

FEM analysis of temperature distribution of CF RTP curved pipe mold heated by high-frequency direct resistance heating

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Abstract

Carbon fiber reinforced thermoplastics (CF RTP), which have advantages in terms of high-specific strength and high-specific stiffness, are expected to be used for automotive parts to attain automotive lightening for good gasoline mileage. Not only straight-shaped parts but also curved-shaped parts are well used for pipe-shaped structural components, and low-cost and high-speed molding method is required for CF RTP pipe molding. High-frequency direct resistance heating has been developed so as to heat only the mold surface rapidly by skin effect, resulting in better energy consumption than that of induction heating methods. In the case of a curved pipe mold, however, uniformity of its temperature distribution is one of the important issues to be solved. In order to obtain uniform temperature distribution of the curved mold, the novel mold structure with hollow was proposed and its temperature distribution was revealed using FEM analysis.

Keywords: CF RTP pipe, FEM analysis, temperature distribution, skin effect, high-frequency direct resistance heating.

1 Introduction

In view of the environmental problems, saving fuel consumption of the car is important. Carbon fiber reinforced thermoplastics (CF RTP) have many superior mechanical properties such as high-specific strength and high-specific modulus [1]. It is possible to reduce the weight of the car by using CF RTP as substitute material. In automobile parts, a lot of high strength steel tubes are used for shock absorber parts such as the door guard bar and impact beam, and are also used for automobile undercarriage components such as suspension arm and torsion beam



[2, 3]. Although CFRTP is a candidate material to replace steel tubes, however, CFRTP is too high-cost to use for automobile parts [4]. Therefore, the low-cost and high-speed CFRTP pipe molding method is required. For high-speed heating method of the mold, there are high frequency induction heating and high-frequency direct resistance heating, in which only the surface of the mold is heated by using skin effect [5]. In the case of the high-frequency direct resistance heating, it is possible to reduce the equipment cost, since a coil which is used in induction heating method is not used. In the high-frequency direct resistance heating, uniformity of temperature distribution is one of the important issues to be solved. In previous study, columnar mold was rapidly heated by high-frequency direct resistance heating, and the effects of the frequency and shape of electrode was discussed [6, 7]. As pipe shaped components have various shapes, not only the straight line shapes but also the curve shapes, it is necessary to clarify the heating condition for the curved mold. In this study, to reveal the temperature distribution of the curved mold and to obtain uniform temperature distribution of the curved mold, the influence of the frequency of alternating current on the curved mold is analysed using FEM analysis and the novel mold structure with hollow is proposed.

2 FEM analysis

2.1 Governing equation

COMSOL Multiphysics (COMSOL AB) is used for finite-element analysis. Electric and Induction Currents (AC/DC Module) and General Heat Transfer (Heat Transfer Module) is used for modules. In consideration of frequency properties, magnetic permeability as μ' and conductivity as σ' are expressed in equations (1) and (2) [8]:

$$\mu' = i\omega\sigma - \omega^2\varepsilon_0\varepsilon_r \quad (1)$$

$$\sigma' = \sigma + i\omega\varepsilon_0\varepsilon_r \quad (2)$$

where ω is angular frequency, σ is conductivity of the conductor, ε_0 is dielectric constant of vacuum, and ε_r is dielectric constant of the conductor. The governing equation of AC/DC Module is expressed in equations (3) and (4):

$$-\nabla \cdot (\mu'\mathbf{A} + \sigma'\nabla V - \mathbf{J}) = 0 \quad (3)$$

$$\mu'\mathbf{A} + \nabla \times (\mu_0^{-1}\mu_r^{-1}\nabla \times \mathbf{A}) + \sigma'\nabla V = \mathbf{J} \quad (4)$$

where μ_0 is dielectric constant of vacuum, μ_r is dielectric constant of the conductor, \mathbf{J} is current, \mathbf{A} is magnetic field, and V is electric potential. The governing equation of heat transfer module is expressed in equation (5):

$$\rho C_p \frac{\partial T}{\partial t} - \nabla(k\nabla T) = Q \quad (5)$$

where ρ is density, C_p is specific heat, T is temperature, t is time, k is heat conduction coefficient, and Q is heat source. Heat source is calculated from the current density distribution. The coupled analysis is performed based on these expressions.

