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Effect of Coil Geometry on Induction Heating for Injection Mold Part

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Keywords: injection molding, dynamic mold temperature control, induction heating, 3D coil, coil design

ABSTRACT

In this study, a sample mold plate was used to test an induction heating system with different coil designs. Four coil configurations, parallel, spiral, 3D, and serial coil, were constructed for the induction heating process. The mold surface temperature was heated in 2 s. The temperature at three points and the temperature distribution on the heating surface were then collected to evaluate the effect of the coil geometry on the induction heating process. At the same heating power, the spiral coil has the highest heating rate of 35.5 ℃/s, followed by the 3D coil at 25.5 ℃/s. In addition, the spiral coil creates a ring-shaped high temperature area while the 3D coil creates a rectangular high temperature area. The 3D coil also exhibits better temperature uniformity than the spiral coil, which reduced the temperature difference between 3 points from 41 ℃ (spiral coil) to 23 ℃ (3D coil). Results also show that the heating effect of the parallel and serial coil are not good enough for use in the injection molding process. By using the 3D coil, double sided heating was achieved with positive results. Although the heating rate of the double sided heating is not as high as with single sided heating because of the larger area that must be heated, the temperature difference between three points fell from 23 ℃ to 17.5 ℃ in the experiment when double sided heating was used.

INTRODUCTION

seriously concerned us. In the operation of a bulk-liquid transport vehicle, the movement of the liquid from side to side due to partial filling of the tank produces the sloshing force. The liquid slosh within a tank increases the roll moment and may lead to the rollover and is of potential safety concern because the lateral shift of the load reduces the vehicle's stability and controllability in cornering and Injection molding is one of the most common polymer processing techniques in the plastics industry. As products become smaller, thinner, and lighter, the demand for better mold design and new technologies increases. If the molding process is improper, many defects will occur. One of the most important systems is the mold temperature control, often overlooked because of its simplicity. An improper temperature control system can create unwanted aesthetic defects and strength problems. Though high mold surface temperature increases the surface quality of the part, it leads to longer cooling times, increasing the cycle time. Maintaining high mold temperature during the filling process and lowering the mold temperature to below the deflection temperature during the post-filling process without greatly increasing cycle time and energy consumption are not easy. In recent research, before the filling of the melt into the cavity, the mold surface is pre-heated to raise the temperature to the glass transition temperature of the plastic (N et al., 2012; Li et al., 2010). This process is called "Rapid Heat Cycle Molding – RHCM" (Wang et al., 2010, 2013, 2014). RHCM requires a fast heating rate (Wang et al., 2014), low energy consumption (Wang et al., 2013), and easy operation of the cooling step of the injection molding process (Wang et al., 2013).

Two main types of heating systems are used in the RHCM heating process, volume heating (Jeng et al., 2010; Xiao et al., 2014) and surface heating (Chen et al., 2009,2011; Yu et al., 2007). In the volume heating method, the heater system is usually used to raising the mold plate temperature to a target temperature. Based on these papers, the most inexpensive way to achieve high mold temperature appear to be using hot water at a temperature as high as 90 °C or 100 °C for both heating and cooling. If the mold temperature needs to be higher than 100 °C, either a high pressure water supply system or a hot oil

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may be used (Wang et al., 2013, 2014). The former may damage the channel connection and safety may be an issue after long-term use. The latter may not be energy-efficient due to the low heat transfer coefficient of the oil. Local mold heating using an electric heating element is sometimes used to assist in high mold temperature control, especially for thin-wall products. However, this requires extra design and tool costs. According to these papers, the heating process is easy to control. However, with above criteria, this method shows many limitations, including a slow heating rate because the heating energy must increase the temperature of the entire mold plate volume, generating high energy consumption and slower cooling.

Several techniques for surface heating have been researched. One technique in involves coating the mold surface with an insulation layer. A heating layer is then applied to the insulation layer to form the cavity surface. The heating layer can be quickly heated with a pair of electrodes and the insulation layer is used to enhance heating efficiency and decrease energy consumption (Yao et al.,2002). For raising the mold surface temperature in the filling process, coating the cavity surface with TiN and Teflon reduces the heat transfer from the melt to the mold material, which increases the temperature on the cavity surface to 25 °C (Chen et al., 2008, 2009). Furthermore, an infrared heating system has also been used for heating the mold surface. This system can heat the surface of one or two mold halves using a suitable design (Yu et al., 2007). In the newest application of surface heating, a hot air system is integrated into the mold to support the hot air flowing into the cavity. In this way, the heat convection from the hot air can directly heat the surface of the cavity (Chen et al., 2009, 2011). The advantage of surface heating methods is the high rate of heating, which reduces the cycle time of the molding process. However, a special, more complex mold design is required, and more equipment is needed to calculate the parameters for a high quality product.

