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Investigation of Conformal Heating Capability of a Curved Mold Using CNT Film Heater

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In injection molding, hot polymer melt fills a mold cavity and is solidified during the subsequent cooling process. the mold temperature should be kept high to improve flow characteristics during the mold filling stage, it should be kept low to reduce cooling time during the cooling stage. In order to satisfy these conflicting objectives, rapid mold heating technology has been developed to raise mold temperature without a significant increase in the cycle time. While the conventional rapid heating technologies have focused to increase the heating speed, temperature uniformity on the mold surface has also been an important issue to improve the quality of molded parts. This study aims to develop conformal mold heating technology that uses a carbon nanotube (CNT) film heater. The CNT film heater is used to heat a curved mold with high temperature uniformity, by maintaining a uniform distance from the mold surface. The developed CNT heating technology is then applied to the conformal heating of a curved mold. Electric-thermal coupled finite element analysis (FEA) is conducted to investigate the heating characteristics of the CNT heating module, and the relevant conformal heating capability is investigated by comparing to that of the conventional oil heating. The FEA results reveal that the CNT heating shows faster temperature rise and more uniform temperature distribution than the oil heating. Experimental validation is also performed to verify the FEA result, and the experimental result shows a good agreement with the FEA result. Based on the rapid and uniform heating capability, the conformal mold heating technology using the CNT film heater can be used to improve part quality and productivity in various molding processes.

NOMENCLATURE

h = convection heat transfer coefficient
λ = oil thermal conductivity
D = diameter of the heating channel

1. Introduction

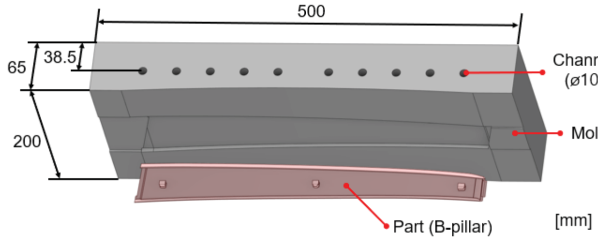
Injection molding is a production process in which a process in which a product is molded by filling the inside of the mold Cavity with a hot polymer melt. In the mold filling stage, the mold temperature should be kept high to improve flow characteristics, while the temperature should be kept low to reduce the cooling time when molding is completed. In order to reduce cycle time, a fast heating technology that heats a mold quickly has been developed, but the temperature uniformity of the surface of the mold has become a problem.

This study conducted a study on the uniform heating technology of curved molds using carbon nanotube (CNT) film heaters. For this study, a CNT film heater was manufactured through electrospinning, direct spinning, and roll pressing processes. The manufactured film heater was inserted into the curved mold to design a structure that could be heated, and the heating characteristics were predicted through finite element analysis (FEA). In addition, the improvement of temperature uniformity of the mold surface was analyzed by comparing the characteristic differences between the mold heating method based CNT film heater and conventional oil heating, and the validity of the analysis results was verified through experimental comparison.

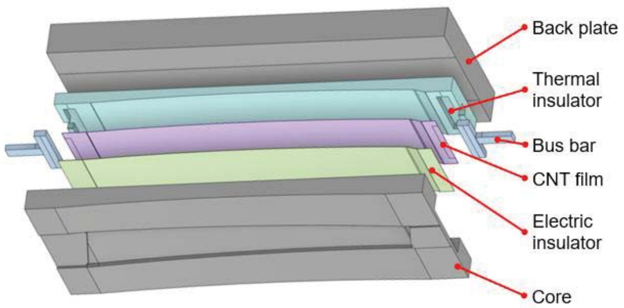
2. A Study on the Uniform Heating Characteristics of Curved Mold

2.1 Design of Heating Structure of Curved Mold

In this study, the mold heating method based CNT film heater was applied to the heating of the mold for automobile exterior parts (B-Pillar). Fig. 1(a) shows the target product and mold shape. The molded article is designed to be 428 mm long and 1.5mm thick, and consists of curved surfaces. For the hot oil circulation type mold, 10 hot oil circuits were designed 38.5mm away from the opposite side of the molding surface. Fig. 1(b) illustrates a curved mold structure to which a CNT film heater is applied. The thickness and material of each component of mold using CNT film heater are shown in Table1, and the physical properties of each material are shown in Table 2.