2.2 Analytical model

Fig. 1 shows the curved mold model and the curved mold with hollow for FEM analysis. The curved mold is columnar form with 30mm in diameter, straight line part of 50mm in length, and curved part of 30mm for the radius of curvature along center line. The curved mold with hollow has a half-cylindrical hollow which is 2mm deep from outer surface of the curved part to the 25mm part from both ends of the mold. In both models, electrodes made of copper, whose size are 40mm×40mm×50mm, are attached to the both ends of the mold made of SUS430. To consider the heat radiation to the air, the layer of the air, 300mm×300mm×100mm, is set around molds. The number of elements for the curved mold model and the curved mold with hollow are 9936 and 10200, respectively. Tetrahedral elements are used.

The material physical properties of each material are shown in Table 1. The initial temperature is set as 20°C. Heating time is set at 60 seconds. To clarify the influence of the frequencies on the surface temperature distribution for the curved mold model, the frequencies of alternate current, 1kHz, 10kHz, 20kHz, 50kHz and 100kHz, are used. The output power is 1.2kW for all the conditions. For the analysis of the curved mold model with hollow, the frequency of alternate current is set for 1kHz and the output power is set for 0.87kW.

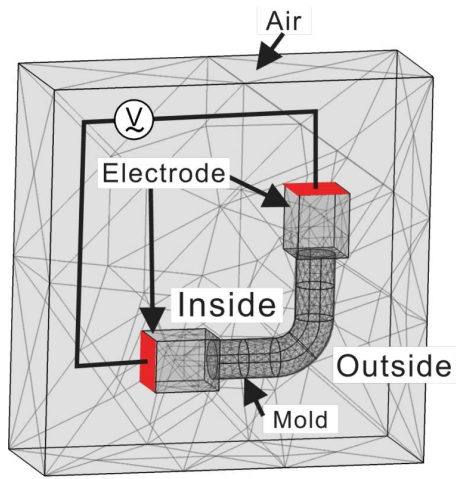
Table 1: Material physical properties of each material.

	Relative magnetic permeability	Electric conductivity [S/m]	Thermal conductivity [W/(m·K)]
Air	1	0	0.257
Copper	1	5.998×10^7	400
SUS430	122.4	1.666×10^6	25.6

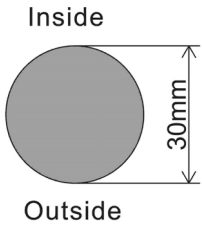
3 Results and discussions

3.1 Influence of the frequency of alternate current on temperature distribution of the mold

Fig. 2 shows the temperature distribution of the mold surface of the curved mold model for the frequencies of 1kHz and 100kHz. The outside of the curved part is

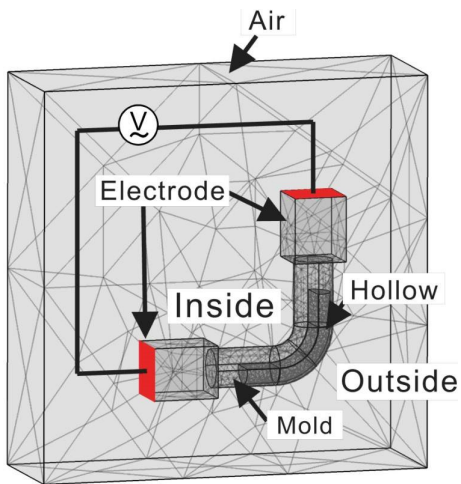


(i) FEM model

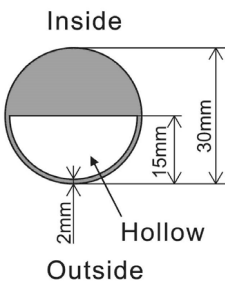


(ii) Cross-sectional view

(a) Curved mold model



(i) FEM model



(ii) Cross-sectional view

(b) Curved mold with hollow model

Figure 1: Curved mold model and curved mold with hollow model.