For the pre-heating step in injection molding processes which do not need mold structure modification, induction heating has been explored (Chen et al., 2004, 2006, 208; Nian et al., 2014). Chen et.al (2004, 2006, 2008) used an electromagnetic induction coil with different configurations to heat the cavity surface. For practical applications, induction heating exhibits many positive effects, such as reducing the weld line, shrinkage, and other defects of the part surface. In a recent investigation series, with the requirement of high heating rate and low energy consumption, we suggested the application of induction heating combined with low coolant temperature for dynamic mold temperature control. Figure 1 shows the principle of induction heating for the injection mold plate. In this method, after the product was rejected, the inductor is moved to the gap between the core plate and the cavity plate. The coil then remains by that location to heat the mold to the target temperature. After that, the coil is removed and the mold plates then close for the filling step of the next cycle. Shorter heating time is required for induction heating because the heat generated from induction appears primarily on the mold surface, about 0.1 mm in depth, because of the skin penetration of the electromagnetic wave.

In general, based on many studies, the heating rate of the induction heating method satisfies the requirements of the injection molding process. However, the application of induction heating remains complicated, and many factors affect the induction heating process. The most important element in the induction heating system is the induction coil, because it strongly impacts the heating effect and temperature distribution on the mold surface. Further, in previous papers, only one mold plate was heated. This creates a temperature imbalance between the core plate and cavity plate. To address these issues in the induction heating process for injection molding, this research focuses on the configuration of the induction coil. This study compares the heating effect of four coil types: a parallel coil, a spiral coil, a 3D coil, and a serial coil. Because the 3D coil has a special geometry, it is used in a double sided heating process with the core plate and cavity plate. In addition, the induction heating process using the four coil types is simulated using COMSOL software. These simulations show the magnetic flux distribution, clarifying the effect of different coil geometries on the temperature distribution. The simulation and the experiment are compared to verify the accuracy of the simulation results.

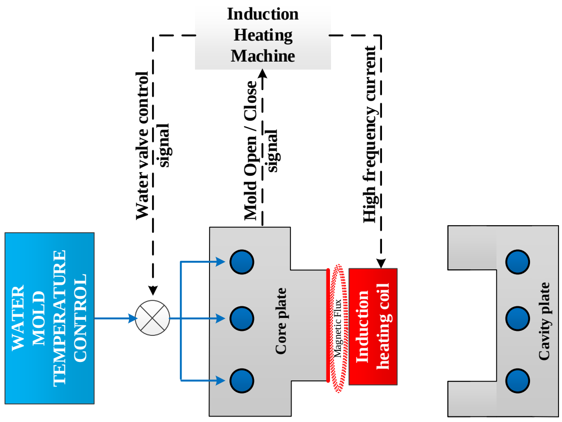

Fig. 1. Induction heating for injection mold plate

PRINCIPLE OF INDUCTION HEATING WITH DIFFERENT COIL GEOMETRIES

In this paper, for single sided induction heating, four coil types were used. The coil geometries are shown in Figure 2. The heating position of the coil and mold plate are shown in Figure 3. For double sided heating with the 3D coil, Figure 4a shows the heating position. The principle of induction heating with four coil types is illustrated in Figure 5 in section A – A, as described in Figure 7. In the induction heating process, when the conductor maintains a high frequency current, the current inside the coil has the direction shown in Fig. 5. This high frequency current will create a magnetic flux around the coil. The magnetic flux will constantly change direction and create an induction current on the heating surface of the mold plate. This current will heat the molding surface because of the combination of skin and proximity effect. The penetration depth near the heating surface, δ (m), may be described by

$$\partial = 503\sqrt{\frac{\rho}{\mu . f}} \qquad (1)$$

Where f (cycle/s) is the alternating current frequency, ρ (Ω.m) is the electrical resistivity, and μ is the relative permeability. The associated eddy current flow in an electrically resistant environment is finally dissipated as heat, which raises the mold temperature. In theory, with different coil designs, the magnetic flux will have different distributions. Therefore, with design 1, the parallel coil, section A- A shows that the current has the same direction, giving the magnetic flux the same direction (Fig. 5a). This type of magnetic direction helps make the magnitude of the magnetic flux stronger. However, because of the parallel coil, the main current separates into the coil branches, each of which has a weaker magnetic flux than the main coil. With design 2, the spiral coil, section A – A in Fig. 5b shows that the current runs in a different direction on each side of the central axis. On each side of the central axis, the current in each coil runs in the same direction, making the magnitude of the magnetic flux stronger because of the resonance effect. In addition, in the spiral coil, the current is the same as the main coil in design 1. Therefore, the magnetic flux in design 2 is much stronger than in design 1. With design 3, the 3D coil, when the conductor is bent to form a 3D configuration, its current is redistributed. The magnetic flux line appears inside and outside the coil. As a result, when the heating surface is close to the coil, the induction current appears on this surface. As in design 2, in section A – A, Figs. 5c and 6 show that the current directions inside the coil are separated into two groups which run in the opposite direction. In this case, the magnetic flux impacting each heating surface lies in same direction. This results in stronger heating because of the resonance effect. For design 4, the serial coil, Fig. 5d shows that the current in each coil section runs in the opposite direction, mutually reducing the magnetic flux. Therefore, this current distribution has a negative heating effect.