(a) Conventional channel-based heating structure



(b) Conformal heating structure using CNT film heater

Fig. 1 Description of the mold heating structure for a curved mold

Table. 1 Part list of the conformal heating structure

Component	Material	thickness (mm)
Core	NAK80	5
Electric insulator	Glass fiber sheet	0.5
CNT film	CNT film	0.02
Busbar	C1100B-C	5
Thermal insulator	ISOL600	10
Back plate	NAK80	29.5

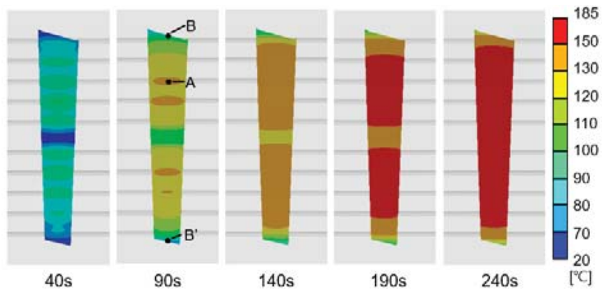
Table. 2 Properties of the mold materials

Material	Thermal conductivity (W/m-K)	Density (g/cm^3)	Specific heat (J/g-K)	Electric Resistivity (Ohm*cm)
NAK80	41.33	7.8	0.481	2.63e-5
Glass fiber	1.3	2.54	0.803	1e+25
CNT	14.65	0.41	0.716	1.63e-3
C1100B-C	390.79	8.89	0.385	1.7e-8
ISOL600	0.33	1.63	0.88	-

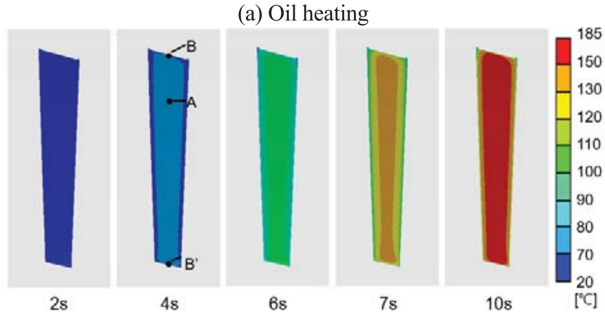
2.2 Finite Element Analysis of Heating Characteristics of Curved Mold

FEA was performed to compare heating characteristics according to the heating method of the curved mold. For FEA, ANSYS Workbench was used. The heat transfer coefficient in the hot oil circuit is 4812.1W/m^2-K. This value was calculated using Equation (1). A mold using a CNT film heater was set to be charged with 18kW of power, and natural convection conditions were applied to the outer surface of the mold.

$$\begin{cases} h = (5 + 0.015Re^a Pr^b)\frac{\lambda}{D} \\ a = 0.88 - 0.24/(4 + Pr) \\ b = 0.333 + 0.5exp(-0.6Pr) \end{cases} \quad (1)$$



(a) Oil heating



(b) CNT film heating

Fig. 2 Surface temperature changes of the curved mold according to the mold heating types (Unit: ℃)

Fig. 2(a) shows the change of mold surface temperature by heating time of the hot oil circulation mold. It was confirmed that the temperature slowly rises due to the circuit gap, and heating of more than 240 seconds is required to make the temperature of the molding part 150 degrees or more as a whole.

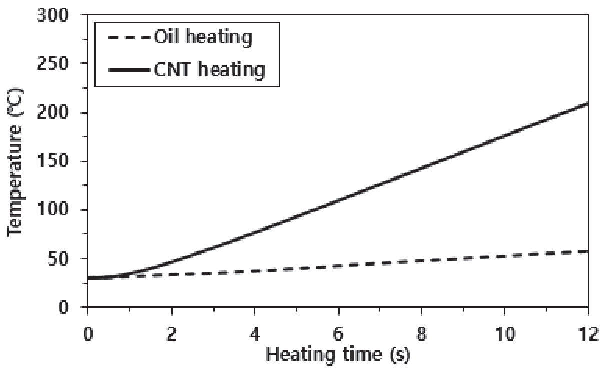
Fig. 2(b) shows the change of mold surface temperature by heating time of the mold using a CNT film heater. It may be seen that the surface temperature of the mold is uniformly increased and the temperature of the molding part is generally 150˚ or more at the time of 9.8 sec heating. The heating rate is 1/24th of the hot oil circulation mold.

Fig. 3(a) shows a comparison graph of temperature changes overtime at point A. The hot oil circulation mold showed a heating rate of 2.7℃/s, while the mold using CNT film heater at the same point showed a heating rate of 15.1℃/s. This is 5.6 times faster than the oil circulation mold.

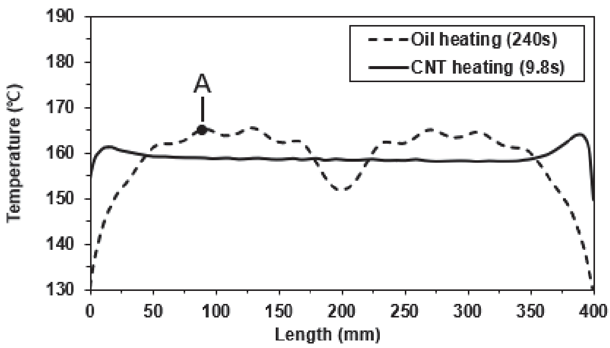
In order to confirm the temperature uniformity after heating the hot oil circulation mold and the mold using CNT film heater, the surface temperature distribution in path B-B’ was compared in Fig. 3(b). The comparison reference time point was set as the time when the molding part in each mold rises above 150℃ overall, corresponding to 240 seconds for heating oil and 9.8 seconds for heating CNT film heater.