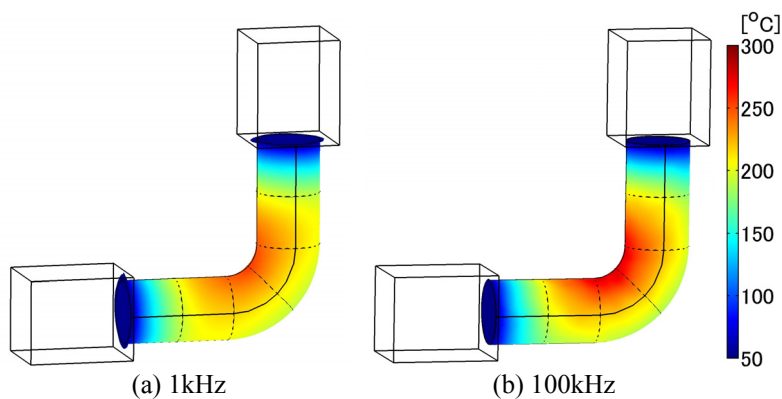


Figure 2: Temperature distribution of the mold surface.

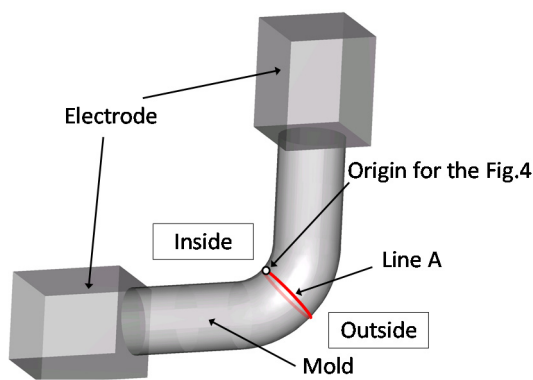


Figure 3: Position of Line A.

lower in temperature than its inside. In Fig. 3, Line A is illustrated on the circumference in the middle of the mold. Fig. 4 shows temperature profiles of Line A for the frequency of 1kHz, 10kHz, 20kHz, 50kHz and 100kHz. Table 2 shows the maximum temperature, the minimum temperature, and temperature difference along Line A for each condition. The higher the frequency is, the larger the temperature difference is. The temperature difference of the curved part of the mold surface with the frequency of 1kHz has the lowest value of 65°C.

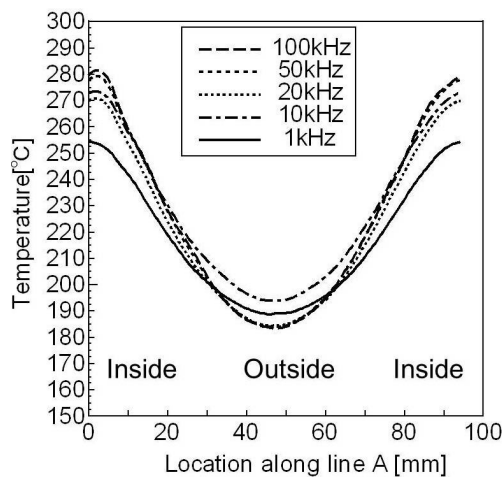


Figure 4: Temperature profiles of Line A.

Table 2: The maximum, minimum temperature and temperature difference for profiles of Line A.

