Dynamic Mold Surface Temperature Control Using Induction Heating and Its Effects on the Surface Appearance of Weld Line

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ABSTRACT: Electromagnetic induction heating combined with coolant cooling is used to achieve dynamic mold surface temperature control. A simulation tool was also developed by integration of both thermal and electromagnetic analysis modules of ANSYS, and capability and accuracy were verified experimentally. To evaluate the feasibility and efficiency of induction heating on the mold surface temperature control, a mold plate (roughly about an inset size of cellular phone housing) with four cooling channels was utilized for two demo experiments with varying mold surface temperature between 110 and 180°C , and 110 and 200°C, respectively. During induction heating/cooling, it takes 4 s to increase mold surface temperature from 110 to 200°C and 21 s for mold surface to return to 110°C. The mold plate surface temperature can be raised at about 22.5°C and cooled down at 4.3°C/s within the aforementioned temperature range. Mold plate temperature distribution exhibits good uniformity as well in all stages of the heating/cooling process. Finally, mold surface temperature of a double-gated tensile test part mold was induction heated to above glass transition temperature for few seconds prior to melt injection. The surface mark of weld line was eliminated, and the associated weld line strength enhanced. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 101: 1174–1180, 2006

Key words: induction heating; dynamic mold temperature control; thermal and electromagnetic analysis; weld line elimination

INTRODUCTION

Injection molding is one of the most widely used processing technologies in the plastics industry. The cooling process occupies about two thirds of the cycle time in an injection cycle. As a result, efficient cooling can significantly reduce cycle time and operating costs.[1,2] Unfortunately, many molding problems, such as weld lines, part surface gross, residual stress, and warpage, occur when mold temperature is low and mold temperature distribution is not uniform. High mold temperature may reduce or eliminate many molding problems.

The most inexpensive way to achieve high mold temperature is to run cold water at temperatures as high as 90°C or even 100°C. When a mold temperature exceeding 100°C is required, either a high-pressure water supply system (to prevent the water from steaming) or heated oil may be used. The former may cause channel connection damage and safety issues after long-term operation, while the latter may not be energy-efficient because of the low heat transfer coefficient of oil. Local mold heating using electrical heating elements is sometimes used to assist high mold temperature control, especially for thin-wall cavity areas. However, this requires additional design and tool costs. Further, electrical heating is usually used as an auxiliary heating and is limited to increase mold temperature by roughly several tens of degrees Celcius.

Nowadays, the rapid growth of the 3C (computer, communication, and consumer electronics) industry has driven demand for ever lighter, thinner, and smaller parts. Injection molding of thin-wall parts creates new challenges in every aspect of the mold process, including the requirement of high-speed injection machine, suitable product and mold design, materials selection, and process control. Among them, rapid melt cooling due to the thin wall is one of the major factors causing this molding challenge. If mold temperature during the filling stage can be maintained relatively high, e.g., greater than the glass transition temperature, then the molding pressure can be greatly reduced. Further, under such conditions, a high-speed melt injection is not required, and the residual stress and part warpage can be minimized. The weld line and other surface faults can be

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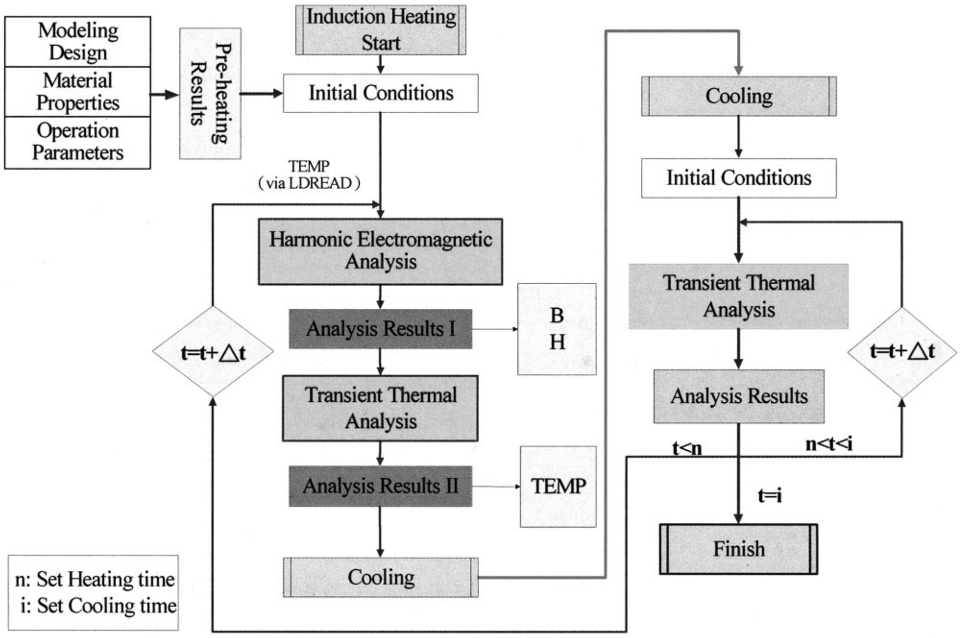

