Variothermal mold heating by infrared radiation – an interaction between material and technology

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Summary – Injection molding is one of the main manufacturing processes of the plastics industry. To meet criteria in the means of product quality and economic requirements, a new mold technology considering variothermal mold heating in an economical way is developed.

In this paper, the concept of a double divided injection molding mold is investigated. It consists of a two-part separated mold cavity and a two-part mold core which allows rapid heating and cooling of cavities in injection molding processes. The inner low mass molds of the cavities are heated rapidly with infrared radiators. Hence, the injection molding process starts with high temperature cavities manufacturing high quality plastic products in an economical way. Starting with a rating of different variothermal heating concepts, a need of more flexible variothermal mold heating technology is derived. Heat transfer mechanisms conduction, convection and radiation between high mass body and low mass inlay are explained. The advantage of a variothermal mold heating by infrared radiation is demonstrated by a mathematical and physical modeling of heat exchange. Finally, the influences on heat transfer via infrared and contact cooling are investigated experimentally. The results show promising recognitions regarding the potential of variothermal molds using infrared radiation.

Keywords: Manufacturing of Tools, Injection Molding, Variothermal heating, Heat transfer mechanisms

1 Introduction

The domestic plastics industry is one of Germany's most important industry sectors. It is separated into different business areas according to the used material and production technique [1–3]. Especially thermoforming and injection molding are together with plastics extrusion the main manufacturing processes [4; 5]. For all of them a forming tool called mold is required. In general, all molds have the following tasks to fulfill [6; 7]:

- Shaping the geometrical form
- Controlling the parts temperature during the process
- Absorbing the forces that occur during manufacturing

Especially the temperature control of molds is an important aspect from an economical and technical point of view. Regarding a typical injection molding cycle for an isothermal tempered mold, approximately one third of the cycle time is necessary to cool down the part to demolding temperature [8]. Thus, a reduction of cycle time through a minimization of the cooling time is a promising approach to increase the economic efficiency of injection molding processes. In general, there are two concepts for controlling the temperature of injection molding molds. Most frequently, a mold with a fixed temperature level so-called isothermal temperature control is used. The temperature depends on the used plastic, the geometry and the desired surface quality in means of appearance and surface feel. Isothermal molds realize a compromise between a good mold-filling, surface quality and cooling time [9].

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The second concept is variothermal temperature control. In this case, the temperature varies depending on the current process step of the production process. In case of injection molding, a cavity temperature near to the melting temperature of the used plastic supports the filling process and formation of high quality surfaces. The solidification starting at the cavity surface is inhibited or even stopped. That allows to form micro structured surfaces or to produce parts with high ratios between flow path and wall thickness [10–12]. After filling the cavity and partly during the holding pressure step, the part has to be cooled down to the required temperature for demolding [8]. The heat flux between the molten or afterwards solidified plastic becomes higher in relation to the difference between the mold and the melt-temperature. For this reason, the objective of variotherme temperature controlled molds is to meet both, a cavity surface temperature close to the melt temperature for the filling process step and a possibly low temperature for the cooling process step. The time to apply those temperature changes is decisive for the economical evaluation of the whole injection molding process. It is influenced by the technology used for heat transfer, the mold material, the shape of the part and the mold dimension.

2 Requirements for variothermal mold heating

There exist many technologies for mold temperature control using dynamic temperatures. The general task of every of those variothermal heating concepts is to change the mold temperature as fast as possible. Mainly, there are five concepts used for variothermal heating as shown in **Figure 1**.

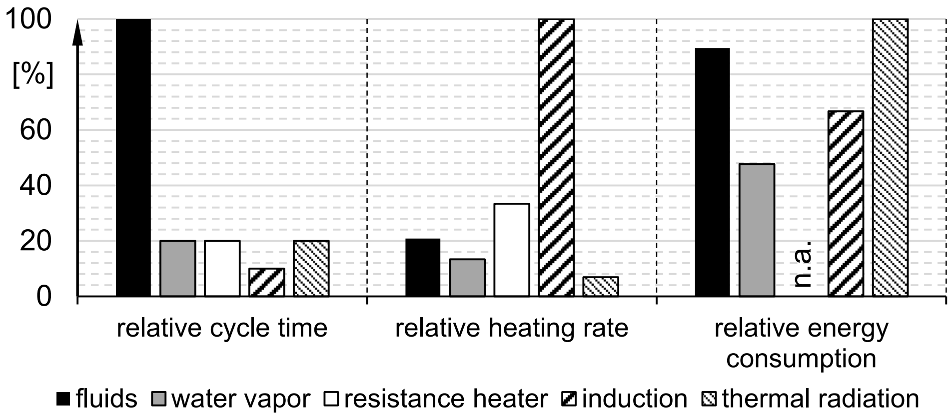

Figure 1: Variothermal heating concepts compared [13–17]