Frequency	Maximum temperature [°C]	Minimum temperature [°C]	Temperature difference[°C]
100kHz	282	183	99
50kHz	279	184	95
20kHz	271	184	87
10kHz	273	194	79
1kHz	254	189	65

3.2 Influence of hollowing-out of the mold on temperature distribution

Fig. 5 shows the temperature distribution of the surface of the curved mold with hollow model with the frequency of 1kHz. Fig. 6 shows temperature profiles along Line A on the curved mold model and curved mold with hollow model. Fig. 7 shows temperature distribution of cross section along Line A for each model. The temperature of the outside of the curved part of the curved mold with hollow model is higher than that of the curved mold model. While the temperature difference along Line A for the curved mold model is 65°C in Fig. 6, that of the curved mold with hollow model has smaller temperature difference of 17°C.

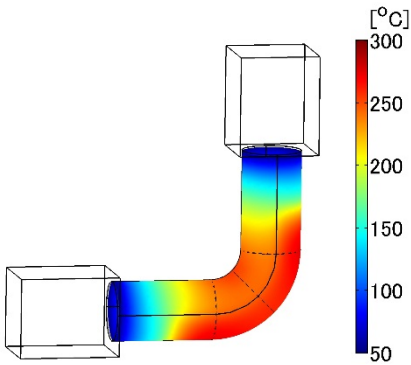


Figure 5: Temperature distribution of the surface of curved mold with hollow model.

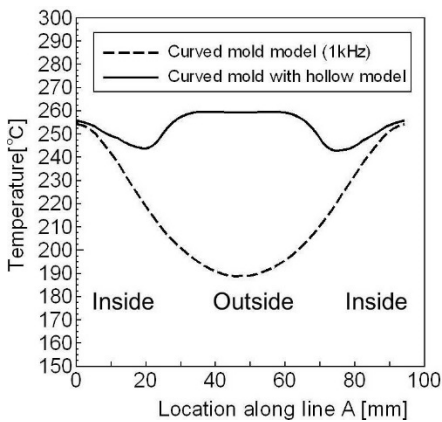
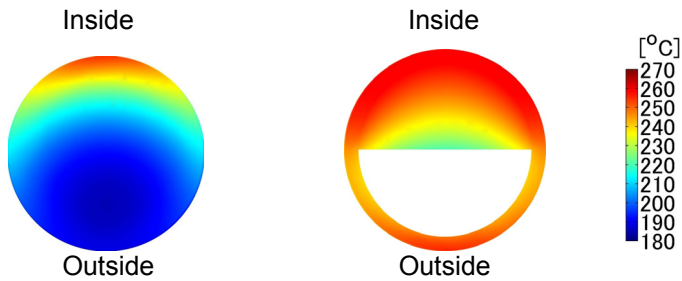


Figure 6: Temperature profiles along Line A.



(a) Curved mold model (b) Curved mold with hollow model

Figure 7: Temperature distribution in the cross section along Line A.

Fig. 8 shows current density distribution in cross section along Line A for each model. For both models, current density distribution is high at the inside and low at the outside. In spite of hollow structure, current density of the curved mold with hollow model is similar to that of the curved mold model. Skin depth as σ is expressed in equation (6):

$$\sigma = \sqrt{\frac{1}{\pi F \rho \mu}} \quad (6)$$

where F is frequency, ρ is relative permittivity, μ is relative magnetic permeability. Because skin depth is related these value, mold shape doesn't affect the skin depth. So current density distribution of both models is similarly.

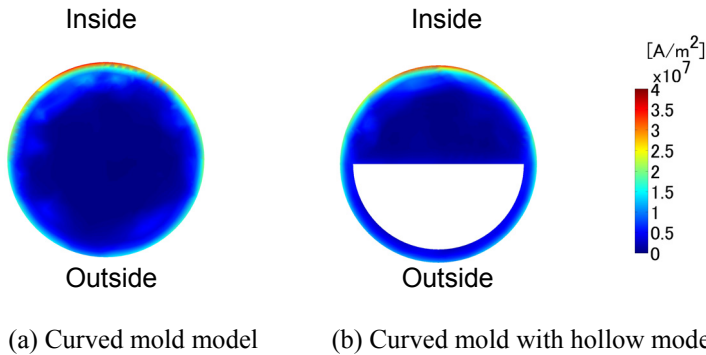


Figure 8: Current density distribution in the cross section along Line A.