Figure 1 Flowchart of coupled electromagnetic-thermal and cooling analysis.

easily eliminated as well. Similar ideas can be applied to frozen layer elimination.[3,4]

However, maintaining high mold temperatures during the filling process while lowering the mold temperature to below deflection temperature during the postfilling process without a great increase in cycle time and energy consumption is not easy. The most popular approach to dynamic mold temperature is to alternate heating fluid and coolant, either by switch pumping in the same cooling circuits or by circulating in separate cooling channels. Either way, the massive mold base is either heated or cooled at the same time, resulting in great power consumption and longer cycle times. More recently, gas flame heating has been proposed.[5] Although the efficiency of flame heating is quite good, issues of safety and repeatable, quantitative temperature control remain to be solved. A method proposed by Yao et al.[6,7] uses a conductive (metal) layer coated on the mold surface to provide direct heating and an insulating (oxide) layer beneath to prevent heat from entering the massive mold base. This method does provide efficient heating, but the weak mechanical properties and difference in thermal expansions of the conductive and insulating layers hinder the application of this method to real molding processes.

In the present study, dynamic mold surface temperature control using electromagnetic induction heating technology was investigated. Although induction heating has been successfully used in many industrial applications, such as induction metal melting, its use in mold surface heating requires solutions to several problems, including coil design, system operations, and parameter control. Few systematic studies of mold surface induction heating have been conducted. Although Wada et al.[8] proposed the idea of using induction heating more than twenty years ago and a feasibility study on induction heating on mold heating was also reported recently,[9] stable utilization of induction heating by the molding industry will not be practical without a full understanding of induction heating from both the simulation and experimental point of view.

In our previous study,[10,11] simulated results were verified by experimental measurements on a flat steel mold plate subjected to pure induction heating using single turn coils of circular and rectangular shape. It was found that coil current and coil to plate distance are major parameters affecting the heating efficiency for identical coil designs. Single turn coils are able to increase the mold surface temperature at just 10°C/s, and temperature uniformity is not acceptable. As a result, a spiral coil was used in this study. Induction heating using a spiral coil combined with coolant cooling was investigated by both simulation and experiment to determine its rapid heating/cooling capabilities as well as the temperature uniformity in the mold plate surface. Finally, induction heating was applied to the mold surface temperature control on a double-gate tensile test specimen mold, and its effects on the surface mark and the associated weld line strength were examined.

THEORETICAL MODEL AND SIMULATIONS

The governing equations used to describe the electromagnetic field during the induction[12] are the Maxwell equations expressed as:

