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Key parameters and optimal design of a single-layered induction coil for external rapid mold surface heating

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ABSTRACT

Setting high mold temperatures for injection-molding plastics facilitates favorable flow conditions for filling cavities with melted materials and provides an esthetically pleasing surface as well as a high replication rate of high-quality products; however, the cooling times are typically prolonged. Electromagnetic induction heating incorporating surface heating instead of conventional volume heating for mold-heating processes is advantageous because it provides a rapid heating time and a reduced cooling time, is environmentally friendly, and saves energy; therefore, it has been adopted in various variotherm injection-molding systems. Although previous studies have discussed how induction heating is influenced by major factors, such as the number of coil turns, working frequency, and heating distance, few studies have investigated other crucial factors, such as the thickness of the heated target and the position of the induction coil. In this study, the effects of the thickness of a heated target, pitch of coil turns, heating distance, position of the induction coil, working frequency, and waiting time on the heating rate and temperature uniformity of induction heating on a mold surface by using a single-layered coil were analyzed. In addition, the Taguchi method and principal component analysis were applied to determine the optimal combination of control factors for achieving a high heating rate and low temperature deviation. Both simulation and experimental results indicated that the thickness of a heated target plays a crucial role in affecting the heating rate; specifically, a thicker workpiece slows the heating process and generates rapid heat dissipation after induction heating. Moreover, the position of the induction coil exerts the most notable effect on heating uniformity.

1. Introduction

Featuring the advantages of low cost, and high efficiency and capacity for producing complex products, injection molding has become one of the most crucial mass-production techniques. Accordingly, it has been widely applied in most manufacturing fields involving plastic products. In the injection molding process, temperature, pressure, and velocity are essential process parameters that exert a marked effect on the properties of injection-molded parts; mold temperature is particularly crucial. Mold temperature not only determines the final quality of a product but also affects the minimal injection pressure and velocity, which ensure that a mold is completely filled and that melted plastics are well packed into cavities. Low mold temperatures cause solid layers to form rapidly when melted plastics contact cavity surfaces, thereby resulting in poor injection-molding properties, such as short shot, imbalanced filling, sink marks, fiber streaks, weld lines, and warpage. By contrast, a high mold temperature facilitates complete filling and reduces the number of defects; however, it also prolongs the cooling time to more than 70% of the cycling time, thus markedly reducing production efficiency. Currently, variotherm-controlled systems, namely dynamic mold temperature control, that support rapid heating and cooling while maintaining a reasonable cycle time are effective in improving the quality of plastic parts. Current methods for rapid mold heating include induction heating [1,2], thin-film resistance heating [3], high-pressure air heating [4], infrared heating [5], and vapor heating [6]. Among these methods, induction heating is considered highly efficient and environmentally friendly, and it is highly suitable for rapidly heating mold surfaces. Rather than heating entire mold blocks, induction heating heats only the mold surface; thus, the mold can be cooled rapidly and, accordingly, the cycle time is slightly increased.

The location of the induction coil relative to the heated target determines which modes of induction heating can be applied. The induction heating modes are fixed, moving, wrapping, and insertion modes [7]. The fixed mode involves heating the surface of an injection mold by initially moving the induction coil to the front of the processed surface, and then fixing it at a constant distance from the target when the mold is

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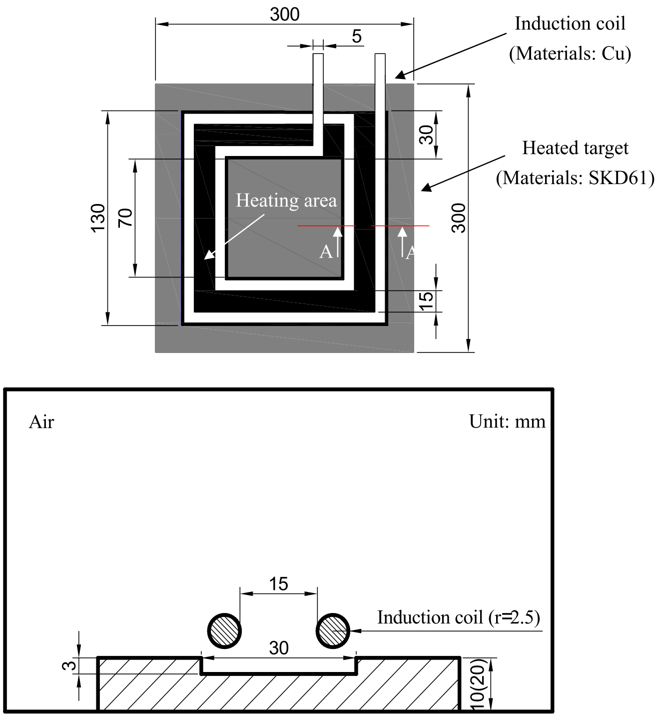
opened. After the mold surface has been heated to the desired temperature, the mold is closed and injection molding is performed [8–12]. In the moving mode, the induction coil heats the surface of a static workpiece while moving at a constant rate. This method has been used mainly for welding metallic materials and heat-treatment processes [13,14]. The wrapping mode involves using the heating coil to surround the entire workpiece, thereby yielding a high heating rate and optimal temperature uniformity [15]. Finally, the insertion mode involves mounting heating coils within a mold, typically from behind the workpiece. This method is based on the penetration effect of induction heating, by which induction heat is transferred to the surface of the mold [16]. Both the insertion and wrapping modes are advantageous because they require less time than the other two modes for moving the coil; however, the mold structures are more complex.

