Guidelines for Generating Mesh in Induction Heating Simulations

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Abstract :

A mesh accounting for the skin depth needs to be generated to perform a magnetic field frequency response analysis. The time varying phenomenon of the magnetic flux penetrating the heated workpiece using induction heating needs to be taken into account when the temperature of the workpiece exceeds the Curie point.

This presentation indicates guidelines to generate optimal mesh by investigating the effects of the mesh density on the heat generation using a workpiece and coil with simple geometry. In addition, the analysis results using the guidelines for generating mesh are compared to actual testing results.

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Guidelines for Dividing Mesh Used for Radio-frequency Induction Heating Simulations

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Objective

In radio-frequency induction heating analyses:

- Mesh divisions account for the skin depth
- Magnetic flux has time varying phenomena when heating penetrates to the inside of the workpiece

Generate a finer mesh → Improves analysis accuracy
Generate a finer mesh → Increases calculation time

★What is the appropriate element size based on the relationship between analysis accuracy and calculation time? ★ What is the relationship between the number of elements and analysis error?

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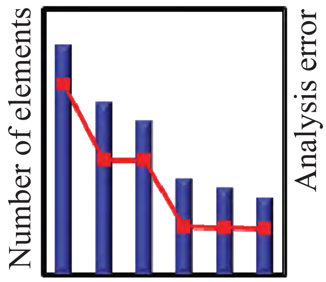
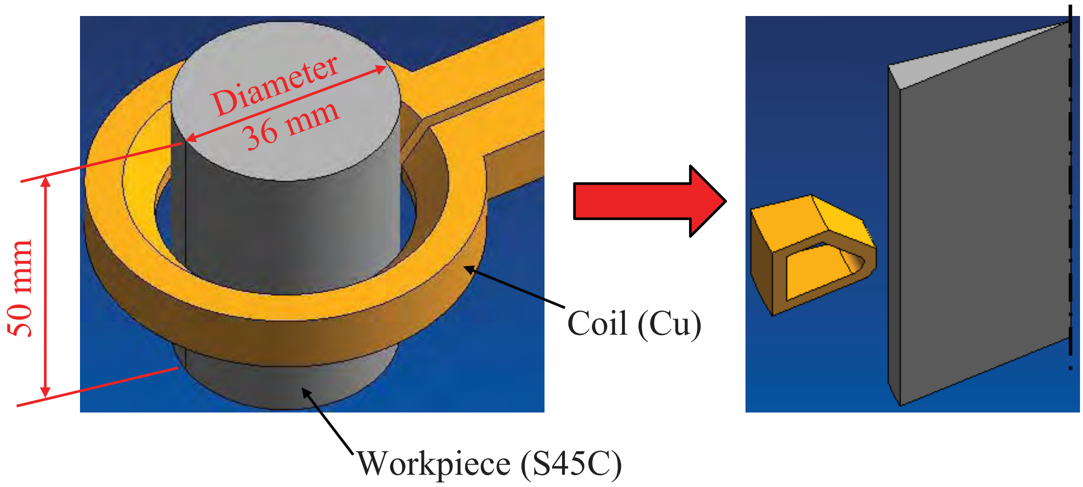
The effects of the mesh density for the heat generation was examined by performing analyses with various mesh densities for the heating coil, workpiece, and air region.

↓

Guidelines indicate the settings for dividing mesh



Analysis Model



Model of analysis target

5 degree model

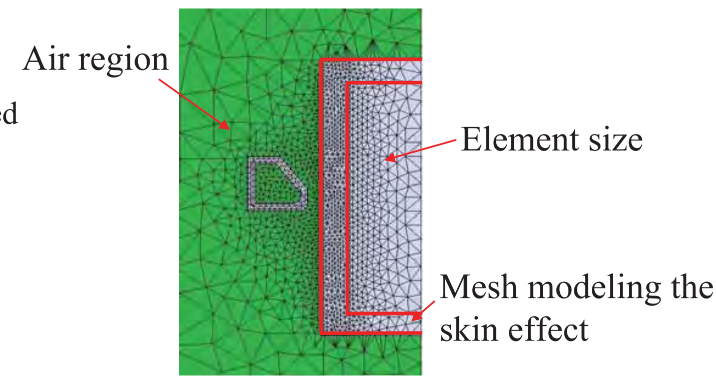
Examination and Guidelines for Mesh -Approach -

STEP 1: Run a magnetic field analysis and investigate the effects of the mesh divisions on the heat generation of the workpiece.

STEP 2: Run a coupled magnetic field and thermal analysis based on the results obtained in STEP 1 and investigate the effects on the heat generation.

STEP 3: Investigate the effects of the size for the air region on the heat generation of the workpiece.

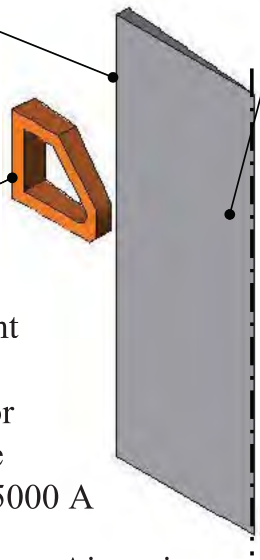
- Specifications of the machine used for the calculation
  - Windows Server SP1 64-bit
  - Xeon X5560 2.8GHz
  - Memory 12 GByte
  - 4 thread parallel computing



STEP 1 Independent Magnetic Field Analysis
STEP 1-1 Divide Mesh for the Heating Coil

STEP 1-1: Specify the conditions

Heat transfer boundary
- Reference temperature 20 degrees Celsius
- Heat transfer coefficient 10 W/m^2/degrees Celsius



Heating coil
- Use temperature dependent material properties
- Specify an FEM conductor condition, and then set the excitation to 10 kHz and 5000 A

Air region
- 2.5 times

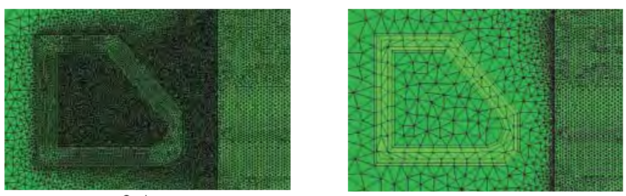
Workpiece
- Use temperature dependent material properties
- Initial temperature 20 degrees Celsius
- Mesh density
- Element size 0.15 mm
- Mesh modeling the skin effect 0.075 mm
- Divisions of mesh modeling the skin effect 1

The analysis is performed by changing the element size, mesh modeling the skin effect, and divisions of the mesh for the heating coil.