Fig. 9 shows heat flux distribution in cross section along Line A for each model. In the cross section of the mold, heat is transferred from heated surface part to the center. For the curved mold with hollow model, Point A in Fig. 9 which is high heat flux has low temperature in Fig. 6. This results means that the heat flux play an important rule for the temperature distribution of the surface of the mold. In Fig. 9, heat flux of outside of the curved mold with hollow model is lower than that of the curved mold model. Because of this low heat flux, the temperature at the outside of the curved mold with hollow model became high. By hollowing out the mold, it is possible to suppress the heat flux at the outside of the curved part and resulting the uniform temperature distribution.

4 Conclusions

In this study, to reveal the temperature distribution of the curved mold and to obtain uniform temperature distribution of the curved mold, the influence of the frequency of alternating current on the curved mold is analyzed by using FEM

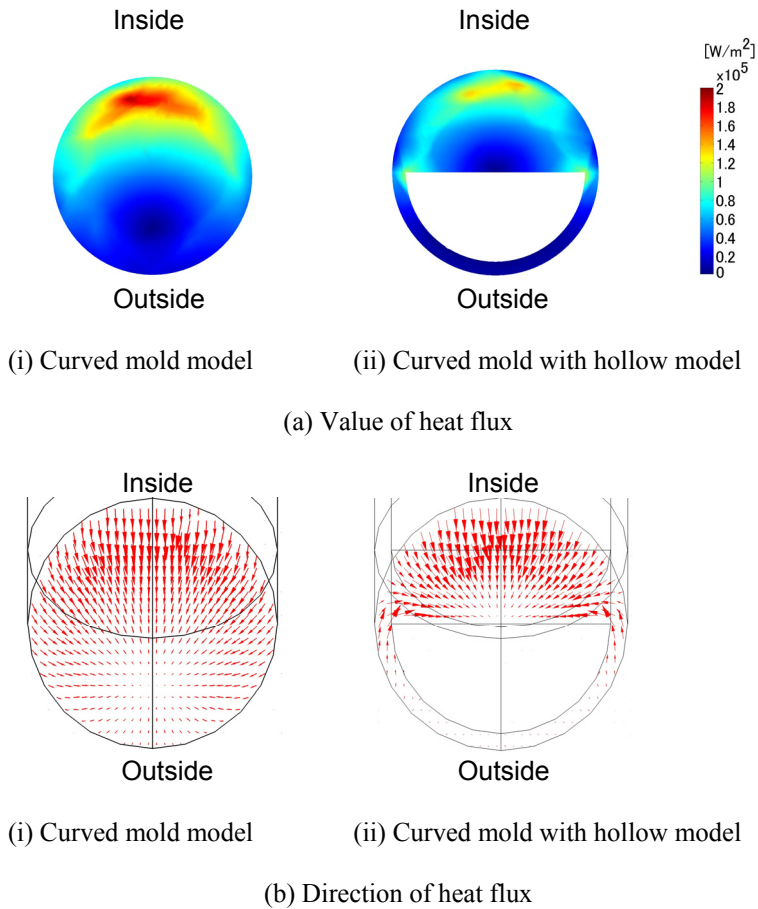


Figure 9: Heat flux distribution in the cross section along Line A.

analysis and the novel mold structure with hollow is proposed. The investigation yields the following conclusions:

1. For the curved mold model, the temperature difference of the mold surface become larger when the frequency become higher. The temperature difference of the mold surface with the frequency of 1kHz has the lowest value of 65°C.
2. By hollowing out the mold, it is possible to suppress the heat flux on the outside of the curved part and resulting the uniform temperature distribution.

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