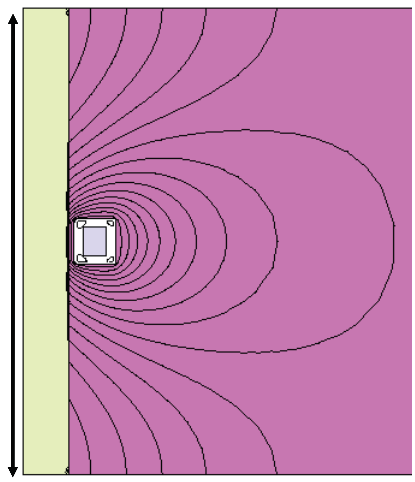
1. Confirm the saturation of magnetic flux in a magnetic field analysis, and then determine the range of modeling. The validity is confirmed by the amount of heat generation, etc.
2. The heated body is modeled including the above range of modeling, and a translation periodic boundary is set.
3. An axisymmetric boundary or virtual movement is used if possible to reduce the calculation time.



Flux lines for a model with a length of 40 mm







Flux lines for a model with a length of 100 mm

In this example, a model that has a length of 100 mm handles the saturation of magnetic flux and maintains a small model scale.

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3.2 Evaluating Results

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■What do I do when there is 'a discrepancy between the measured and analysis results?

What is related to the physical quantity A

What is the discrepancy?

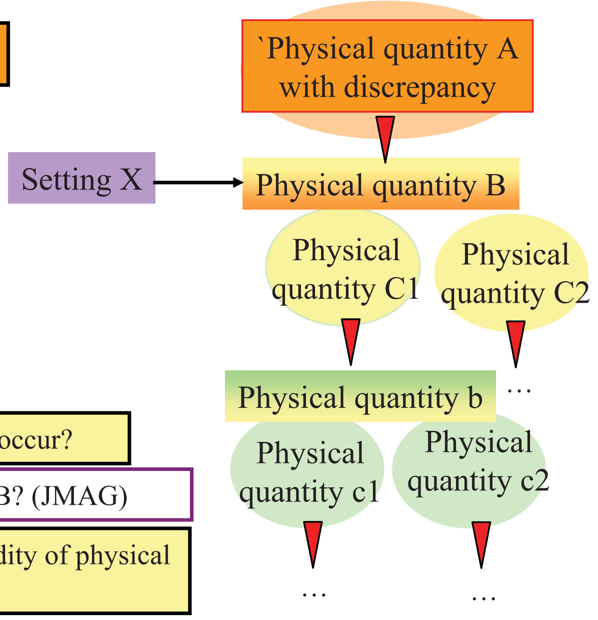
- It is a little small/ large.
- The digits are wrong.
- The size of the time variations is wrong.

The priority of items to check changes by the degree of discrepancy

What physical quantity B does physical quantity A occur?

What are the settings X handling physical quantity B? (JMAG)

What is the physical quantity C confirming the validity of physical quantity C?



The modeling of physical phenomena causing the discrepancy may be missing depending on the analysis.