The quantities shown are normalized values based on the highest amount of heating rate, energy consumption or rather longest cycle time of the shown technologies. Induction reaches the highest heating rate, which means the highest change in temperature within a period. It also reaches the shortest cycle time while it ranks in terms of energy consumption in upper midrange. Thermal radiation compared to that takes one of the longest cycle times while using the highest amount of energy and reaching the lowest heating rate. However, regarding economic criteria, thermal radiation is the concept with one of the lowest investment for manufacturing molds [12; 13]. The reasons for the poor rating are due to the way thermal radiators, in particular infrared

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radiators, are used for heating molds. First, there must be a distinction between two utilization concepts: external heaters and integrated heaters.
External heaters have to move between the mold-halves while they are opened. During that time, there cannot be any primary (mold closing) mold movement. Thus, the cycle time rises. Integrated systems provide the opportunity to work simultaneously to any other step of the injection cycle. Even if the mold is closed it can be heated up. Compared to external systems the cycle time lowers. Today, infrared radiators are mainly used as external systems [14–16].
The surface treatment has an influence too. Especially polished surfaces – most cavities are treated like – show a very high reflection coefficient [17–19].

3 Mold concept for variothermal mold heating using infrared radiation

Regarding the disadvantages of infrared radiation as method for heating molds in general (see **Figure 1**) and the challenges arising by using external infrared heating systems, an innovative variothermal heating concept has to be developed. The main challenge of the state of the art is the cavity surface and in particular its condition that highly affects the quality of the injection-molded part and procedural factors as forces for demolding [20]. For this reason, the surface roughness should be as low as possible, which is mostly reached by polishing. However, polished surfaces show a high reflection coefficient and low absorption resulting in a low efficiency regarding energy input by the use of infrared radiation. To meet this disadvantage a mold concept as shown in **Figure 2** is developed. Both halves of the mold (fixed and moveable) become separated into two parts each. One part consists of the mold-body with high mass, which stays at a fixed (isotherm) temperature as low as possible. Infrared radiators are integrated in the high-mass body for radiating onto the low-mass inlays side facing away from the melt (radiated side). The low-mass inlay is moveable mounted in relation to the high-mass body. The low-mass inlays non-radiated side forms the cavity.

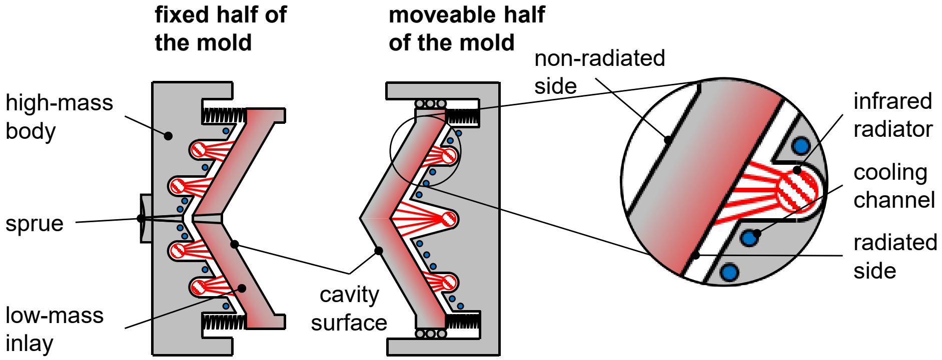

Figure 2: Variothermal heating concept using infrared radiation and contact cooling

The advantage of this concept is that the radiated side of the low-mass inlay can be optimized in order to maximize the energy input by infrared radiation while its non-radiated side can be treated to optimize the function as cavity (e.g. polishing for low surface roughness). On the other hand, heating the backside means that it takes more time until the cavity surface reaches its process temperature. Hence, a material is suggested with a high temperature conductivity like aluminum alloys.
Cooling starts when the whole mold is closed. By the movement of the clamping unit of an injection molding machine itself or by external systems, the low-mass inlay and