STEP1-1 Divide Mesh for the Heating Coil

★Mesh divisions for the heating coil

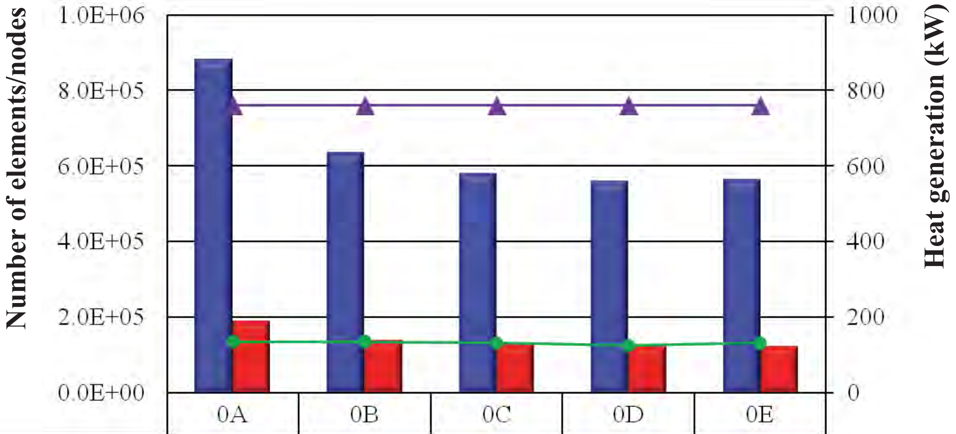
Model name	Element size (mm)	Mesh modeling the skin effect (mm)	Divisions of mesh modeling the skin effect
0A	0.15	0.075	1
0B	0.3	0.15	1
0C	0.6	0.3	1
0D	1.2	0.6	1
0E	1	0.5	2



0A 0E

Mesh density

STEP1-1 Divide Mesh for the Heating Coil

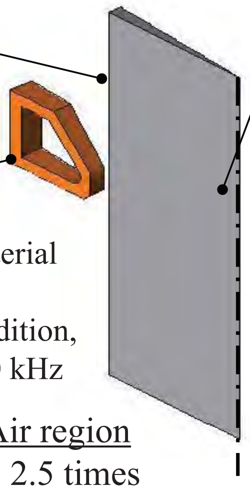


	0A	0B	0C	0D	0E
Number of elements	881679	635033	580132	559432	564322
Number of nodes	189723	139071	126735	121831	123177
Heating coil (kW)	134.4	134.3	131.4	124.1	130.5
Workpiece (kW)	759.6	759.6	759.6	759.6	759.6

➡ The difference in the heat generation of the workpiece is minimal for different mesh densities of a ring coil.

STEP1-2 Divide Mesh for the Workpiece

STEP1-2: Specify the conditions



Heat transfer boundary
- Reference temperature 20 degrees Celsius
- Heat transfer coefficient 10 W/m²/degrees Celsius

Heating coil
- Use temperature dependent material properties
- Specify an FEM conductor condition, and then set the excitation to 10 kHz and 5000 A
- Mesh density
  Element size 1 mm
  Mesh modeling the skin effect 0.5 mm
  Divisions of mesh modeling the skin effect 2

Air region
- 2.5 times

The analysis is performed by changing the element size, mesh modeling the skin effect, and divisions of mesh for the workpiece.

Workpiece
- Use temperature dependent magnetic/material properties
- Initial temperature 20 degrees Celsius

Theoretical values for skin depth at a 10 kHz frequency

$$d=\sqrt{\frac{1}{\pi f \sigma \mu^0 \mu^r}}$$

Frequency: f (Hz)
Conductivity: σ (1/Ωm)
Vacuum permeability: μ_0
Relative permeability: μ_r

d=0.15 mm

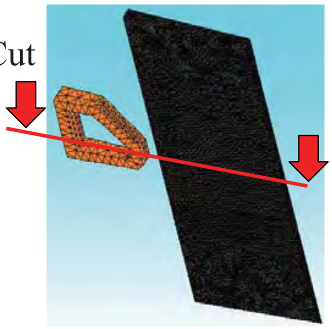
STEP1-2 Divide Mesh for the Workpiece

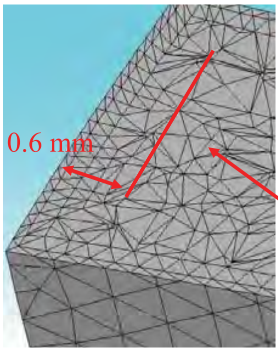
★The theoretical skin depth for the divided mesh is 0.15 mm

		Mesh modeling the skin effect (mm)				
		0.075	0.15	0.3	0.45	0.6
Element size (mm)	0.15	○-A1	–	–	–	–
	0.3	○-A2	○-B1	–	–	–
	0.6	○-A3	○-B2	○-C1	–	–
	0.9	○-A4	○-B3	○-C2	○-D1	–
	1.2	○-A5	○-B4	○-C3	○-D2	○-E1