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3. Evaluating Results

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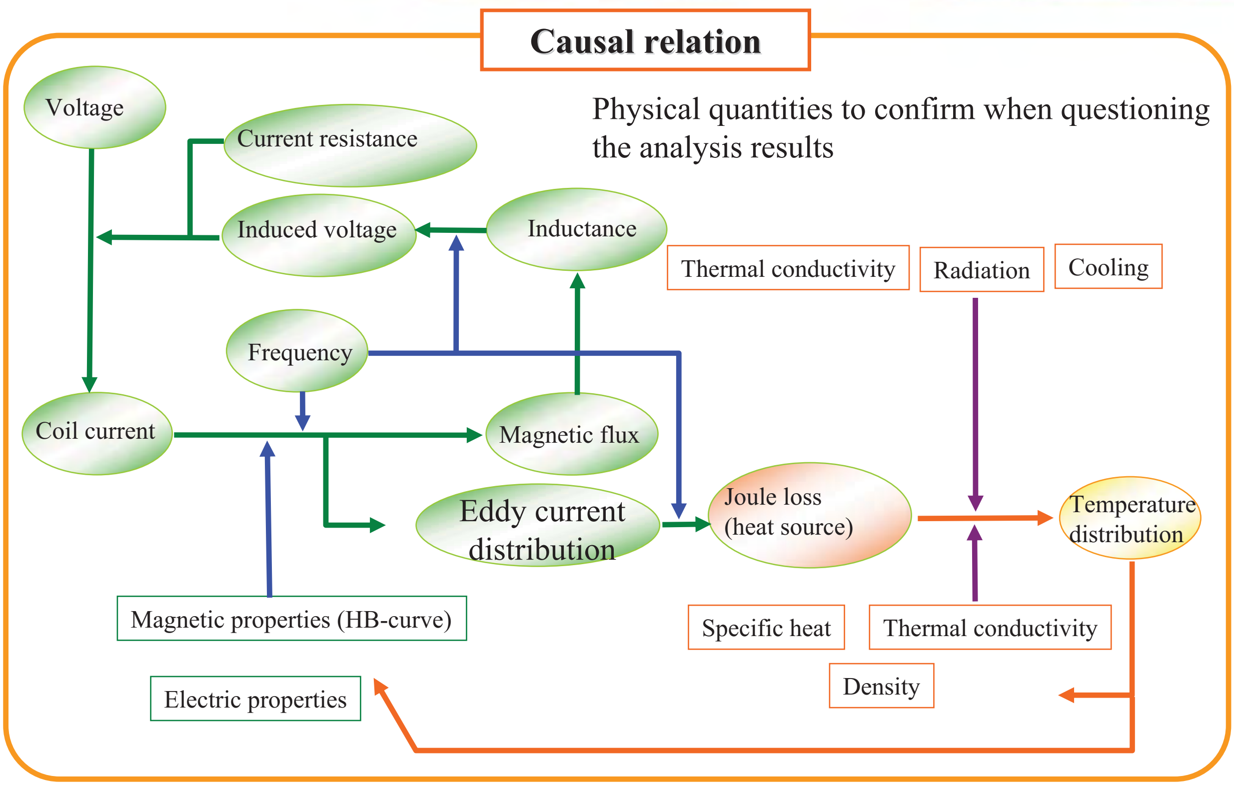

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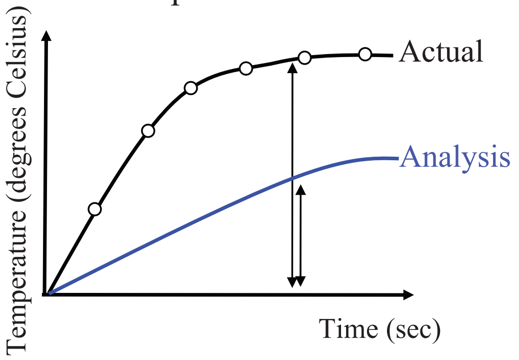
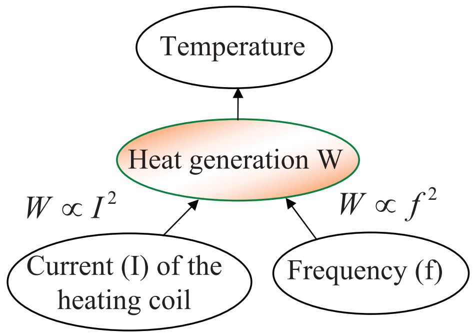
3.1 Case 1 (Evaluating Results)

- Case 1: The temperature is much lower than the actual temperature ⇨ Cause: The heat generation is too low





The heat generation (Joule loss) is not obtained correctly if the temperature in the analysis results is calculated extremely low for the amount of time of heating. The heat generation is proportional to 2 times the current and frequency of the coil. Special attention should be paid to whether the current of the heating coil is specified correctly.