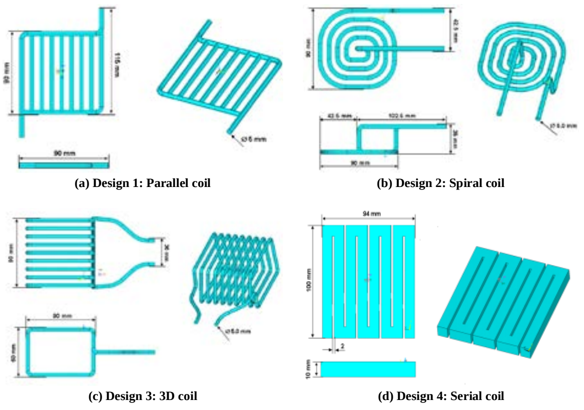

Fig. 2. The coil design

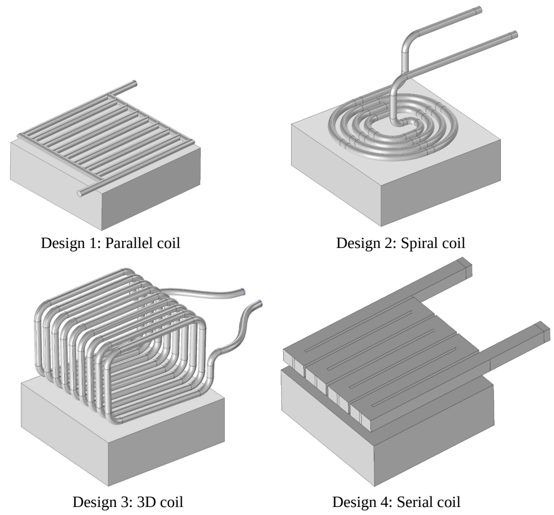

Fig. 3. The research model of induction heating with 4 types of coil geometry

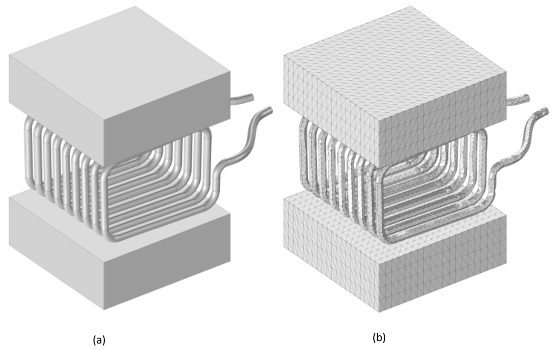

Fig. 4. The heating position (a) and meshing model (b) of induction heating with 3D coil for double side heating case

