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Enhancement of induction heating efficiency on injection mold surface using a novel magnetic shielding method[☆]

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ABSTRACT

Mold temperature is a major factor in the quality of injection molding process. A high mold temperature setting is feasible to enhance the molding quality but prolongs the cooling time. Induction heating is the method currently used to heat the mold surface without increasing the molding cycle. However, one unresolved problem of induction heating is the proximity effect resulting from two adjacent coils with different current directions. The proximity effect substantially decreases heating efficiency, which then causes non-uniform heating. This effect is difficult to avoid in a single-layer coil. The most common solution, which is to use magnetic concentrators to reduce the proximity effect, does not obtain satisfactory results. In the novel magnetic shielding induction heating method developed in this study, heating efficiency and temperature uniformity are enhanced by using ferrite materials to separate the conflicting magnetic fields caused by the repulsive proximity effect. Three typical single-layer coils are investigated in this study, including a reciprocated single-layer coil, a single-layer spiral coil, and a rectangular frame coil. Appropriate placement of ferrite materials on these induction coils successfully eliminated the proximity effect, increased the heating rate, and improved temperature uniformity.

1. Introduction

In the injection molding process, mold temperature is an important factor in the quality of injection molding process. A high mold temperature setting is feasible to enhance the molding quality but increases the cooling time and parts' demolding temperature. To enable cavity filling under a high mold temperature and parts' ejection under low temperature, a variotherm process was developed for high-precision injection molding, thin-walled injection molding and micro-injection molding [1–3]. The variotherm process dynamically controls the mold temperature, preheats the mold to a higher temperature before the melt enters the mold cavities, and then decreases the mold temperature to the ejection temperature after the cavities are filled.

Common mold heating approaches for a variotherm process include infrared heating [4,5], gas-assisted heating [6], thin-film resistance heating [7], resistance cartridge heating [8,9], steam heating [10], and induction heating [11–14]. The advantages of induction heating, in which only the mold surface is heated, include rapid heating and cooling, good controllability, energy saving, and allowing local heating. Compared with conventional oil heating, induction heating has better potential for increasing mold temperature and reducing cycle time.

The induction heating method has been widely used in the various industrial manufacturing processes. Since the skin effect of induction heating concentrates the resulting Joule heating at the surface of processed workpiece, the surface can be heated by using a high-frequency current. Therefore, induction heating is an efficient variotherm process for injection molding. Studies show that induction heating rapidly increases mold surface temperature, substantially shortens cycle time [11], increases the molding ability of thin-walled injection molding and micro-injection molding [12], improves the replication of micro-features [13], and reduces the welding line defect of injection molding parts [14].

Induction coil designs can be classified into four types: unmovable external hung-up type, movable external hung-up type, wrapped type, and inserted type. The first type is easily implemented because the induction coil is independent of the processed workpiece. Chen [15] used induction heating to increase the surface temperature of injection molds and found that both heating rate and uniformity are satisfactory when the area of the processed workpiece is 100 mm × 100 mm. The movable external type can be either a fixed induction coil with a movable processed workpiece or a fixed processed workpiece with a movable induction coil. The former is more common, particularly in metal welding or surface treatment [16–18]. In wrapped induction heating, induction coils are used to embed the whole workpiece. Chen [19] reported that wrapped induction heating is effective for injection molding. In the inserted type, the induction coils are placed behind cores and cavities so that the penetration effect and heat conduction provide indirect heating of the mold surface. This technique is superior in terms of reduced cycle time because the induction coils do

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not have to be moved. However, the placement of induction coils inside the molds requires consideration of the layout of the cooling channel, the layout of the ejection system, and the rigidity of the mold structure.

Induction heating is apparently an effective solution for heating the mold surface without increasing the molding cycle period. However, the main unresolved problem of using induction heating in injection molding is the non-uniform temperature distribution on the heating surface. The various causes of differences in heating temperature include the coil turn space, heating distance, cavity geometry, magnetic interference, and the proximity effect. For instance, different directions of electric current along induction coils can cause a non-uniform temperature distribution by introducing a repulsive proximity effect. For a practical coil design, however, opposite directions of coil current are difficult to avoid.

In a study of the effect of repulsive proximity on non-uniform temperature distribution, Sung et al. [20] compared temperature uniformity in the heating surfaces of different induction heating coils. The experimental results showed poor heating efficiency in the single-layer coil with opposite current directions. However, the double-layer reciprocating coil and the coil with magnetic flux concentrator efficiently increased heating speed and provided uniform temperature distributions. Huang [21] designed a multi-layer coil for improving heating efficiency and temperature uniformity in a conventional single-layer coil. The experimental results showed that the multi-layer coil has a more uniform temperature distribution and better heating efficiency compared to the conventional single-layer coil.

Although, the double-layer reciprocating coil can avoid the heating layer (i.e., the layer near the heating surface) with opposite current direction, the double-layer coil must have reduplicate coil length of single-layer reciprocating coil. However, the increased coil length increases coil manufacturing cost and energy consumption. The local multi-layer coil has a more uniform temperature distribution and better heating efficiency; applications of the local multi-layer coil are limited to spiral-like forms. Applying magnetic flux concentrator to control magnetic flux field and eliminate proximity effect is the most popular method in the induction heating process, but fails to completely isolate the conflicting magnetic fluxes when opposite current coils were induced.