The following items should be compared when confirming the validity of results:

1. Input power (product of current and voltage)
2. Output power (heat generation of heated body: Joule loss)
3. Estimated necessary power for approximation from the size of the heated region and heating time

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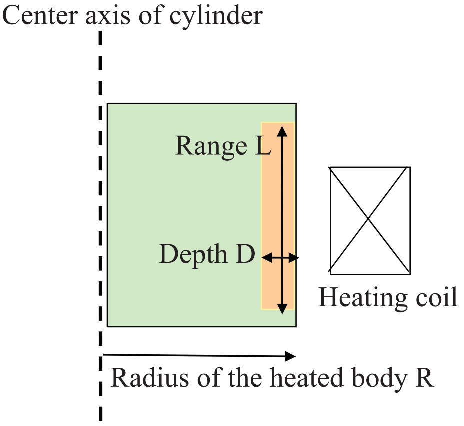
3.1 Case 1 (Supplementary Information)

- Confirming the validity of the input and output power
  - Approximately estimating the necessary power
    - What is the necessary output power (P_{out}) to raise the temperature from 20 to 900 degrees Celsius when heating the side of a workpiece that has cylindrical geometry?



$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) - Q = 0$$

$$Q = \rho C \frac{900 - 20}{10}$$

$$V = \left(R^2 - (R - D)^2\right)\pi L$$

$$P_{out} = VQ$$

Density ρ (kg/m^3)
Specific heat C(J/kg℃)
Thermal conductivity k(W/m℃)
Heat generation density Q(W/m^3)

– The settings of the analysis model need to be re-evaluated if the digits are different when comparing the input and output power from the calculation results in JMAG and the values estimated above.

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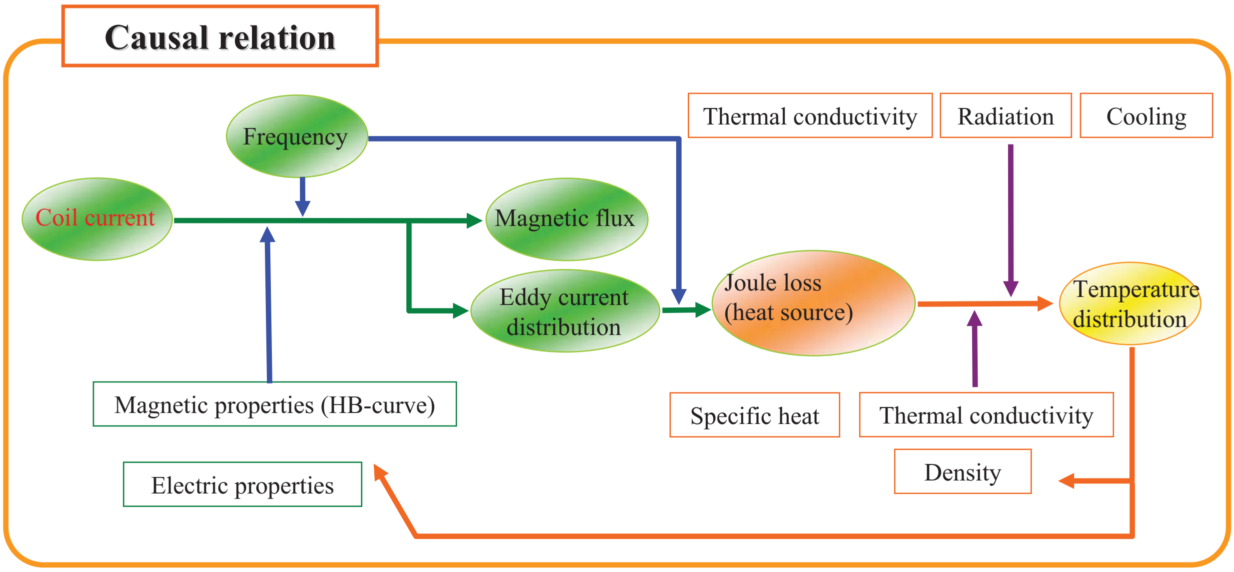
3.1 Case 1 (Determining Causes of Discrepancies)

- Determining the cause of discrepancies from the actual measurements is difficult if an analysis uses a voltage source.
  - This is because the magnetic and electric properties largely change with raising temperatures and the inductance largely varies.
- First, the analysis is confirmed from the validity of the current (input power) by running an analysis using a current source.