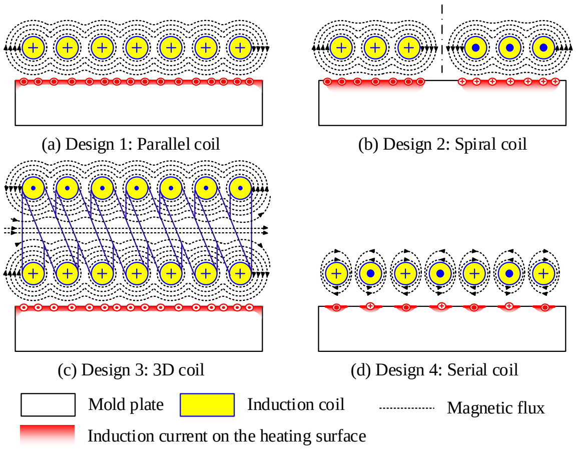

Fig. 5. The principle of induction heating with different coil type

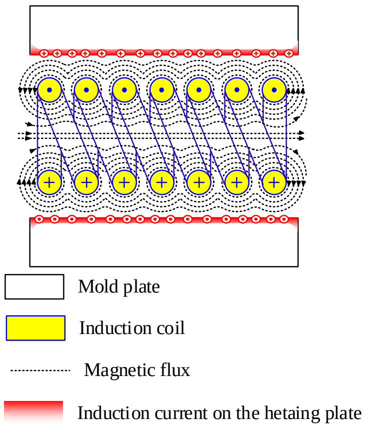

Fig. 6. The principle of 3D coil for double side induction heating

Simulation and Experimental Works

As shown in Fig. 1, the mold temperature control process using external coil induction heating consists of an induction heating machine, a water mold temperature control system, a control and monitoring unit for operating the heating/cooling process and observing the mold temperature change, a mold plate (32 x 100 x 100 mm3), and an external coil system. The induction heating machine supports a high-frequency current flows through the conductor and the mold plate with a maximum power of 45 kW. This machine can support a maximum current of 150 A, and a frequency of 75 kHz. Fig. 7 shows the mold design with the cooling channel insert system. This system controls the plate temperature, which includes pre-heating the plates to the initial temperature of 40 °C at the beginning of the experiment, and cooling them after the heating period by receiving the water from the mold temperature control. During each case of the experiment, the mold surface temperature will be measured and collected at points T1, T2, and T3. The location of these measuring points is shown in Fig. 7. In this study, four types of coil were designed. The coil designs and the position between coil and mold in the heating process are shown in Figs. 2 and 3. The distance from the coil to the mold surface is set at 3 mm. To cool the coil, a hollow channel is fashioned inside each coil. The coils are made of copper. In the experiment, with single sided heating, the spiral coil and 3D coil will be achieved, then, the double side heating will be done with the 3D coil. The experimental models are shown in Figs. 8 and 9.

To observe temperature at the plate surface, an infrared thermal imaging system (Avio NEO THERMO TVS-700) and thermal couples were used to measure the mold temperature. The experimental results were collected to verify the simulated predictions. In this study, the mold plate is pre-heated to 40 °C by the 40 °C water flowing through the cooling channel. The induction heating machine will then be turned on to heat the mold surface. The heating rate and temperature distribution of the mold surface will be observed by the infrared camera and the sensors. All material properties are shown in Table 1.

In all cases, the mold plate made of stainless steel 420 was used to study the effect of coil designs on the heating rate and the temperature distribution. Because induction heating has a high heating rate, in every case in both the experiment and simulation, the temperatures at points T1, T2, and T3 will be collected after 2s of heating. These results will be compared to study the differences in heating rate and temperature distribution for different coil designs. In this study, with the same heating parameters and material properties as the experiment, the COMSOL software package is used to run simulations of the induction heating process. After that, the simulation results will be compared with the results of the experiment result to estimate the accuracy.

Table 1. Material properties

Physical Property	Unit	Air	Stainless steel 420	Copper
Density	Kg/m^3	1.18	7700	8940
Electrical Resistivity	Ωm	-	5.5 E-7	1.7 E-7
Relative Permeability	-	1	200	0.99
Specific Heat	J/kg*K	1000	448	392
Thermal Conductivity	W/*K	0.0256	14	400

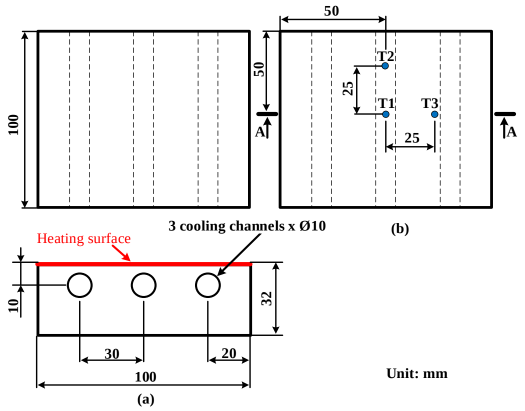

Fig. 7. Mold design (a) and temperature measurement point (b).

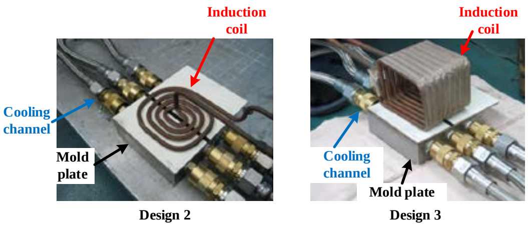

Fig. 8. The experiment model with spiral and 3D coil type.

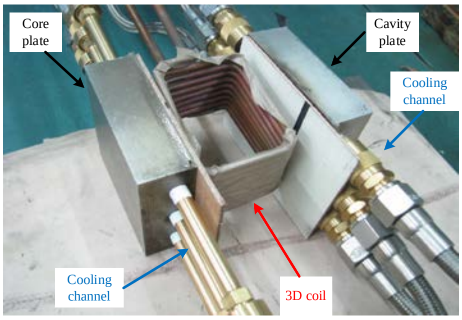

Fig. 9. The experiment model of 3D coil for double side heating.