Successful magnetic induction heating relies on the design and manufacture of the employed induction coils. Heating rate and uniformity performance may vary among induction coils. Previous studies on induction heating have typically addressed two topics; (1) the effect of coil turns and cross section on induction heating [17,18], and (2) the effect of process parameters, such as working frequency and heating distance, on induction heating [19]. Although induction heating quickly heats the surface of a given workpiece, the heat loss after heating is affected considerably by the thickness of the workpiece. However, few studies have examined the effect of target thickness on heating performance, and sensitivity analysis reports on the location of induction coils relative to the position of processed workpieces are scant. In particular, any deviation in the position of a coil should be considered because it can affect the temperature distribution during the heating process. The purpose of this study was to achieve a uniform temperature distribution by controlling the induction heating process parameters for applications involving mold plates of various thicknesses. In addition, the influences of varying the coil position were examined. The commercial simulation software COMSOL Multiphysics was used to analyze the magnetic and thermal properties of the materials [20]. Moreover, the Taguchi method was applied and an ANOVA was performed to identify the contribution rate of each factor. Furthermore, a principal component analysis (PCA) was performed to determine the optimal combination of design factors.



A-A section

Fig. 1. Physical model of induction heating.

Table 1
Properties of materials associated with induction heating.

Materials	Air	Copper	SKD61
Relative permeability	1	1	480
Relative permittivity	1	1	1
Electrical conductivity (S/m)	1E − 2	5.998E7	1.9E6
Heat capacity (J/kg K)	–	385	460
Density (kg/m^3)	–	8700	7850
Thermal conductivity (W/m K)	–	400	24.3

2. Principles of induction heating

Induction heating involves heating ferromagnetic and conductive materials by applying an alternating electromagnetic field in the kilohertz–megahertz frequency range. According to Faraday's law and Lenz's law, passing an electric alternating current through heating coils produces an alternating electromagnetic field. When processed magnetic or nonmagnetic conductive workpieces are placed in the field, the cutting-of-flux causes eddy current I_c at various depths. The resistance of workpiece R and the induced eddy current generates heating power equal to I_c^2R, thereby heating the target.

The major influences of the induction setup originate from the coil geometry, applied electrical power, coil current, and magnetic flux concentrators. Particularly, the frequency and the coupling distance play critical roles [8]. A higher frequency facilitates rapid heating of a given workpiece, although higher frequencies also limit the penetration depth of the electromagnetic field; this phenomenon is called the skin effect, and it relies on the electromagnetic fields produced by induced currents. The penetration depth δ can be derived from Maxwell's equation, and it is expressed relative to the resistance of inductive material ρ, relative permeability μ_r, and current frequency f, as shown in Eq. (1):

$$\delta = 5053\sqrt{\frac{\rho}{\mu_r f}}. \tag{1}$$

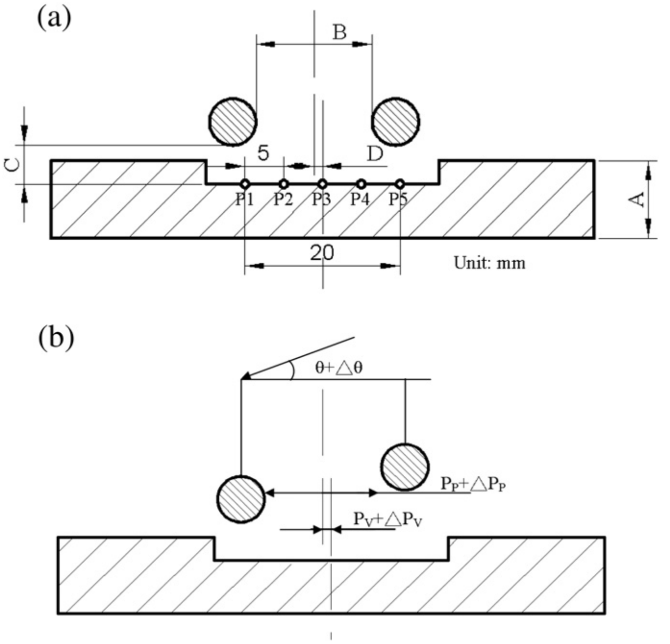


Fig. 2. Factor selection for the Taguchi analysis: (a) control factors (*A*–*D*) and measuring positions (P1–P5); (b) noise factors.