the high-mass body get into contact. Due to the lower temperature of the high-mass body compared to the low-mass inlay, a heat flux from inlay to body reduces the temperature on the contact surface. Because of thermal balancing inside the low-mass inlay a heat flux from warmer areas like the cavity surface to cold areas lowers the cavity surface temperature. By the inlays thermal inertia this will not happen immediately after closing the mold so that the injection step can be completed before. After part ejection the cycle can start again.
The heat transfer mechanisms can be divided into conduction, convection and radiation. **Figure 3** illustrates the heat transfer mechanisms in the mold. During heating, there is no metallic contact and the heat flux $\dot{q}_{ir}$ is transferred into a low mass inlay by radiation, realizing rapid heating (3). Starting the injection process the mold is closed and with increasing contact pressure an increasing heat transfer $\dot{q}_{cl}$ is realized by radiation (2) and conduction (1). This allows the injected plastic to enter a high temperature mold to meet quality criteria, while pressure dependent conduction [21] allows rapid cooling rates of low mass inlay.

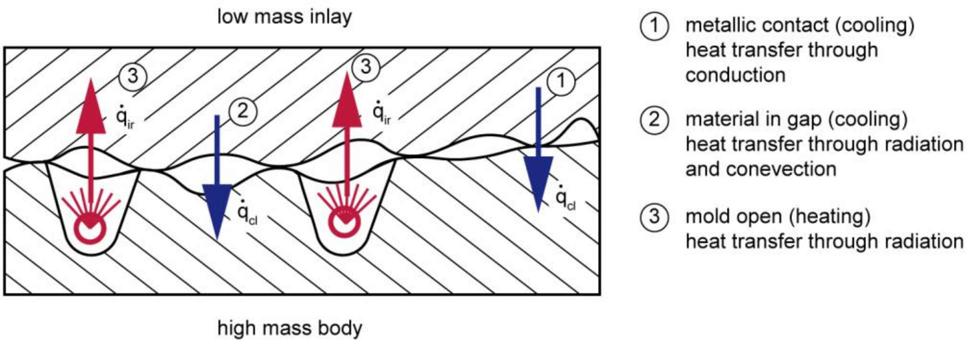

Figure 3: heat transfer mechanisms conduction, convection and radiation between high mass body and low mass inlay

4 Mathematical and physical modeling of heat exchange by infrared heating

Equation (1) expresses the fundamental connection between energy and a change in temperature of a body [17].

$$Q=m\cdot c_p\cdot \Delta T \quad (1)$$

Therein, Q denotes the amount of energy in the form of heat, m equals the mass of the heated body, c_p is the specific heat capacity and ΔT the temperature change. While using infrared radiators, energy is provided by radiation. Infrared is defined as electromagnetic radiation with a wavelength λ equal or above 780 nm.
Following equation (2), those waves can hit another bodies surface and can be absorbed (A),reflected (R) or transmitted (T) [17].

$$A(\lambda)+R(\lambda)+T(\lambda)=1 \quad (2)$$

All of the coefficients depend on the wave length of the radiation. Absorption of radiation on metallic surfaces is localized which means the transfer of radiation into energy (mainly heat) takes places in near-surface layers [18]. Hence, there is nearly

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no transmission. Infrared radiators are mainly made of glass tubes with inner wires working as resistive loads. By applying a voltage, the electrical energy is transformed into thermal energy. The temperature increase of the of the wire can be estimated using equation (1). Equation (3) describes the exchange of heat flux density $\dot{q}_{12}$ between two parallel plates with the same surface area radiating as gray bodies [17]. Each of the surfaces has a specific emission factor $\varepsilon_{1/2}$ and temperature $T_{1/2}$. The Stefan-Boltzmann constant is denoted as σ.

$$\dot{q}_{12}=\frac{\sigma}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}\cdot\left(T_1^{\ 4}-T_2^{\ 4}\right) \qquad (3)$$

Another important aspect is the position of the radiating surfaces to each other, which can be expressed by the view factor φ_{12}. Equation (4) is used to calculate the view factor for a cylindrical shaped body radiating on a flat surface with width W, its central axis parallel to the surface and laying directly over the middle of the surface in a distance of R [17]. The heat flux density has to be multiplied with the view factor to get the amount of radiation that is used to heat the irradiated surface.

$$\varphi_{12}=\frac{1}{\pi}\cdot\tan^{-1}\left(\frac{W}{2R}\right) \qquad (4)$$

5 Experimental investigations on heat transfer via infrared radiation

In order to analyze the different effects of surface treatment, specimen thickness, power and distance to the infrared source, experiments are carried out. A specimen made of AlZnMgCu1,5 is investigated using the experimental setup as sketched in **Figure 4**.