RESULT AND DISSCUSSTION

The induction heating of a single side of the mold plate with different coil designs

In this paper, the heating behavior of four coil designs was compared to determine which offered the best uniformity of temperature during the heating process. We performed a simulation with the distance between the coil and heating surface set to 3mm, and a heating time of 2 seconds. The temperature results of these simulations use a standard temperature range, from 25.0 ℃ to 215.0 ℃. Hence, the results of each coil heating can be compared. The temperature distributions across the heating surface for the 4 coil types are shown in Figure 10. Next, the temperature at points 1, 2, and 3 was collected and compared in Figure 11. The simulation results show that designs 2 and 3 can produce better uniformity of temperature during the heating process. Additionally, these two designs had more rapid heating speeds than the other two coil designs. Comparison of the temperature at the three points (Fig. 11) shows that the heating rate of the parallel coil, spiral coil, 3D coil, and serial coil are 14.27 ℃/s, 35.5 ℃/s, 25.5 ℃/s, and 2.17 ℃/s with maximum temperature differences of 8.1 ℃, 60.5 ℃, 17.0 ℃, and 4.1 ℃, respectively.

The temperature distribution at the heating surface can be explained by the effect of the magnetic flux. With design 1, the parallel coil, the current was strongest at the main branch, and these locations produced a stronger magnetic flux, giving it much greater heating effect than the other branches. In addition, the current in the secondary branch is lower than in the main branch. Therefore, the magnetic flux generated by the secondary branch was weaker than that of the main branch, and lower than the other coil designs. The magnetic flux of the parallel coil may be clearly observed in Figure 12. With design 2, the spiral coil, the area of temperature had a ring shape as shown in Fig. 10. This is because the magnetic flux was strongest in this area. The magnetic flux in section A – A is shown in Fig. 12. This temperature distribution is the same as in our previous research. The disadvantage of this result is that the low temperature area is located at the center of the heating surface. Designing the molding cavity location would be difficult with these results. With design 3, the 3D coil, Fig. 12 shows that the highest magnetic flux appeared at the center of coil. Along the outside of the coil, there was also magnetic influence on the heating surface. This influence is not as strong as with the spiral coil (design 2), but is much stronger than the parallel coil (design 1) and serial coil (design 4). The temperature distribution of this coil is a rectangular area at the center of the heated surface. This type of distribution is quite easy for injection mold design. With design 4, the serial coil, as mentioned in Fig. 2, because the current runs in the opposite direction in each coil section, the magnetic flux in section A – A also runs in the opposite direction, and they offset each other. This is the reason for the weak magnetic flux on the heating surface, as well as the low temperature on the heating surface.

Based on the temperature distribution as shown in Fig. 10, the edge effect is clearly observed with all four coils. With design 1, the edge effect is found with the main branch of the coil. With design 2, the edge effect has less influence because of the distance between the coil and the edge of the mold plate. With design 3, the edge effect is the most serious. The temperature at the edge can reach over 200 ℃. This is because the distance between the coil and the edge of the mold plate is shorter than with the other coils. With last design, the edge effect is also serious, especially at the beginning and end of the coil.

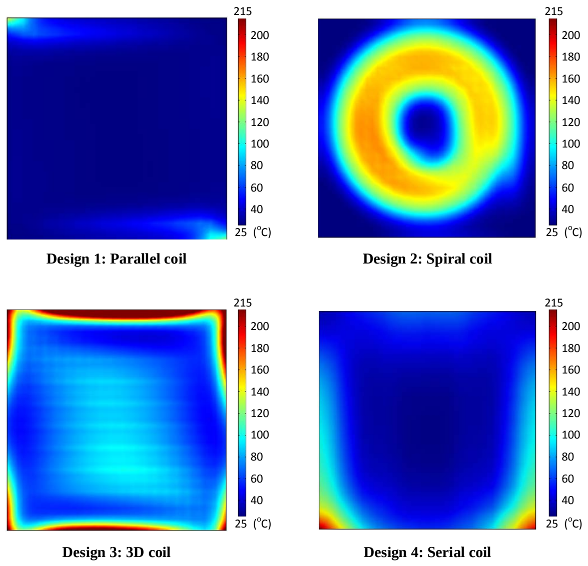

Fig. 10. Simulation Comparison of temperature distribution at the plate surface with 4 coil types