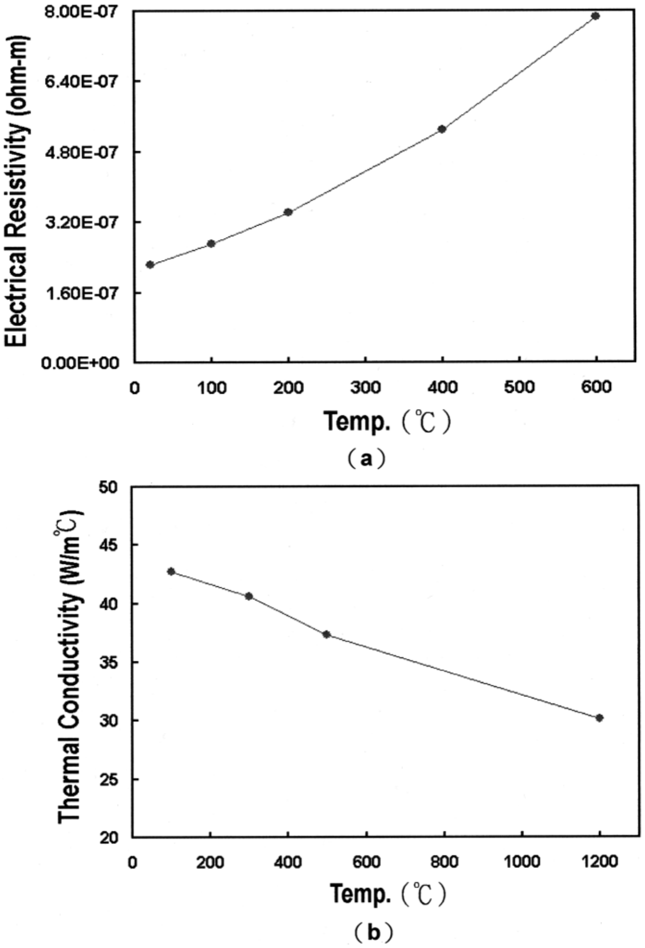

Figure 2 (a) Temperature dependence of mold plate electrical resistivity. (b) Temperature dependence of mold plate thermal conductivity.

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

$$\nabla \cdot \mathbf{D} = \rho \tag{3}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{4}$$

where **H** is the magnetic field intensity, **J** is the current density, **E** is the electric field intensity, **B** is the magnetic flux density, **D** is the electric flux density, and ρ is the electrical resistivity. The electromagnetic (EM) wave induces an eddy current in the mold plate. The EM wave decays exponentially as it enters the mold plate surface because of free electron scattering. As a result, most induced eddy currents exist in a thin-layer region beneath the mold plate surface. This thin layer is designated as the penetration depth. The penetration depth, ä, near surface can be described by

$$\delta = \sqrt{\left(\frac{\rho}{\mu x f}\right)} \tag{5}$$

where f is the alternating current frequency, and £g denotes the permeability. The energy required for the eddy currents to circulate around the working object within the induction area is finally dissipated as heat, which causes mold temperature rise. The volumetric heat generated, **Q**, from dissipated power due to eddy current flow can be calculated as

$$\mathbf{Q} = \rho |\mathbf{J}|^2 \tag{6}$$

Hysteresis loss in magnetic induction may also introduce heat. However, its contribution is much less than eddy current heating.[11,13] Therefore, it is ignored in the analysis.

A 3D thermal analysis of ANSYS on a mold plate with heating sources was first conducted to check and test the analytical capability and accuracy.[11] Then, the distributions of the electromagnetic (EM) field generated from the induction coil were simulated via ANSYS, from which the EM wave and the associated eddy current were calculated. The heat generated from dissipated power due to eddy current flow was further simulated according to the eq. (6). The temperature dependence of the material properties was also

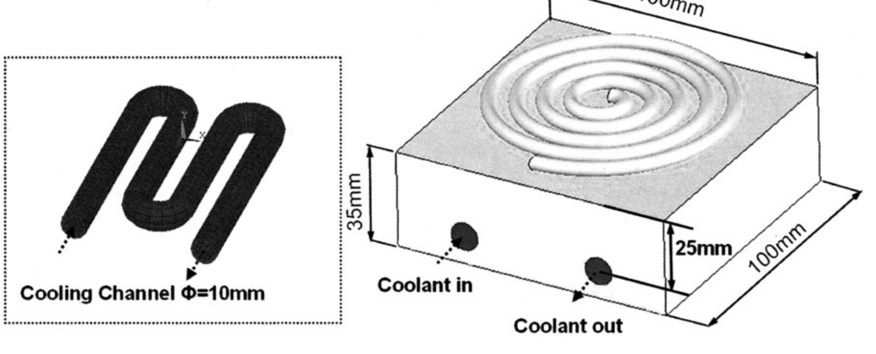

Figure 3 Multiple-turn coil in a spiral shape was designed to improve the heating capacity. Cooling channel and heaters installed in a steel plate to evaluate the efficiency of fast mold heating/cooling.