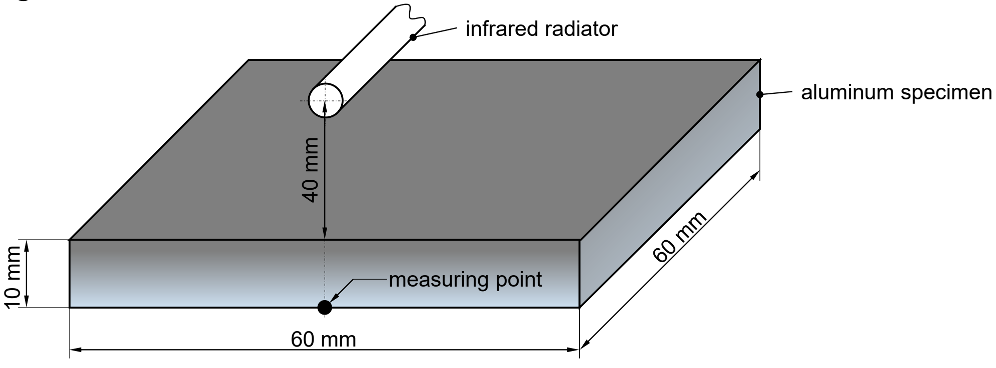

Figure 4: principal of the experimental setup, shown in reference configuration

The radiator operates as a short-wave infrared radiator with a power of 1000 W and a reflective coating on one half of the glass tube where the heating wire is mounted in. The maximum of its spectral emissivity is about 1,2 µm. The configuration shown in **Figure 4** is referred to as reference configuration (r) . Over a time of 60 s the specimen is heated via infrared radiation. The initial temperature of the specimen is 30 °C. The change of temperature on the non-radiated side is measured directly under the center of the specimen (see **Figure 4**).

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Configuration	Sheet thickness	Distance to radiator tube	Surface coating	Number of short wave radiators (1000 W)
Reference (r)	10 mm	40 mm	none	1
(a)	**20 mm**	40 mm	none	1
(b)	10 mm	**30 mm**	none	1
(c)	10 mm	40 mm	**black**	1
(d)	10 mm	40 mm	**black**	**2**

Table 1: Parameters for experimental investigation

In order to analyze the influence of the radiation parameters on the heating behavior, the parameters listed in **Table 1** are varied throughout the experiments. The results of the temperature measurement are shown in **Figure 5**.