Quantitative comparison was made using Equation (2). In the case of the circulating mold, the temperature uniformity at 240 sec is 83.9%, while in the case of heating the mold using CNT film heater, the temperature uniformity at 9.8 sec is improved to 94.4%. Additionally, comparing the temperature uniformity over time, it can be seen that the difference occurs between 79.4% at 120 sec and 83.9% at 240 sec in the case of the hot oil circulation mold. On the other hand, in the case of heating the CNT film heater, the uniformity at 5 seconds is almost similar to 94.3% and 94.4% at 9.8 seconds, which means that a uniform temperature distribution can be obtained regardless of the heating time due to the planar heating effect of the CNT film.

$$\left(1 - \frac{\max T - \min T}{2\ avg\ T}\right) \times 100 \qquad (2)$$



(a) Comparison of temperature changes at point A



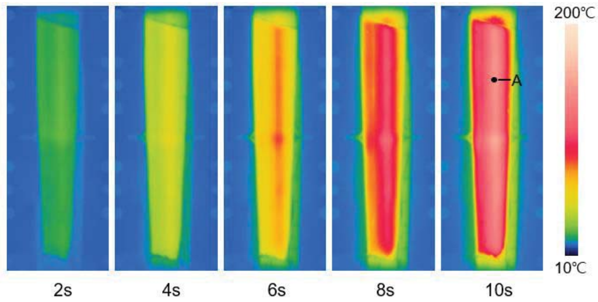
(b) Temperature profiles along path B-B'

Fig. 3 Comparison of heating performance of the curved mold

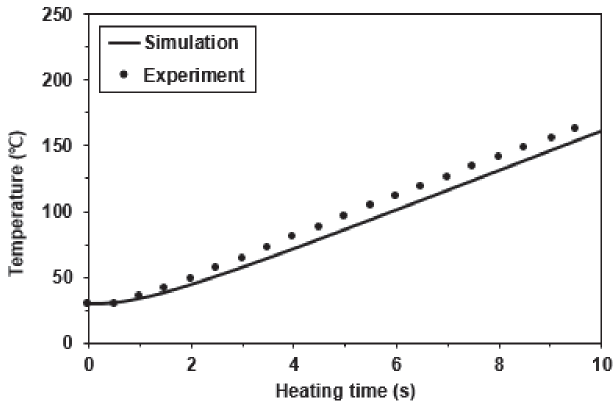
2.3 Experimental Verification

Experimental verification was performed to confirm the heating performance of the CNT film heater. The heating mold was manufactured in the structure shown in Fig. 1(b). 18kW of power was applied to heat the CNT film, and the power density corresponds to $53.5W/cm^2$. Fig. 4(a) shows the temperature distribution on the surface of the mold by heating time. It can be confirmed that the temperature of the molding part as a whole rises uniformly, and the average temperature of the molding part reaches 150℃ or higher at the time of 10 sec heating.

In Fig. 4(b), the temperature change of the molding part (point A) with the result of FEA (see Fig. 3(a)) was compared. The analysis results showed a heating rate of 15.1℃/s, while the experimental results showed a heating rate of 16.1℃/s, showing similar results overall.



(a) Change of the mold surface temperature (Unit: ℃)



(b) Comparison of temperature changes at point A

Fig. 4 Experimental results of the curved mold with the CNT film heating

3. Conclusions

This research conducted a study on a uniform heating technology of a curved mold using a CNT film heater, and conducted a study for conformal heating of the curved mold. For conformal heating of a curved mold, a CNT film heater was mounted close to the curved part, and an electrical insulation and thermal insulation structure were applied to effectively heat the curved part. The CNT film heater heating structure was designed for conformal heating of curved molds, and it was verified that the heating speed could be improved up to 24 times compared to hot oil circulation molds and the temperature uniformity could be improved dramatically. The temperature distribution of the surface of the mold was predicted by performing an electric-heat linked FEA during the heating process of the two molds, and the reliability of the analysis was proved through comparison with the experimental results.

From the above results, it can be seen that the CNT film heater proposed in this study shows advantages in terms of heating speed and uniformity compared to the conventional hot oil circulation mold in the heating of the curved mold. In the future, it is expected to increase the completeness of the technology by conducting additional studies to apply it to the injection molding process of more complex shape products.

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