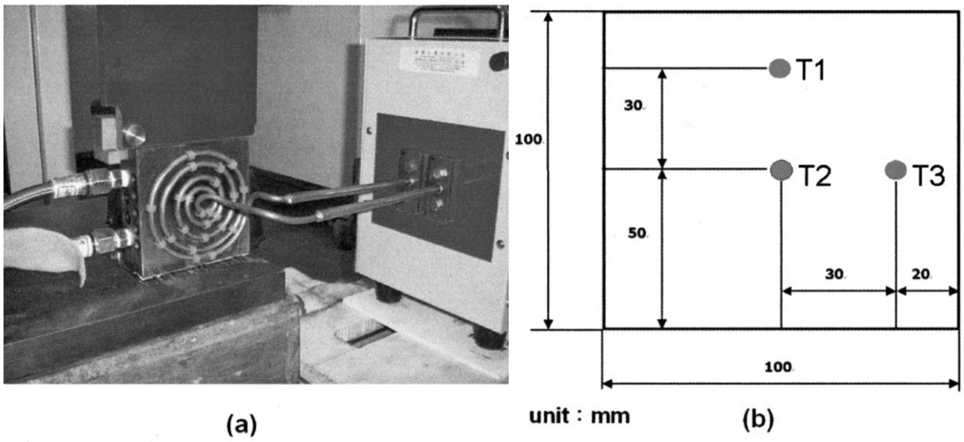

Figure 4 (a) Spiral coil and power supply equipment. (b) Check points, T1 (top), T2 (center), and T3 (right).

considered for both the thermal analysis and the electromagnetic calculation. Figure 1 shows the flowchart of the simulation algorithm for induction heating combined with coolant cooling. All simulated predictions were compared with experimental results.

Relevant materials properties and operating conditions for mold plate (AISI 4130 steel) and coil are used in the present simulations. The density and specific heat of mold plate are 7800 kg/m^3 and 465 J/(kg °C), respectively. The specific heat and density of coil are 383 J/(kg °C) and 8954 kg/m^3, respectively. Surface emissivity for the mold plate is 0.8. Temperature-dependence of materials properties was also taken into account during the simulation (Fig. 2).

EXPERIMENTAL

A steel plate of 100 × 100 × 35 mm^3, roughly about the size of a cellular phone housing inset, with four cooling channels (10 mm diameter with center 25 mm beneath the surface) looped in two circuits was used for rapid heating and cooling experiments (Fig. 3). The coolant running through the channels is 12°C. We used a multiple-turn coil in a spiral shape, which was expected to have better heating capacity than a single turn coil design of either circular or rectangular shape. In the dynamic mold surface control experiment, the mold was preheated to 110°C. An induction coil of spiral shape was turned on and brought to the mold plate surface with a 2-mm gap distance via a guided slide [Fig. 4(a)]. Temperature variations (T1, T2, and T3) at plate top, center, and right locations [Fig. 4(b)] from the measured thermal image were analyzed for further discussions.

Induction heating was performed and continued until the mold plate center temperature reached 200°C. When the mold plate center reached the target temperature, induction heating was turned off, and induction coil was removed. The mold plate was subjected to pure coolant cooling. The first experiment ran through a cycle with plate center temperature varying from 110 to 180°C and back to 110°C. In the second experiment, plate center temperature varying from 110 to 200°C and back to 110°C was investigated for comparison and evaluation purpose.

Experimental results were then used to verify simulated predictions. During all experiments, mold surface temperature distributions were measured using an infrared thermal imaging system. Detailed measurement procedures were developed in our earlier study.[14]

Finally, induction heating was applied to a double-gated tensile specimen mold (Fig. 5) with 1.4-mm thick cavity prior to mold close for ABS melt injection. The induction heating time was varied from 2.5 to 5.5 s, with an interval of 1 s. The cooling time was carefully chosen so that the mold temperature returned to 50°C prior to induction heating. The effects of dynamic mold surface temperature variation on surface marking and the associated strength of the weld line were investigated and compared with those on surface marking and weld line molded by regular injection without induction heating.

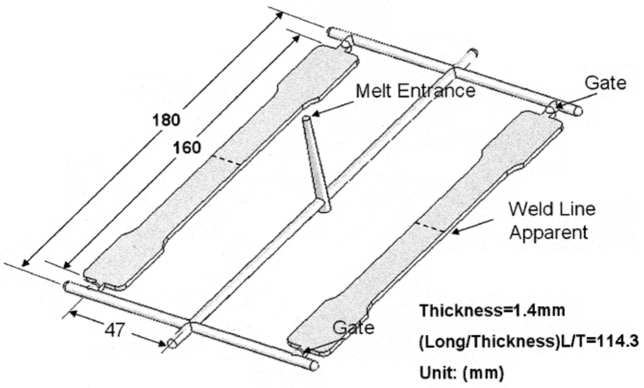

Figure 5 The double-gated tensile test specimen with length/thickness = 114.3 as thin-wall molding and the weld line appearance in the middle of the part.