* ○: 1 to 4 divisions for the skin depth

Cut



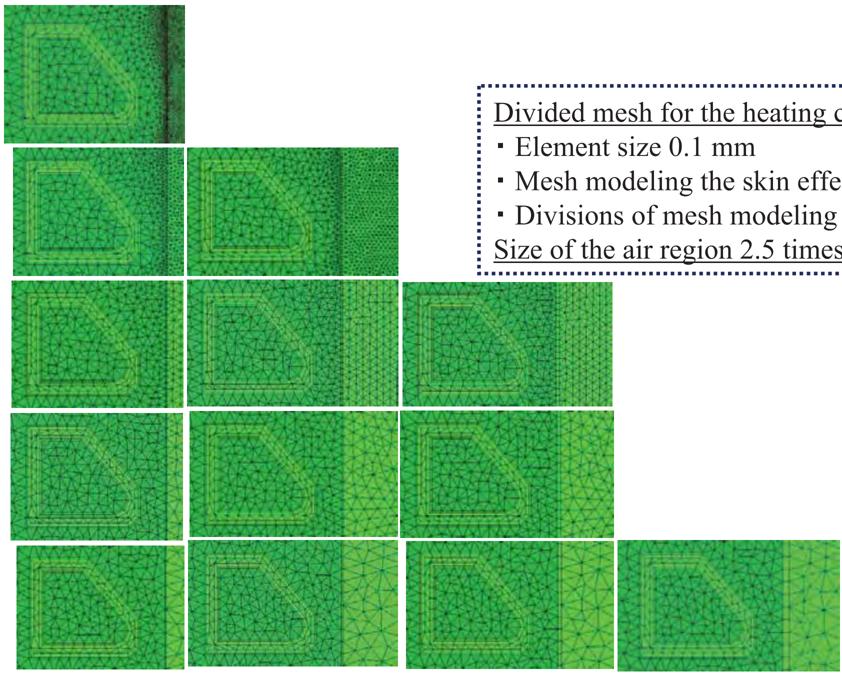


Mesh divisions of workpiece
- Element size 0.15 mm
- Mesh modeling the skin effect 0.6 mm
- Divisions of mesh modeling the skin effect 4

The mesh modeling the skin effect is set to 4 divisions, but the specified mesh is not generated

STEP1-2 Divide Mesh for the Workpiece

Element size of workpiece: 0.15 mm, 0.3 mm, 0.6 mm, 0.9 mm, 1.2 mm



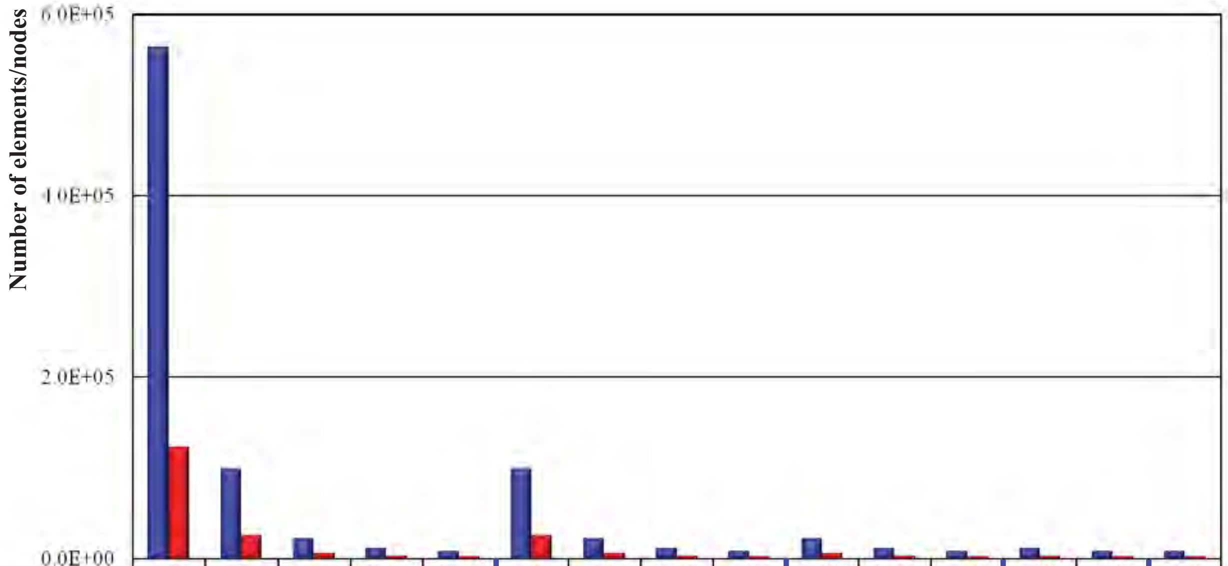
0.075 mm 0.15 mm 0.3 mm 0.6 mm

Skin depth of workpiece (1 division)

Divided mesh for the heating coil
- Element size 0.1 mm
- Mesh modeling the skin effect 0.5 mm
- Divisions of mesh modeling the skin effect 2