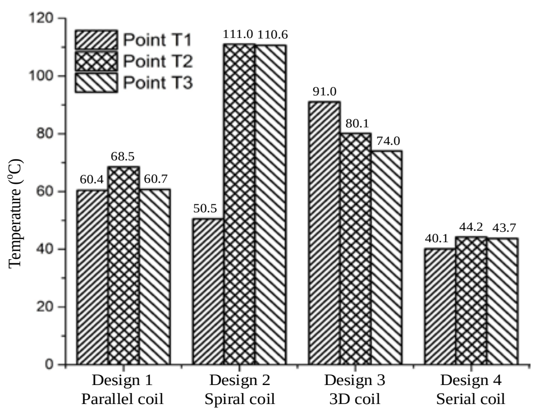

Fig. 11. Temperature comparison at 3 points with 4 coil types by simulation

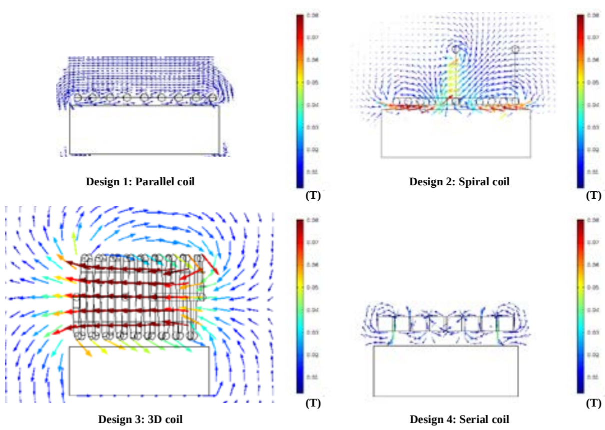

Fig. 12. Magnetic flux at cross section A – A under different coil types

Given the goal of high heating rate, these simulations show that the second and third design are acceptable for the induction heating process. Therefore, to verify the accuracy of simulation, designs 2 and 3 were selected for experiment. The experimental models of designs 2 and 3 are shown in Fig. 8. To estimate the heating uniformity, the temperature distribution was observed by the infrared thermal camera in the experiment. These results are compared with the simulation results in Figure 13. The lowest temperature is located at the center area of the heating surface when the spiral coil (design 2) is used. This shows that this type of coil is very difficult to use in the injection molding heating process, especially with flat products. With the 3D coil (design 3), the heating effect appears as a rectangular area with the highest temperature located at the center. This temperature distribution is a great improvement, and may easily be used for heating in the injection process.

Comparisons of heating temperatures using a spiral and 3D coil with an initial mold temperature of 40 ℃ are provided in Figure 14. Figure 14a shows the temperature at points T1, T2, and T3 with a heating time of 2 s using the spiral coil for both the experiment and the simulation. In the experiment, the temperature of points T1, T2, and T3 are 64.2 ℃, 108.7 ℃, and 105.4 ℃, respectively. This shows that the temperatures at points T2 and T3 are almost the same. However, the heating effect at the center plate (point T1) is significantly lower. The temperature difference between the 3 points is about 41 ℃. This is an issue for the heating process in injection molding because it will increase the warpage of the molding product because of unbalanced shrinkage in the cooling step. Figure 14b shows a comparison of temperatures at points T1, T2, and T3 with the 3D coil in the simulation and experiment. Using the same boundary conditions as with the spiral coil, the temperatures at points T1, T2, and T3 are 89.0 ℃, 78.5 ℃, and 66.1 ℃, respectively. Although the maximum temperature in this case is lower than with the spiral coil, the temperature difference between the three points fell to 23 ℃. This improvement is important for injection molding because it can meaningfully reduce part warpage. Moreover, the heating rate of the 3D coil, which varied from 13.0 ℃/s to 25.5 ℃/s, can easily satisfy the target temperature of the heating process in the injection molding field within a short time. Figures 10, 13, and 14 also show that the simulation can predict the heating effect with different coil designs.

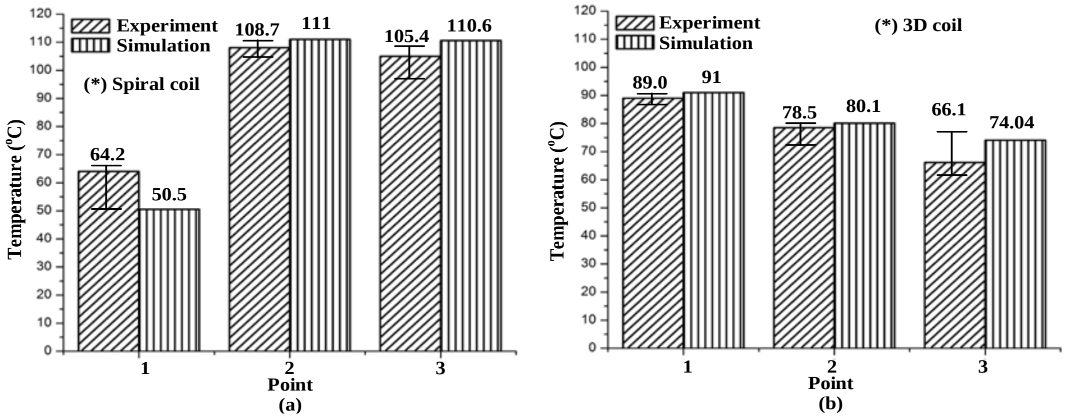

Fig. 14. Comparison of temperature at T1, T2 and T3 on the surface of plate with spiral (a) and 3D (b) coil types