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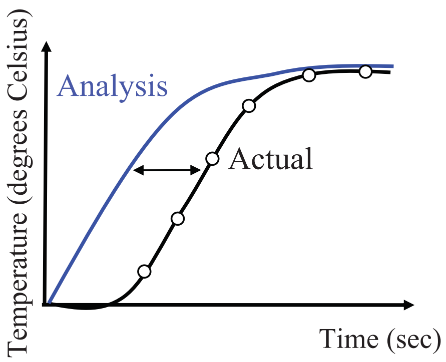
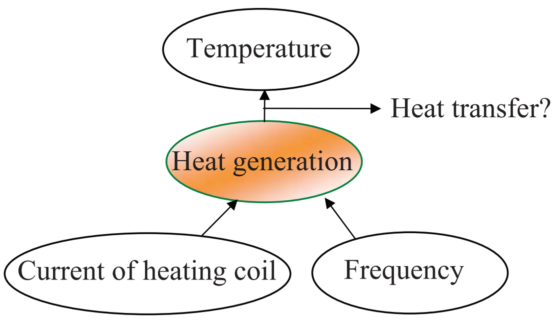
3.2 Case 2 (Evaluating Results)

- Case 2: The time to reach the final temperature differs ⇨ Cause: A problem related to heat transfer





A problem that is not caused by the total heat generation of physical properties may be the problem if the final temperature and the actual measurements as well as the speed of temperature rise match.

The following items should be compared when confirming the validity of results:

1. A problem preventing the temperature from rising for the initial time interval in the prototype/measuring environment may be the cause
2. A problem limiting the heat generation at the measuring point may be the cause. Confirm the motion condition settings to displace the heat generation areas

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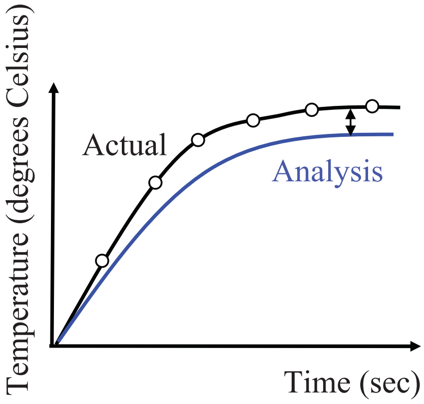
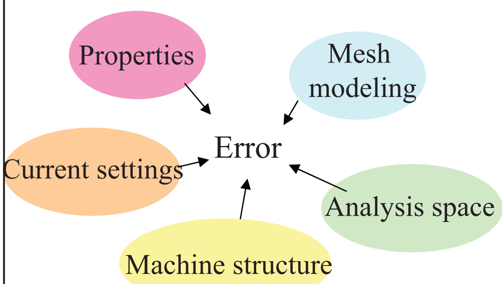
3.3 Case 3 (Evaluating Results)

- Case 3: The analysis under calculates the final temperature ⇨ Cause: The heat generation is a little low.





There are many reasons the heat generation is a little low, such as those that follow:

1. Generating the heat is difficult because the electric conductivity is set higher than the actual conductivity.

2. The current of the heating coil is slightly smaller than the actual current.

3. The frequency is slightly lower than actual frequency.

4. The eddy currents on the surface of the heated body is not simulated because the mesh modeling the skin effect has not been generated.