Size of the air region 2.5 times

STEP1-2 Divide Mesh for the Workpiece



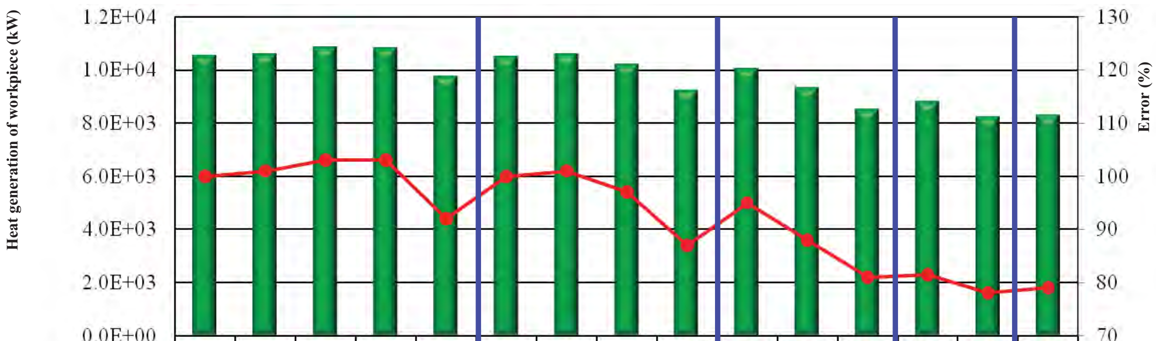
	1-A1	1-A2	1-A3	1-A4	1-A5	1-B1	1-B2	1-B3	1-B4	1-C1	1-C2	1-C3	1-D1	1-D2	1-E1
Elements	564322	99761	22694	12705	9041	99743	22692	12705	9041	22678	12701	9041	12693	9033	9029
Nodes	123177	26968	7281	4421	3221	26944	7275	4417	3221	7261	4413	3217	4399	3209	3205

STEP1-2 Divide Mesh for the Workpiece

Mesh modeling the skin effect 1 division		Mesh modeling the skin effect (mm)				
		0.075	0.15	0.3	0.45	0.6
Element size (mm)	0.15	1-A1	-	-	-	-
	0.3	1-A2	1-B1	-	-	-
	0.6	1-A3	1-B2	1-C1	-	-
	0.9	1-A4	1-B3	1-C2	1-D1	-
	1.2	1-A5	1-B4	1-C3	1-D2	1-E1

→ Calculation takes a long time

Larger element size
→ larger error



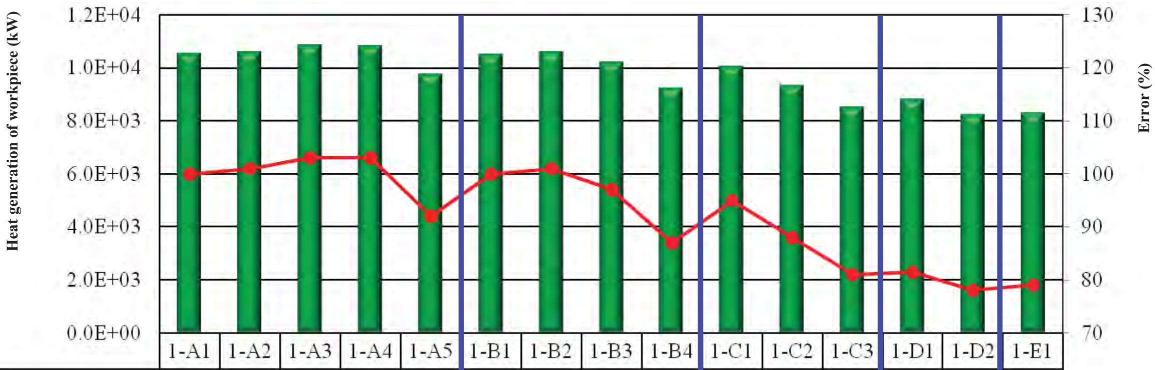
	1-A1	1-A2	1-A3	1-A4	1-A5	1-B1	1-B2	1-B3	1-B4	1-C1	1-C2	1-C3	1-D1	1-D2	1-E1
Workpiece (kW)	10550	10620	10870	10820	9755	10510	10620	10220	9227	10060	9334	8521	8818	8235	8314
Error (%)	100	101	103	103	92	100	101	97	87	95	88	81	81	78	79

STEP1-2 Divide Mesh for the Workpiece

Mesh modeling the skin effect 1 division		Mesh modeling the skin effect (mm)				
		0.075	0.15	0.3	0.45	0.6
Element size (mm)	0.15	1-A1	–	–	–	–
	0.3	1-A2	1-B1	–	–	–
	0.6	1-A3	1-B2	1-C1	–	–
	0.9	1-A4	1-B3	1-C2	1-D1	–
	1.2	1-A5	1-B4	1-C3	1-D2	1-E1

Calculation takes a long time

The error increases as the element size of the mesh modeling the skin effect gets larger because the eddy current distribution cannot be simulated.

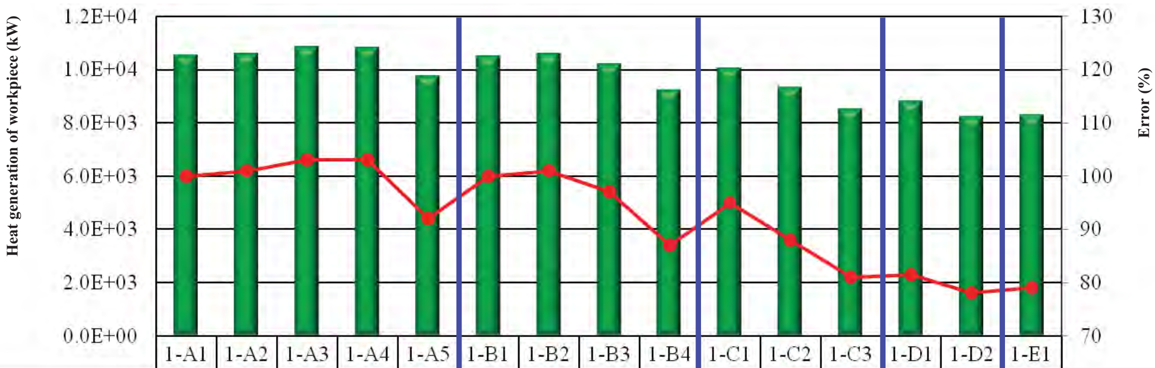


	1-A1	1-A2	1-A3	1-A4	1-A5	1-B1	1-B2	1-B3	1-B4	1-C1	1-C2	1-C3	1-D1	1-D2	1-E1
Workpiece (kW)	10550	10620	10870	10820	9755	10510	10620	10220	9227	10060	9334	8521	8818	8235	8314
Error (%)	100	101	103	103	92	100	101	97	87	95	88	81	81	78	79

STEP1-2 Divide Mesh for the Workpiece

Mesh modeling the skin effect 1 division		Mesh modeling the skin effect (mm)				
		0.075	0.15	0.3	0.45	0.6
Element size (mm)	0.15	1-A1	–	–	–	–
	0.3	1-A2	1-B1	–	–	–
	0.6	1-A3	1-B2	1-C1	–	–
	0.9	1-A4	1-B3	1-C2	1-D1	–
	1.2	1-A5	1-B4	1-C3	1-D2	1-E1

STEP 2 is run with an element size 2 times larger for each mesh modeling the skin effect.