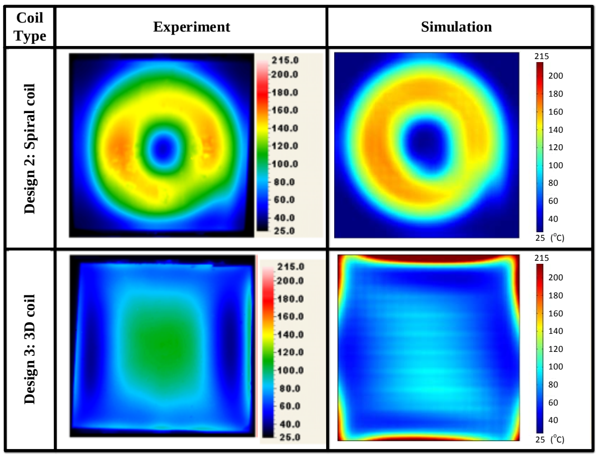

Fig. 13. Simulation and experimental comparison of the temperature distribution with the 2D coil (a) and 3D coil (b).

Double-sided induction heating of mold plates with the 3D coil

In recent research on temperature control for injection molding, the mold is only heated on one side, either the cavity side or the core side. This procedure helps improve the surface quality of the product on that side. The other faces remain at the common temperature and part quality at these locations is not as good as at the heated position. In addition, with the single sided heating method, the difference in temperature between the cavity and core sides of product will be greater. This will lead to greater part warpage. Thus, in this research, the 3D coil is used for double sided heating to verify the heating ability with two mold sides. The principle of this heating method is shown in Fig. 6. The models for the simulation and experiment are shown in Figs. 4 and 9, respectively.
Using a thermal infrared camera, the temperature of each mold plate with a heating time of 2 s was collected. The induction heating power settings were the same as single sided heating. In addition, the temperature at points T1, T2, and T3 on the two mold plates was also collected. These data were compared with the simulation results. Figure 15 shows a comparison of the temperature distribution between the simulation and experiment. The temperature distribution of the heated surfaces are almost identical. As in single sided heating, the highest temperature was located in a rectangular area at the center of the heated surface. The edge effect also appears at the edges of the two mold plates, especially with the simulation results.

Figure 16 shows the temperature comparison of three points at the heated surface with two mold sides. The results of both the experiment and the simulation showed that the application of 3a D coil design to heating both sides of the molds was acceptable. In the experiment, at the T1 point, the cavity reaches a maximum temperature of 64.5 ℃, while the core can produce a maximum temperature of 62.5 ℃. Across all three points, the temperature difference between the cavity and the core was small. Further, the simulation results were close to the experimental results. The small difference is because in the experiment time was needed to open the mold plate and measure the temperature. This delay time can cause a temperature difference between the cavity and the core.

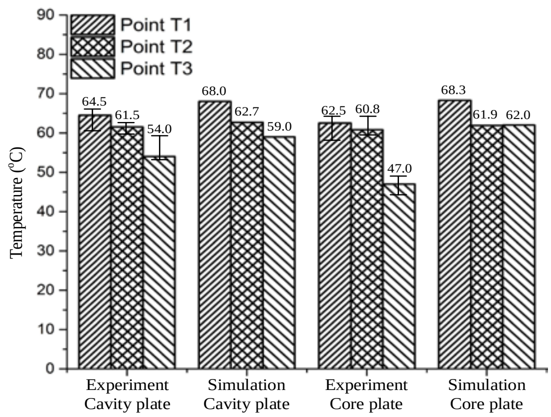

Fig. 16. Comparison of temperature at T1, T2, and T3 on the surface of core and cavity with 3D coil types

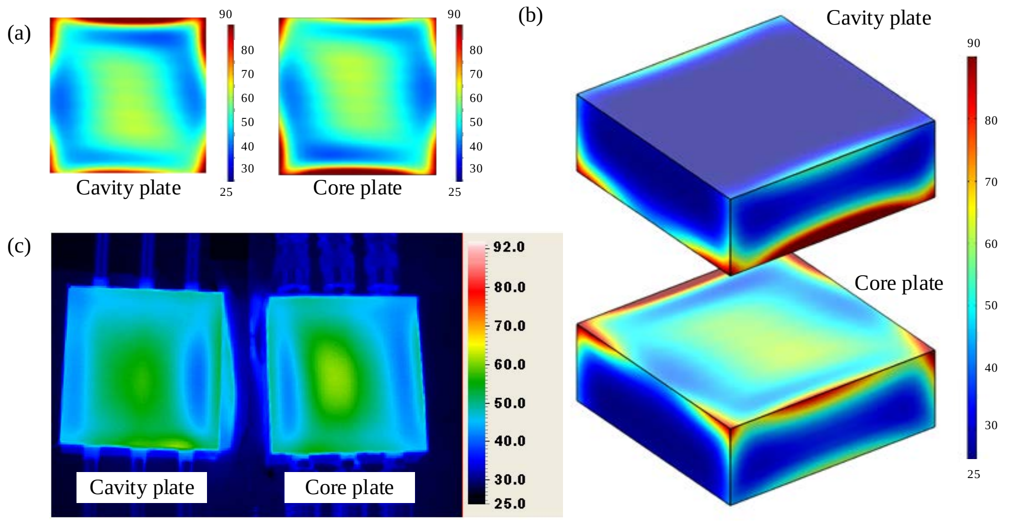

Fig. 15. Simulation (a, b) and experiment (c) comparison of temperature distribution with the 3D coil for double sided heating mold plates