5. The magnetic flux is reduced by magnetic resistance because some of the mesh in the magnetic is too coarse.

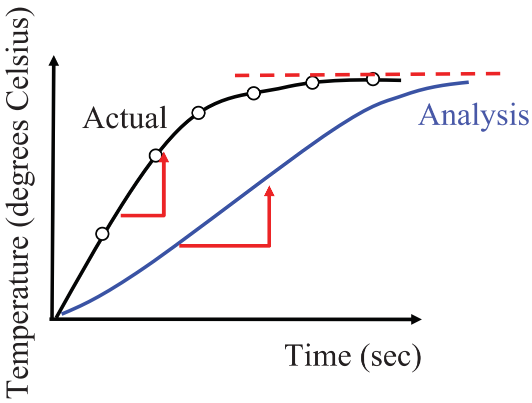
6. The air region is less than 5 times the analysis model trapping the magnetic flux in this area.

7.The prototype includes magnetic properties, such as jigs, that are not taken into account in the analysis.

8. Other

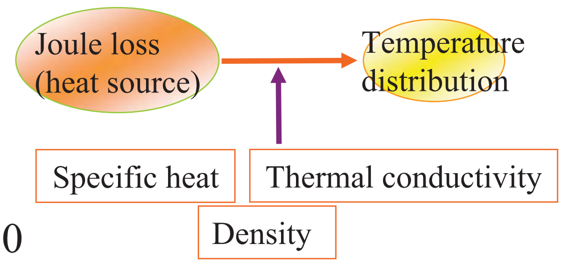
3.4 Case 4 (Evaluating Results)

- Case 4: The final temperature is almost the same, but the raising speed differs ⇨ Cause: Is it the physical properties?



If the final temperature equals the measured temperature, the total heat generation (magnetic field analysis results) are probably correct.

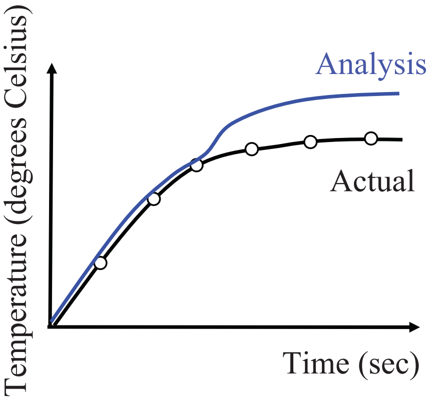
The specific heat and thermal conductivity as well as the density settings should be confirmed If the heat generation is correct because a problem exists in the heat transfer.



$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) - Q = 0$$

3.5 Case 5 (Evaluating Results)

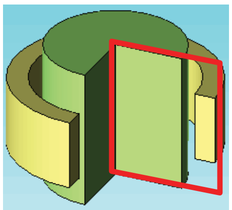
- Case 5 A jump occurs in the analysis results when the curie point is exceeded.



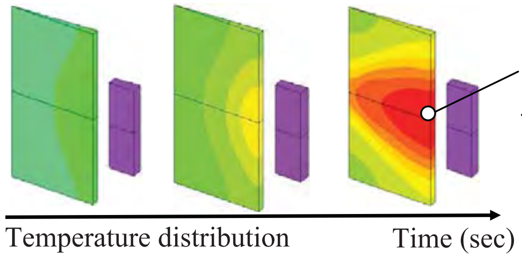
Cause: Relative permeability/constant voltage that is used.

A sudden jump appears around the point the curie point is exceeded for an induction analysis using simple settings for the temperature dependent relative permeability in the magnetization properties. The areas generating heat in the heated body has a sudden variation because the magnetic saturation is not taken into account if the relative permeability is used.

Results are obtained for an extremely large f the analysis is run with a constant power voltage because a large reduction of the inductance occur after exceeding the curie point. Therefore, a large jump in temperature



Sample model



Temperature distribution

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3.6 Pointers for Induction Heating Models

- Modeling the heated body
  - Material properties
    - The correct settings for material properties accounting for their temperature within range.
      - Nonlinear magnetization properties ← Affects of magnetic saturation and flow of magnetic flux
      - Electric properties (conductivity/resistivity) ← Using heat generation areas and total heat generation
      - Specific heat C ← Using speed of temperature rise
      - Density ρ ← Using speed of temperature rise
      - Thermal conductivity ← Define the temperature distribution