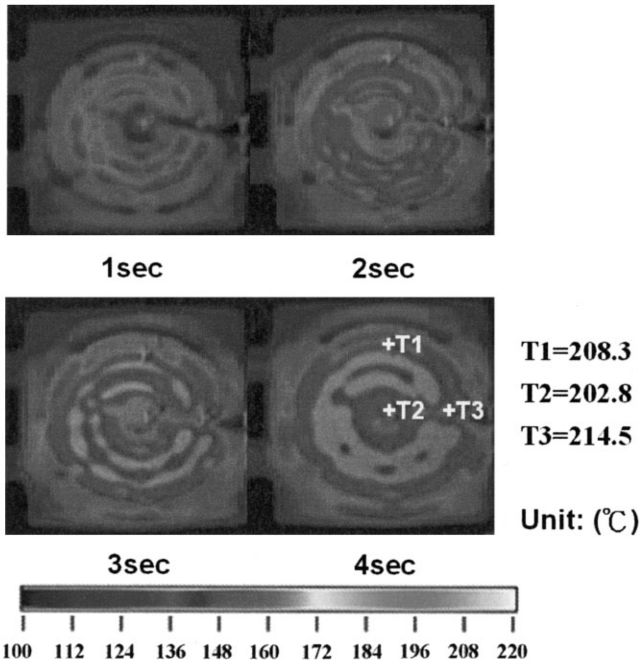

Figure 6 Mold plate surface temperature distribution measured by infrared thermal imaging system at various time intervals, during the induction heating process. (Heating target temperature is 200°C.)

RESULTS AND DISCUSSION

The experimental results showed that during induction heating and coolant cooling, it takes 3 s for plate center temperature to increase from 110 to 180°C and 21 s to return to 110°C. For the second heating/cooling cycle, it takes 4 s for plate center temperature to increase from 110 to 200°C and 21 s to return to 110°C. Mold plate surface temperature distribution as measured by the infrared thermal imaging system at various time intervals (1, 2, 3, and 4 s after heating) during 110–200°C heating cycle is shown in Figure 6.

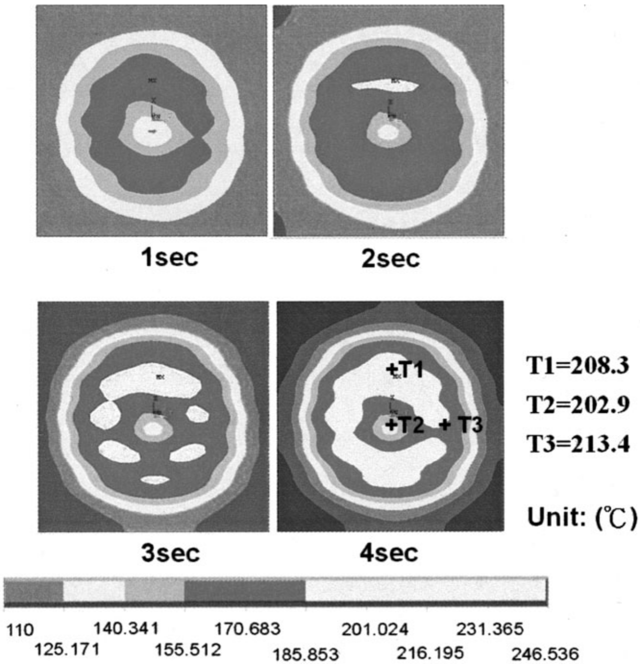

Figure 7 Simulated temperature distributions at the end of induction heating period. (Heating target temperature is 200°C.)

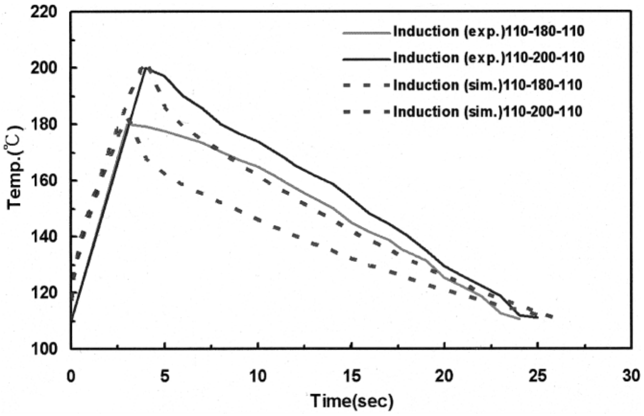

Figure 8 Comparisons of measured and simulated temperature variations at plate center during induction heating and subsequent cooling process.