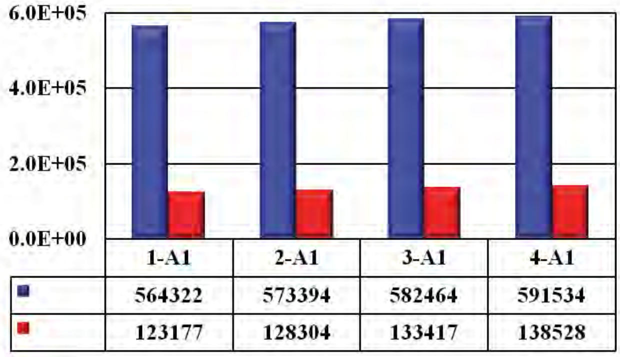
	1-A1	1-A2	1-A3	1-A4	1-A5	1-B1	1-B2	1-B3	1-B4	1-C1	1-C2	1-C3	1-D1	1-D2	1-E1
Workpiece (kW)	10550	10620	10870	10820	9755	10510	10620	10220	9227	10060	9334	8521	8818	8235	8314
Error (%)	100	101	103	103	92	100	101	97	87	95	88	81	81	78	79

STEP1-2 Divide Mesh for the Workpiece

★Investigating the number of divisions for the mesh modeling the skin effect

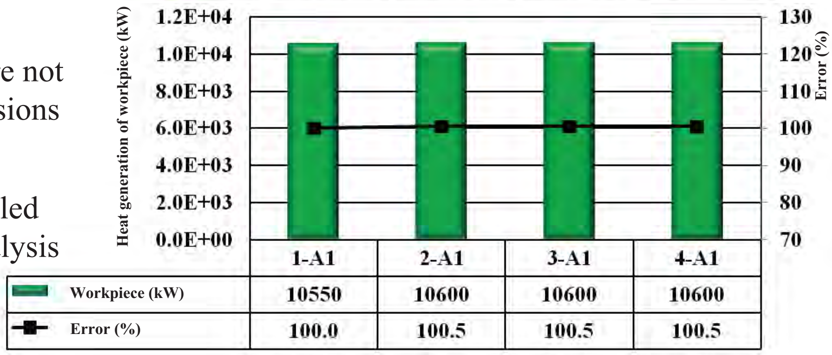
Element size (mm) \ Mesh modeling the skin effect 1 division	Mesh modeling the skin effect (mm) 0.075	0.15	0.3	0.45	0.6
0.15	A1				
0.3					
0.6					
0.9					
1.2					

Divisions for mesh modeling the skin effect is set between 1 and 4



In this research, the results were not affected by the number of divisions

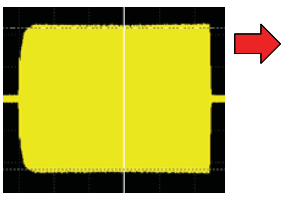
→STEP 2
Examine results using a coupled magnetic field and thermal analysis



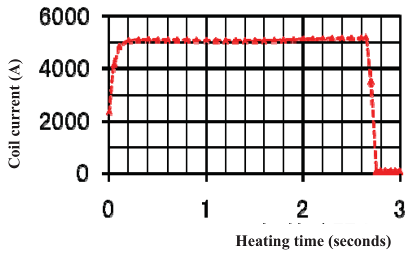
STEP 2 Coupled magnetic field and thermal analysis

STEP 2: Specifying the conditions (frequency 10 kHz/heating time 3.0 seconds)

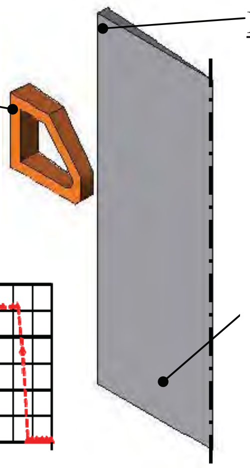
Heating coil
- Use temperature dependent material properties
- Setting the FEM conductor
- The current value of the coil is calculated from the actual measured value.



Coil current waveform



Coil current data



Heat transfer boundary
- Reference temperature 20 degrees Celsius
- Heat transfer coefficient 10 W/m²/degrees Celsius

Air region
- 5 times

Workpiece
- Use magnetic/material properties accounting for the temperature dependency
- Initial temperature 20 degrees Celsius

- Mesh density
  Element size 1 mm
  Mesh modeling the skin effect 0.5 mm
  Divisions of mesh modeling the skin effect 2

The analysis is performed by changing the element size, mesh modeling the skin effect, and divisions of the mesh for the workpiece.