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) - Q = 0$$

  - Mesh modeling
    - Mesh modeling the skin effect is generated focusing around the range of heating based on the estimated depth of heating and the range.
    - The highest heat generated on the surface of the metal just after heating has a slope, but the areas generating heat change to the surrounding areas as the heating time progresses. Therefore, a finer mesh needs to be generated in the areas around the heating depth
    - Generate finer mesh following the magnetic circuit the magnetic flux flows
  - Heating with motion
    - As described earlier, use caution simulating the motion and maintaining accuracy

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3.6 Pointers for Induction Heating Models

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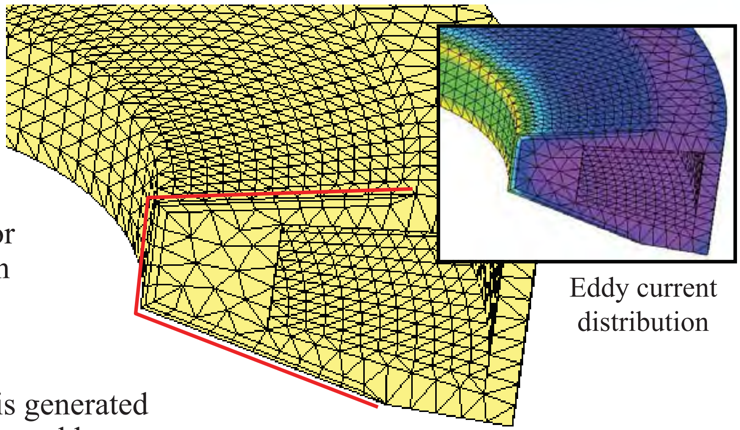
- Modeling the heating coil
  - Material properties
    - Simply enter characteristics such as copper
    - A constant value can be used for temperatures that don't rise such as cooling
  - Mesh modeling
    - Mesh modeling the skin effect is generated because the heating coil produces eddy currents in areas of the heated body near the heated coil.
    - Evaluate the current distribution using the FEM conductor condition
  - Excitation condition
    - Specify the current and frequency flowing in the actual heating coil.
      - These settings need to be set carefully because they affect the heating temperature and accuracy.
      - The amplitude is specified for the current rather than the absolute value in JMAG.



Eddy current distribution

Mesh cross-section for copper heating coil (Mesh modeling the skin effect is only generated in the necessary areas)

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3.6 Pointers for Induction Heating Models

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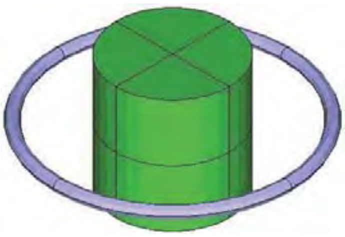
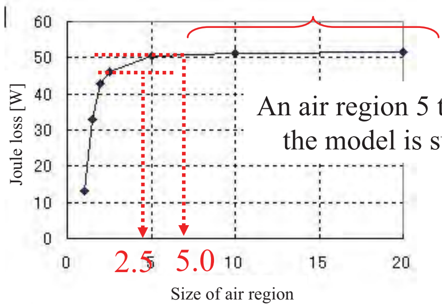
- Modeling around the heating equipment
  - Magnetic properties need to be modeled if parts have magnetic properties.
    - ➢The magnetic flux intensifies if there are magnetic materials in the magnetic circuit produced by the heating coil.
    - ➢However, the increased magnetic flux is only several percent in cases that have a large portion of the magnetic circuit that is air.
  - The air region should be generated at 5 times the size of the model.
    - ➢The air region is determined by the range of the magnetic flux saturation. The magnetic flux is weakened if the air region is small because the magnetic flux is trapped in that area. Be aware that he heat generation is reduced 10% if the default value of 2.5 times the length of the model is used in JMAG.





Confirm the size of the air region using the Joule loss produced in the heated body by exciting the heating coil.

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