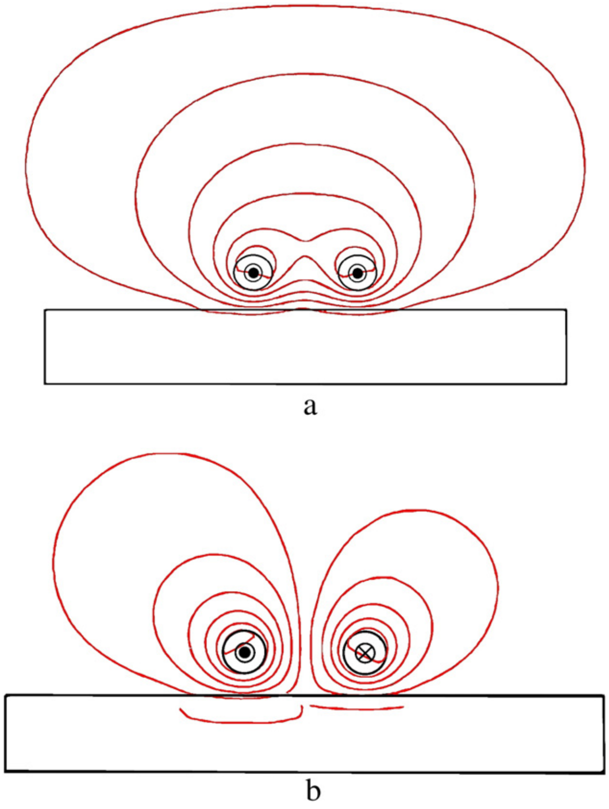

Fig. 1. Effect of current direction on magnetic flux line: (a) coils with identical current direction; (b) coils with opposite current direction.

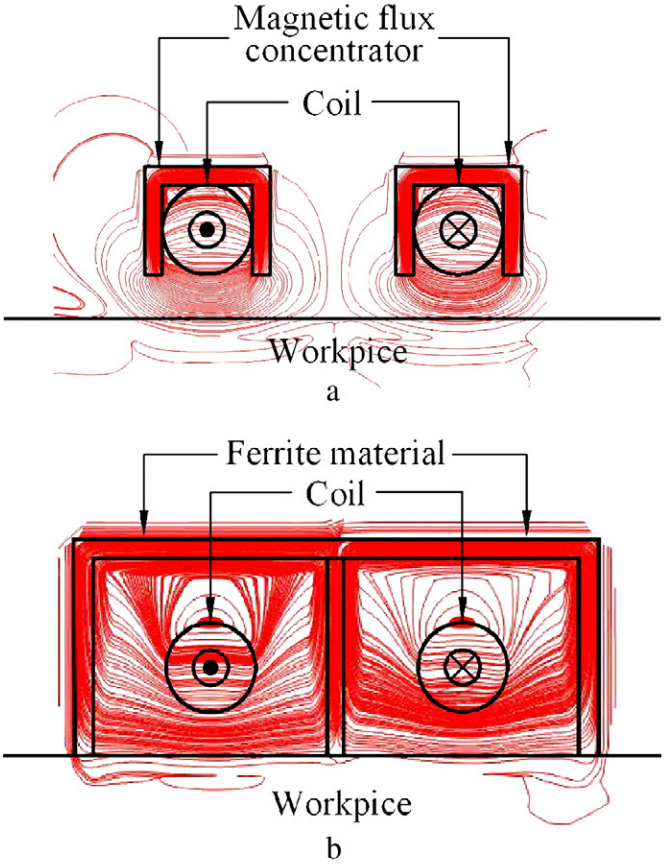

Fig. 2. Magnetic flux fields of two adjacent opposite current coils: (a) with magnetic concentrator; (b) with magnetic shielding material.

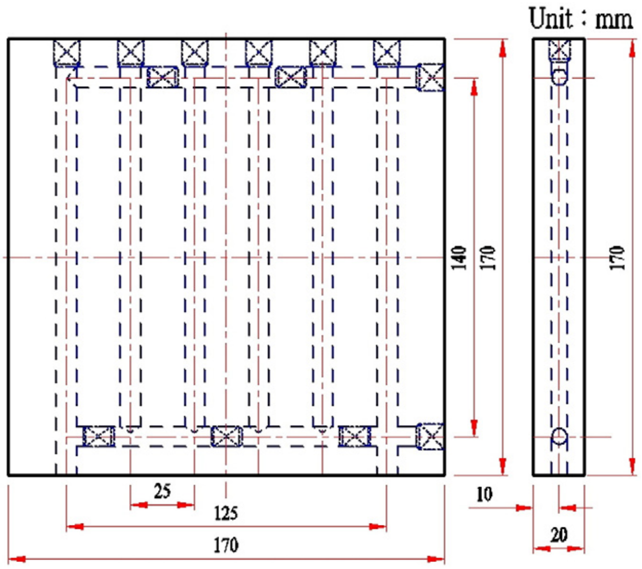

Fig. 3. Dimensions of the heated plate with cooling channels.