STEP 2 Coupled magnetic field and thermal analysis

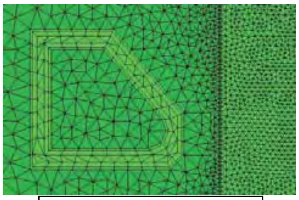
★ Mesh divisions of the workpiece

Theoretical skin depth 0.15(mm)

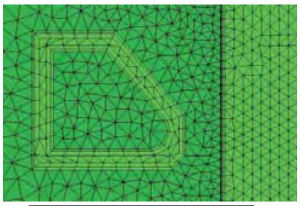
Element size (mm)	Mesh modeling the skin effect (mm) 0.075	0.15	0.3	0.45	0.6
0.15	A1	–	–	–	–
0.3	A2	B1	–	–	–
0.6	A3	B2	C1	–	–
0.9	A4	B3	C2	D1	–
1.2	A5	B4	C3	D2	E1

Model name	Element size	Skin depth	Divisions
2-B1	0.3	0.15	2
3-B1	0.3	0.15	3
4-B1	0.3	0.15	4
2-C1	0.6	0.3	2
3-C1	0.6	0.3	3
4-C1	0.6	0.3	4
2-D1	0.9	0.45	2
3-D1	0.9	0.45	3
4-D1	0.9	0.45	4
2-E1	1.2	0.6	2
3-E1	1.2	0.6	3
4-E1	1.2	0.6	4

STEP 2 Coupled magnetic field and thermal analysis



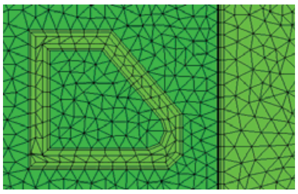
4-B1
- Element size 0.3 mm
- Skin depth 0.15 mm
- Divisions 4



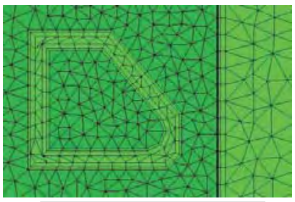
4-C1
- Element size 0.6 mm
- Skin depth 0.3 mm
- Divisions 4

Divided mesh for the heating coil
- Element size 0.1 mm
- Mesh modeling the skin effect 0.5 mm
- Divisions of mesh modeling the skin effect 2

5 times the size of the air region

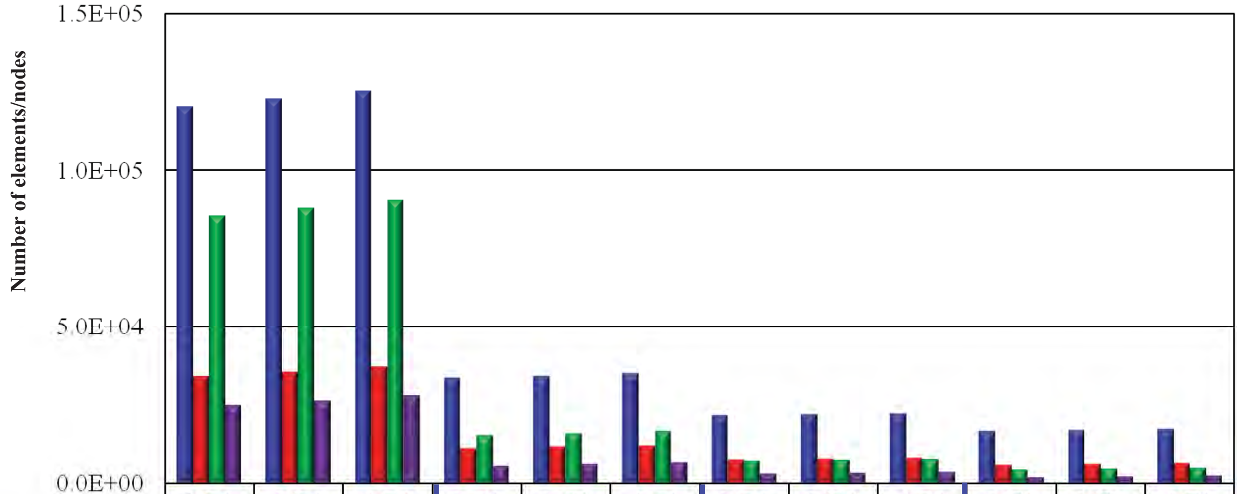


4-D1
- Element size 0.9 mm
- Skin depth 0.45 mm
- Divisions 4



4-E1
- Element size 1.2 mm
- Skin depth 0.6 mm
- Divisions 4

STEP 2 Coupled magnetic field and thermal analysis

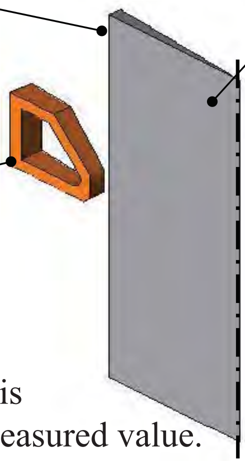


	2-B1	3-B1	4-B1	2-C1	3-C1	4-C1	2-D1	3-D1	4-D1	2-E1	3-E1	4-E1
Elements (Magnetic)	120171	122645	125119	33640	34286	34932	21733	22039	22345	16822	17052	17280
Nodes (Magnetic)	33908	35436	36964	11093	11567	12035	7538	7791	8044	5915	6110	6297
Elements (Thermal)	85375	87849	90323	15352	15998	16644	7255	7561	7867	4476	4706	4934
Nodes (Thermal)	24734	26262	27790	5664	6138	6606	3071	3324	3577	2087	2282	2469

STEP 3 Size of Air region

STEP 3: Specifying the conditions (frequency 10 kHz/heating time 3.0 seconds)

Heat transfer boundary
- Reference temperature 20 degrees Celsius
- Heat transfer coefficient 10 W/m^2/degrees Celsius