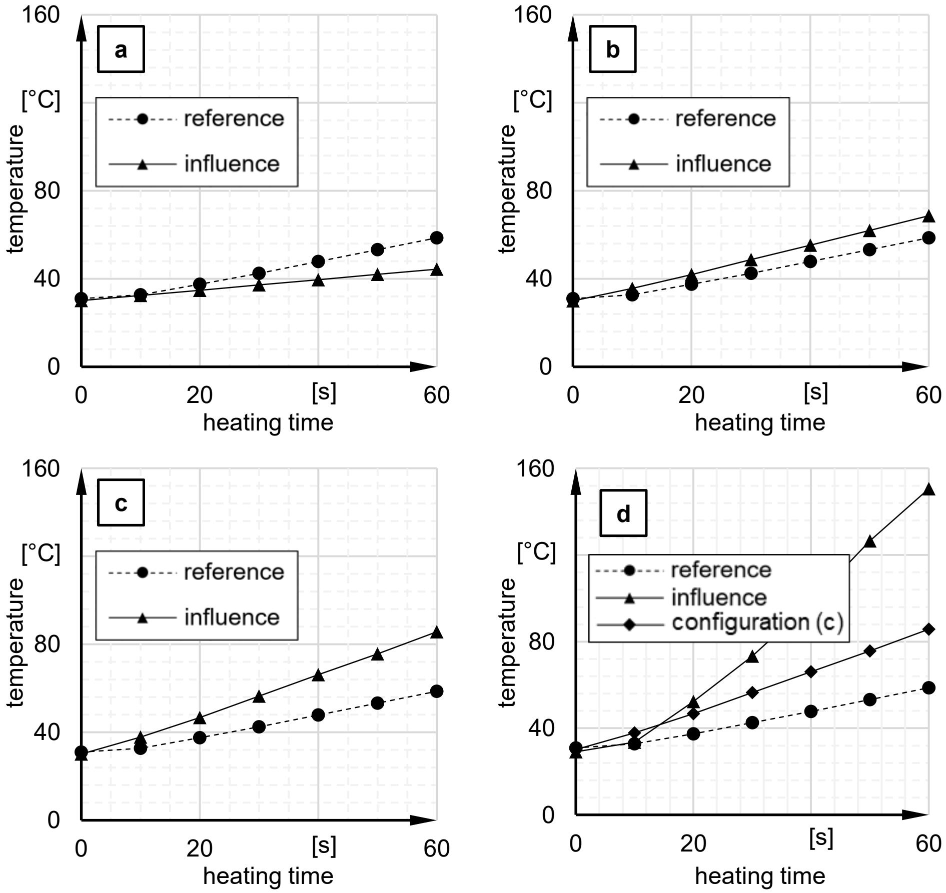

Figure 5: influences on heating rate compared to reference; specimen with thickness of 20 mm (a), specimen with distance to radiator tube of 30 mm (b), specimen with black coated surface (c), specimen with black coated surface and two short-wave radiators (1000 W each) (d)

To evaluate the effect on the heating performance for configurations (a)-(d) the measured temperature after the heating time is an important factor. Regarding that,

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only a larger thickness in (a) shows a negative result. Following equation (1), doubling the mass by doubling the specimens height means a doubled need of energy for the same change in temperature or half the change of temperature while using the same amount of energy. In the reference configuration, the temperature increase is $T_r \approx 28\ K$, for (a) it is $T_a \approx 14\ K$. As a result, the temperature rise is only half as high. In (b), the distance from the radiator tube's center to the specimen surface is reduced by 25 % which results in an increase of the view factor from equation (4) of about 22 %. Hence, the amount of energy and consequently the temperature change rise by 22 % in theory, compared to the reference. The experiment shows an increase of 17 % which could be explained by energy exchange due to free convection and radiation to the environment that is not included in the mathematical model. In (c), the coating influences the emissivity factor of equation (3). A change in temperature rise by 46 % compared to the reference is observed. Thus a rise of the emissivity can be assumed. In (d), the change in temperature is more than twice as high as in (c). This result can be explained by equation (1) since the double energy was used for rising the temperature.

In **Figure 6**, a comparison between the intermediate heating rates of all configurations (a)-(d) with the reference configuration (r) is shown. The intermediate heating rate is defined as the temperature change during the measurement and the duration for temperature change. The results confirm the previous assumptions. The biggest effects provide the surface treatment and the rise of power used for heating. Especially configuration (d) reaches heating rates of about 2 K/s which can be compared to the rates of fluids or water vapor and means an increase of about 240 % in relation to the state of the art [22–24; 14; 13].

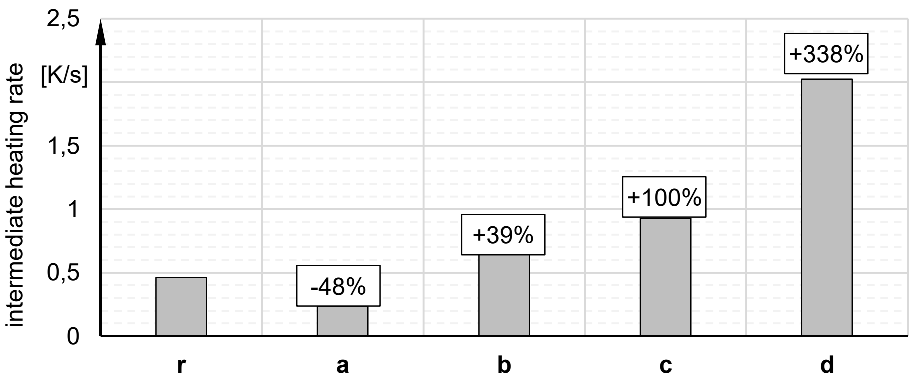

Figure 6: comparison of the intermediate heating rates of configurations a, b, c, d with reference r

6 Conclusion

The use of infrared for heating molds for injection molding shows great potential in terms of heating rate, energy consumption and possible cycle times. The innovative approach shown in this contribution is the use of radiators as mold-integrated heating elements working while the mold is closing or opening. The heating task is handled by the infrared radiators by irradiating a low-mass inlay. The cooling takes place while the mold is closed due to a contact between the heated inlay and a high mass cold mold body. Experimental results have shown that heating rates of 2 K /s can be reached. Those values are comparable to temperature control by fluids or vapor and are suitable for variothermal mold heating [22]. In the following, investigations

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have to be carried out on beam-paths and optimized three-dimensional shapes by designing them in the way that the infrared beams become reflected between the surfaces of the three-dimensional shape as often as possible. The main goal of the future work is to increase the efficiency by transforming as much electrical power of the radiator as possible into thermal energy for a fast heating of the low-mass inlay.

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