Simulated mold plate surface temperature results during the 110–200°C induction heating cycle are given in Figure 7. The pattern of simulated temperature distribution at the end of the heating process is similar to that of the measured results.

Dynamic temperature variations for both cycles of induction heating combined with cooling at plate center are depicted in Figure 8. Simulated results are slightly different but reasonably consistent with measured values. The difference is larger in the cooling cycle than in the heating cycle. Simulation analyses typically assume ideal conditions, but in the real world, extra thermal resistance produces slower cooling. As a result of the slower cooling, the measured experimental values are higher in the heating phase and lower in the cooling phase than the simulated results. However, the predictive accuracy of the simulation is reasonably good, given the complexity of a simulation that models induction heating.

TABLE I
Comparisons of Heating and Cooling Times between Simulated and Measured Results When Mold Plate Center Reaches Target High and Low Temperatures

	Time (sec)	
Process	Measured	Simulation
Heating Stage		
110–180°C	3.0	2.9
110–200°C	4.0	3.8
Cooling Stage		
180–110°C	21.0	20.4
200–110°C	21.0	21.3

TABLE II
Comparisons of Simulated and Measured Temperature Uniformity When Mold Plate Temperature Reaches Target High and Low Temperatures

Process	Temperature (°C)		
	T1	T2	T3
Heating stage (110–200°C)			
Measured	169.7	200.8	183.6
Simulation	208.1	202.3	214.0
Cooling stage (200–110°C)			
Measured	105.1	110.8	106.6
Simulation	109.5	111.9	108.3

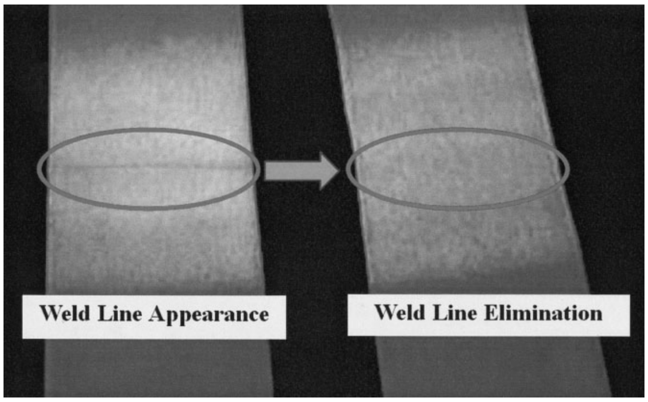

Figure 10 Surface mark of weld line without induction heating (left). Weld line mark was eliminated (right) via induction heating prior to melt injection.

The heating times required to reach target temperature in the heating phase are listed in Table I. It takes 3–4 s for mold surface temperature to rise from 110 to 180°C and 200°C using induction heating, whereas cooling time is 21 s. The shorter heating time required for the induction heating is because heat generated from induction is basically limited to the surface layer, about 0.2 mm in depth, because of the skin penetration of the EM wave. Although only layers close to the mold surface were effectively heated, the path taken by heat to sink to the coolant after the termination of induction heating is long. Predicted heating times and cooling times from simulations are consistent with measured results.

The mold plate surface temperature distribution exhibits good uniformity (Table II), once the plate center temperature reaches the target temperature. The temperature uniformity also remains when the plate center temperature returns to 110°C. Simulation and measured results are consistent. This indicates that the simulation tool is reasonably reliable for design purposes.

Since only the very thin skin layer of the mold surface (less than 0.2 mm) was heated, the required energy to raise the mold surface temperature by 100°C for this mold plate is about 1 kJ. The corresponding power requirement is about 0.2 kW. This requires a 1 kW power supply system for the induction coil (the transmission efficiency is 20%). Compared with the similar dynamic mold temperature control within the same temperature range using electrical heaters, this technique requires the total energy of 60 kJ, and the corresponding heater power supply also needs about 1 kW (heating time is 67 s). The required energy consumption during induction heating is superior to other methods. Detailed efficiency evaluation can be found in separate studies.[15,16]

The results of this research are exciting. They indicate that dynamic surface temperature control by using induction heating combined with coolant cooling is feasible and efficient. The integrated simulation technology for coupled electromagnetic-heat analyses appears to be successful in facilitating rapid heating/cooling design and may become a useful tool in real-world molding applications.