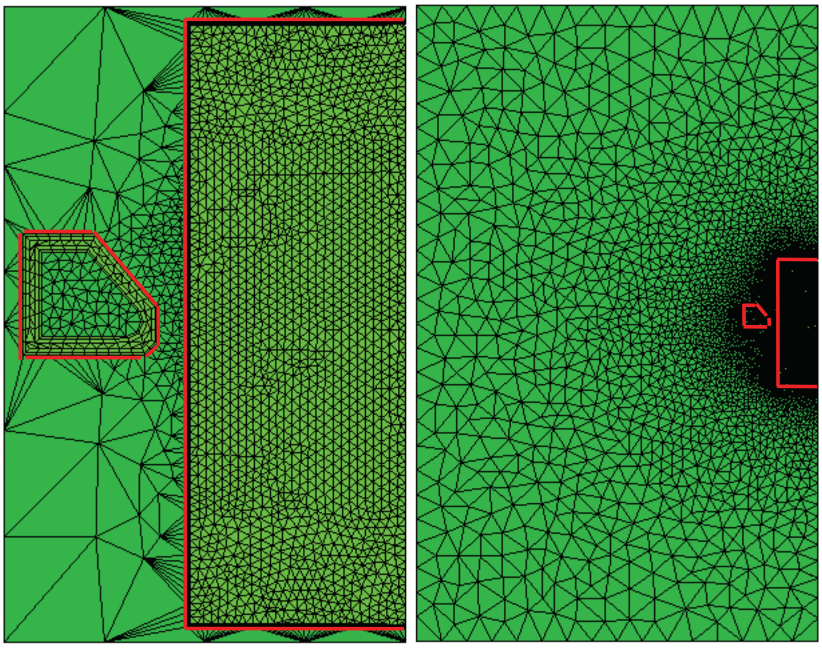
Heating coil
- Use temperature dependent material properties
- Setting the FEM conductor
- The current value of the coil is calculated from the actual measured value.
- Mesh density

Element size 1 mm
Mesh modeling the skin effect 0.5 mm
Divisions of mesh modeling the skin effect 2

Workpiece
- Use temperature dependent magnetic/material properties
- Initial temperature 20 degrees Celsius
- Mesh density
  Element size 0.6 mm
  Mesh modeling the skin effect 0.3 mm
  Divisions of mesh modeling the skin effect 4

Size of air region
- Run analyses by changing the size to 1.05, 2, 3, 4, 5, and 10times

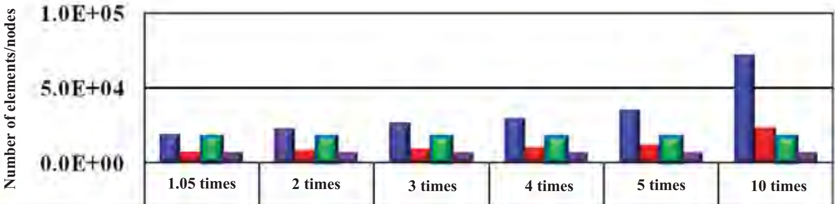
STEP 3 Size of Air region



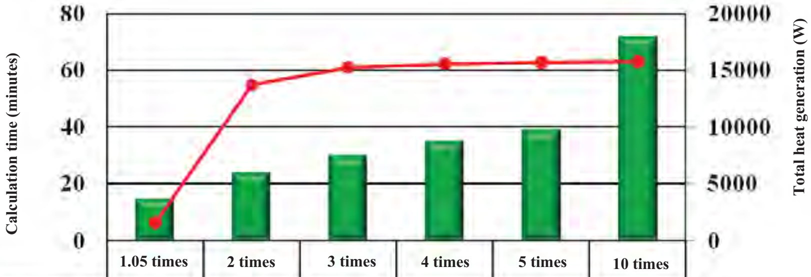
Element size of mesh divisions at 1.05 time

Element size of mesh divisions at 5 times

STEP 3 Size of Air region



	1.05 times	2 times	3 times	4 times	5 times	10 times
Elements (Magnetic)	19339	22740	26901	29737	34932	71701
Nodes (Magnetic)	7010	8076	9406	10361	12035	23200
Elements (Thermal)	16644	16644	16644	16644	16644	16644
Nodes (Thermal)	6606	6606	6606	6606	6606	6606



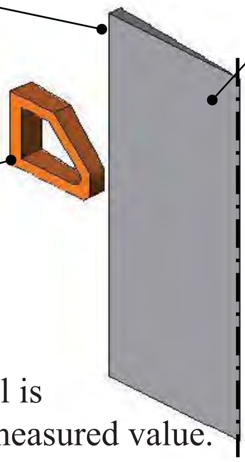
	1.05 times	2 times	3 times	4 times	5 times	10 times
Calculation Time	15	24	30	35	39	72
Total heat generation	1584	13680	15257	15552	15653	15746

Comparing the Actual Results and Analysis Results

Specifying the conditions (frequency 10 kHz/heating time 3.0 seconds)

Heat transfer boundary
- Reference temperature 20 degrees Celsius
- Heat transfer coefficient 10 W/m^2/degrees Celsius

Heating coil
- Use temperature dependent material properties
- Setting the FEM conductor
- The current value of the coil is calculated from the actual measured value.
- Mesh density
  Element size 1mm
  Mesh modeling the skin effect 0.5 mm
  Divisions of mesh modeling the skin effect 2