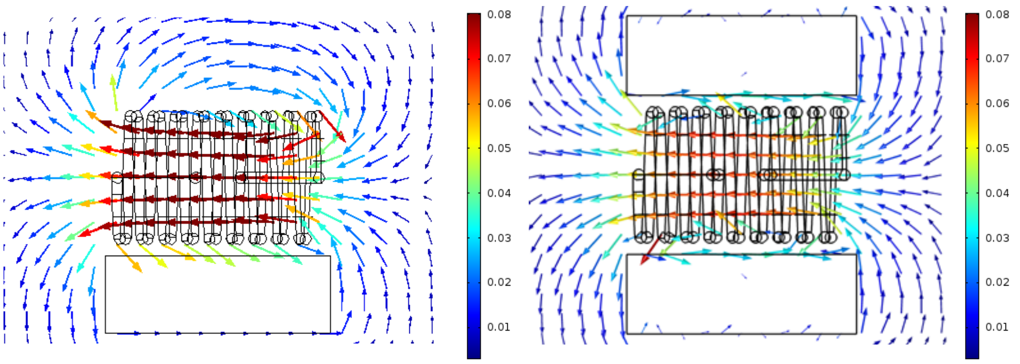

Fig. 17. Magnetic flux with the 3D coil for single sided heating (a) and double sided heating (b).

At the end of the heating process, the maximum temperature in single sided heating is higher than that of double sided heating. This may be explained by the heating power. Though the induction heating power is the same, double sided heating requires heating a larger area. This result may be observed clearly by the magnitude of the magnetic flux in the simulation (Figure 17). In the simulation, with the same heating power, the magnetic flux on the heating surface in single sided heating varies from 0.045 T to 0.063 T. In double sided heating, the magnetic flux is in the range of 0.021 T to 0.048 T. The results in Figs. 15 to 17 show that, by using the 3D coil, both cavity and core side can be heated with an acceptable difference in temperature. This method can help reduce warpage in plastic products, especially with the injection molding cycle used in the pre-heating process.

CONCLUSIONS

In this study, a mold temperature control system using induction heating with four different coil designs was established. Using both experiment and simulation, the temperature on the heating surface was investigated. The heating efficiency of parallel (Design 1) and serial (Design 4) coil was too low in the center and around the mold, both design was not suitable for injection molding process. The spiral coil (Design 2) had the better heating efficiency on the area around the mold but there was a significant low temperature in the center of the mold. For product with no temperature requirements in the middle area, the spiral coil was suitable for use.

Using the 3D coil, double sided heating was achieved with a positive result. In this type of heating, the temperature distribution of the heating surface was the same as in single sided heating. Although the heating rate is not as high as in single sided heating because of the larger area requiring heating, the temperature difference between mold surface fell in the experiment. In all four types of coil designs, the simulation can predict quite accurately the heating process and the temperature values at the mold surface and the temperature distribution. In addition, in the simulation, the magnetic flux in section A – A was observed and compared. This result was used to explain the heating results for all four coils.

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感應加熱線圈之幾何形狀於射出模具之影響性

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摘 要

本研究中，透過感應加熱系統搭配不同幾何形狀之線圈加熱於模板上，探討不同幾何形狀之加熱效果。本研究建構四種不同的線圈設計，分別為平行式、螺旋式、3D 立體式以及串聯式線圈。於 2 秒的加熱過程中，利用溫度感測器收集模板上三處位置的點溫度數據，以及透過紅外線熱影像儀所拍攝之整體溫度分佈，藉此評估不同幾何形狀於加熱過程中的影響。結果中，於相同的加熱功率下，螺旋線圈之加熱速率最高，可達 35.5 ℃/s，其次為 3D 線圈之 25.5 ℃/s。此外，螺旋線圈於加熱過程中會產生環形的高溫區域，而 3D 線圈則產生矩形的高溫區域。但是整體溫度均勻性結果中，3D 線圈有較好的表現，3 處溫度點的溫差由 41 ℃(螺旋線圈)降低至 23 ℃(3D 線圈)。結果還表明了，並聯與串聯線圈的加熱效果，並不適用於射出成型中。通過使用 3D 線圈，雙面模板之加熱效果取得了良好的成果。雖然加熱效率較單面加熱低，因為整體受加熱的面積變大了，但是使用雙面加熱時，三點的溫度差異由 23 ℃降低至 17.5 ℃。