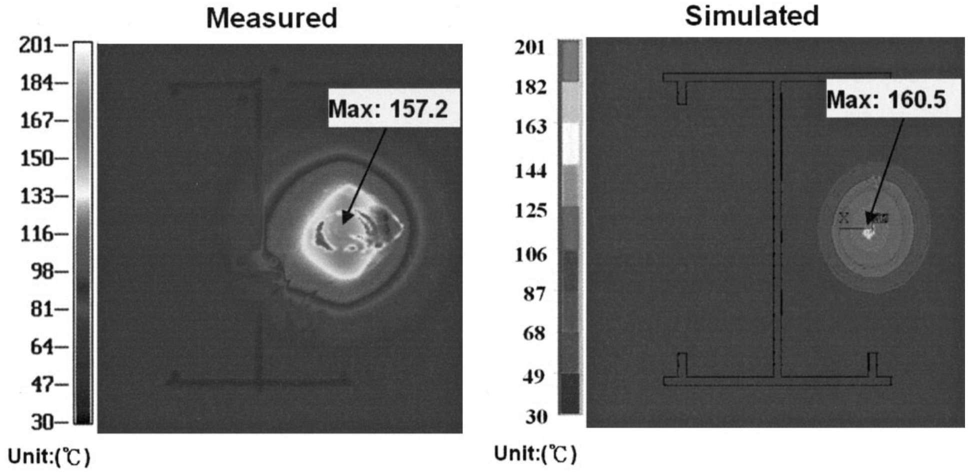

Figure 9 Simulated and measured mold surface temperature distributions on a double-gated tensile test specimen mold after induction heating for 5 s.

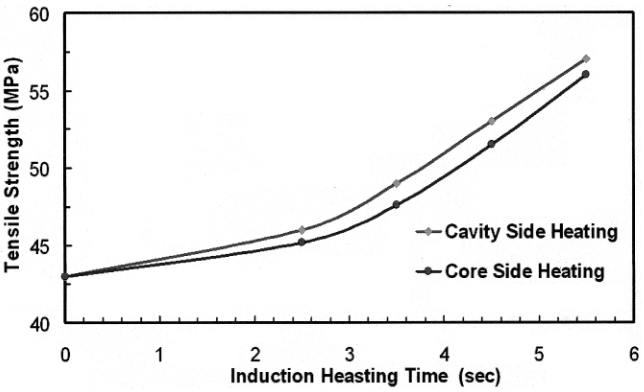

Figure 11 Variation of tensile strength of weld line as induction-heating time increases. Heating effects on both cavity side surface and core side surface are illustrated.

For a demonstration of application purpose, dynamic mold surface temperature control was used to mold ABS tensile test parts. The measured and simulated temperature distribution for the induction heated mold surfaces are shown in Figure 9.

These parts will typically manifest a weld line when molded under regulation conditions (mold temperature is 50°C). When the mold surface is induction heated to a point above the glass transition temperature prior to melt filling stage, the surface mark disappears (Fig. 10). As the induction heating time increases, allowing higher temperature and longer time for molecule chains to diffuse across the interface, the weld line strength also increases, regardless of whether the heat is applied to the cavity side or the core side surface. This is clearly seen in Figure 11. This prior heating process only takes about 3–5 s and does not increase the cycle time significantly.

CONCLUSIONS

Both numerical simulation and experimental observation were carried out on a mold plate for a dynamic heating/cooling cycle development using induction heating combined with water cooling through the cooling channel. The mold plate surface temperature can be raised at about 22.5°C and cooled at 4.3°C. Mold plate temperature distribution exhibits good uniformity as well. The results indicate the feasibility and efficiency of dynamic mold surface temperature control using the combined induction/coolant cooling technology in a real-world injection molding process. The developed simulation algorithm also shows great success and can be used as a helpful tool for system design. The application of induction heating in mold surface temperature control also leads to the surface mark elimination of weld line and the enhancement of weld line strength for injection molded ABS tensile bars.

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