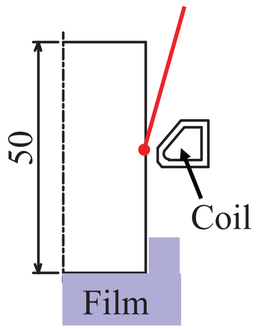
Air region
- 5 times

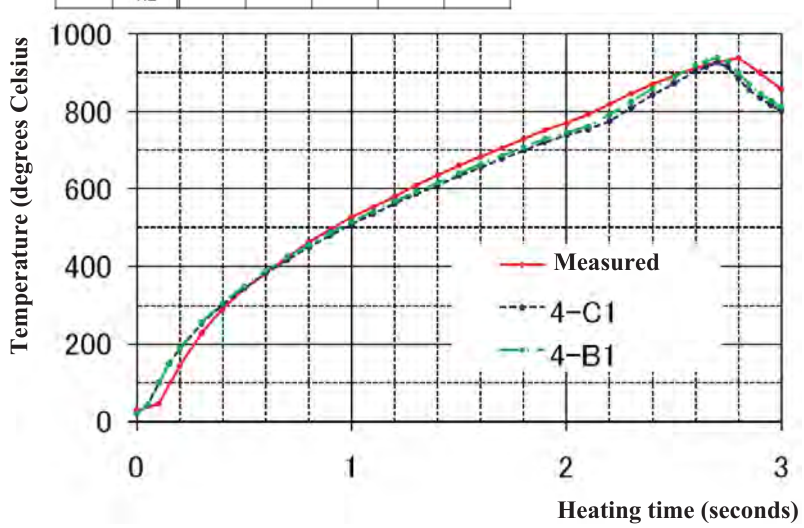
Workpiece
- Use temperature dependent magnetic/material properties
- Initial temperature 20 degrees Celsius
- Mesh divisions (1) (4-B1)
  Element size 0.3 mm
  Mesh modeling the skin effect 0.15 mm
  Divisions of mesh modeling the skin effect 4
- Mesh divisions (2) (4-C1)
  Element size 0.6 mm
  Mesh modeling the skin effect 0.3 mm
  Divisions of mesh modeling the skin effect 4

Comparing the Actual Results and Analysis Results

Mesh modeling the skin effect 1 division		Mesh modeling the skin effect (mm)				
		0.075	0.15	0.3	0.45	0.6
Element size (mm)	0.15					
	0.3		4-B1			
	0.6			4-C1		
	0.9					
	1.2					

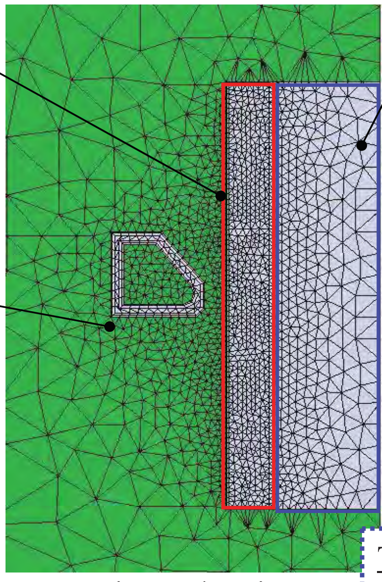
Position temperature is measured





Reducing the Analysis Time

★Examination of the workpiece divisions



Heat transfer boundary
- Reference temperature 20 degrees Celsius
- Heat transfer coefficient 10 W/m^2/degrees Celsius

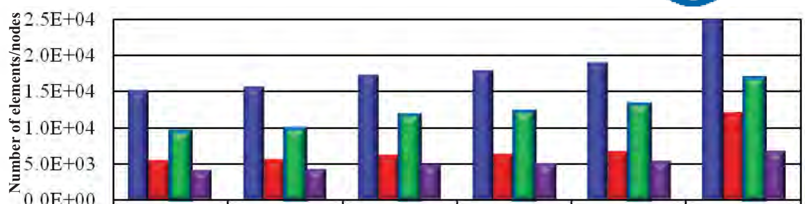
Heating coil
- Use temperature dependent material properties
- Set the FEM conductor
- The current value of the coil is calculated from the actual measured value.
- Mesh density
  Element size 1 mm
  Mesh modeling the skin effect 0.5 mm
  Divisions of mesh modeling the skin effect 2

5 times the size of the air region

Workpiece
- Use temperature dependent magnetic/material properties
- Initial temperature 20 degrees Celsius
- Dense mesh divisions
  Element size 0.6 mm
  Mesh modeling the skin effect 0.3 mm
  Divisions of mesh modeling the skin effect 4
- Coarse mesh divisions
  Not specified

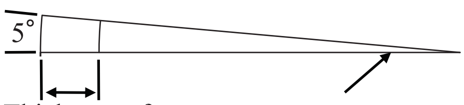
Thickness of dense mesh
- Run the analysis changing the density to 1.25, 2.5 (optimal depth), 5, 7.5, and 9 mm

Reducing the Analysis Time



	1.25	2.5	5	7.5	9	All dense
Elements (Magnetic)	15036	15560	17220	17778	18951	34932
Nodes (Magnetic)	5409	5576	6102	6274	6691	12035
Elements (Thermal)	9436	9715	11628	12135	13142	16644
Nodes (Thermal)	4073	4158	4758	4920	5280	6606

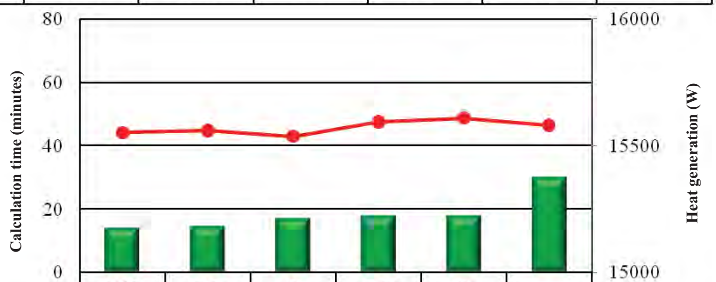
No difference for the 5 degree model



Thickness of dense mesh

The mesh automatically becomes finer toward the center of the features.

The entire model needs to be examined



	1.25	2.5	5	7.5	9	All dense
Calculation Time	14	14.6	17	18	18	30
Total heat generation	15552	15559	15538	15595	15610	15581

Conclusion

1. The analysis accuracy is maintained by having a thickness of mesh modeling the skin effect 2 times the theoretical skin depth, 2 divisions, and an element size of 2 times the mesh modeling the skin effect.

2. The mesh modeling the skin effect affects the analysis accuracy minimally even if the number of divisions is higher than 2.

3. The air region should be set to more than 3 times the size of the model.

4. The analysis results using the mesh divisions described in (1) can analyze the induction heating with a -1.6% accuracy when compared to the actual maximum temperature that is measured.

5. The mesh density will be further investigated in the future because advantages of methods for establishing the density of mesh for the workpiece in this model could not be determined.