High-speed Mold Heating. In the production of certain items, profitability depends in part on „thermal speed“ in the mold. This applies to micro parts, molded parts with micro- and nano-structured surfaces and optical components. Dynamic cavity heating is demonstrably faster and more efficient when mold inserts made from ceramics are used, rather than other heating systems.

In order to accurately shape very finely structured surfaces on materials such as PC and PMMA, a surface temperature is required during cavity filling that is just above glass temperature [1, 2]. Otherwise, the melt is in danger of being too viscous to form the shape. Scarcely has the cavity been filled, when the molded part has to be cooled down for demolding. The temperature drop can then amount to more than 60 K, depending on the material in question. Thus the processor is faced with the problem that he requires high mold wall temperatures, on the one hand, and rapid temperature changes, on the other. If the process takes place in thermal limit ranges, he risks losing quality. Otherwise the cycle times are disproportionately long, so that the profitability of production is endangered.

Consequently, it is desirable to have a highly dynamic, variothermal heating system that heats the cavity surface accurately in the shortest possible time. In the ideal situation, secondary processing time (mold opening, part removal, mold closing) would be sufficient for heating the cavity.

Molding Heating as Practiced

In order to heat molds, the industry utilizes various (quite well known) methods:
- Fluid media as heat transfer agents (water, oil),
- Induction heaters (internal or external),
- Infrared heat lamps,
- Resistance heaters (thick-film heaters, heater cartridges).

Fluid media heating systems using heat exchanger media, such as water and oil have become established. Their disadvantage is their relatively poor level of efficiency due to line losses and sluggish temperature changes. Thus a temperature increase from 60 to 130 °C may take as long as 15 s. If water is used, the available temperature range is also limited. Even spe-
Injection molding involves using high pressure-blanketed heating units which reach maximum water temperatures of only 160 to 200 °C. Induction heaters provide the desired heating power dynamism. However, they have their limitations when it comes to heating molds with non-planar part geometries and to integrating inductors within the mold. And they have a further disadvantage: they are expensive.

Infrared lamps heat the cavity surface externally with heat waves when the mold is open. However, their effectiveness is drastically reduced by the low emission factor of the polished and usually reflective steel surfaces. Their heating dynamism and maximum achievable temperature are considerably restricted by the size of the lamps and the resulting limited power density relative to area. Compared to water heating, infrared lamps are clearly more sluggish.

Conventional resistance heaters still lack sufficient dynamism, since the heating power of these systems is too low relative to the area. Moreover, they are only partially adaptable to complex contours, i.e., their heating output is more or less unfocused.

Especially when rapid temperature changes are required, the heating methods described have only limited suitability for profitable production [3]. Their achievable dynamism as well as the required heating energy are the decisive factors in this evaluation (Fig. 1).

![Diagram](https://example.com/injection_molding_diagram.png)

Fig. 2. Mold wall temperature profile during variotherm injection molding process: (1) start heating, (2) top set mold wall temperature reached, (3) start injection molding cycle, (4) start injection, (5) start cooling, (6) lowest set mold wall temperature reached.
When it comes to cooling the mold, the variety of methods is relatively small. Water-based systems are widely used and preferred for reasons of cost. More expensive and involved systems using a phase change in the coolant (e.g., CO₂ or freon) are rather rare.

**Engineering Aspects**

When evaluating the profitability of injection molding, cycle times play a decisive role. Thus it is natural to shorten, as much as possible, the individual times that add up to the total cycle time without impairing molded part quality. That is complicated enough for standard injection molding, considering that the processor has to venture ever farther into restricted territory. In variothermal processing technology, heat-up time is an additional variable (Fig. 2). Even so, this technology is a good choice for several reasons in order to e.g.

- accurately shape micro- or nano-structures (e.g., structured, functionalized border surfaces or lab-on-a-chip systems),
- produce optical parts that demand accurate contours and excellent surface texture (e.g. thick lenses),
- initiate crosslinking in connection with special methods, or
- control a certain temperature at the sprue bush (e.g. to trigger thermal closing).

In order to satisfactorily reproduce structures no more than a few nanometers thick – 70 to 100 nm for antireflection coatings – a mold would have to be heated up to the glass temperature range of the melt being processed. In this temperature range, reproduction quality may be good, but even if removal is possible, then not until after a relatively long cooling time (Fig. 3).

That is why some processors attempt to compromise by lowering mold temperature as much as the specific material allows – this results in only a very small gain in cooling time, but can impair shaping accuracy. Any further reduction in mold temperature may shorten cooling time significantly, but at the price of accurate surface detail.

**Electrically Conductive Ceramics for Mold Inserts**

The prevailing conditions listed above were described several years ago as part of a joint project at the Polymer Institute of Plastics Technology (Polymer-Institut Kunststofftechnik, PIK) of Heilbronn University [2]. They concluded that highly dynamic variothermal mold heating is required to form nanostructures which, by way of comparison, are three to five times smaller than those on an DVD [4]. Moreover, the system should not just heat up the mold prior to melt injection, but also lower the temperature level during the subsequent locking sequence, in order to facilitate solidification of the polymer.

Further consideration led to the goal of conceiving a close-to-cavity heater in order to concentrate both the heating and cooling processes in the critical areas, i.e., in previously defined mold segments. In cooperation with Krauss-Maffei GmbH of Munich, Germany, and other partners in industry, PIK has optimized an electrically conductive high-performance ceramic to the point that it has become a suitable base material for variotherm mold inserts. This material, meanwhile designated Rapid Heating Ceramics (RHC), can be inserted true to contour and comparatively tightly beneath the cavity surface to regulate the temperature in specific process relevant mold regions. Its efficiency and energy product thereby open a processing window for temperatures up to 500 °C. The tempering channels required for cooling can be laid directly in the ceramic. When used as a heat-
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mal tempering design. The mold inserts

er inserts were compared with an isother-

al cooling techniques, thereby reducing cooling time by 30% and more. The indirect en-

ergy savings thus achieved are also con-

siderable.

All this presumes, however, the such

ideally arranged tempering channels in

the mold are supplied with the right

amount of tempering medium at the right temperature. To do so, both heating

and cooling should be linked together in

a single regulation system [5]. But con-

trolling the heater elements via conven-

tional hot-runner regulators already in-

stalled in many machines can be a eco-

nomical way to integrate them in the ex-

isting infrastructure.

Conclusions

Rapid Heating Ceramics (RHC) enable

highly dynamic and energy efficient tem-

perature regulation of molds and mold

elements. This is due to the proximity of

heating elements to the cavities and to

the consequently small amount of process

relevant mold mass – only the shaping re-

gion of the cavity surface is tempered.

Compared to the steel types widely used

in mold building, this high-performance

material exhibits a higher modulus of elas-

ticity and higher pressure resistance as

well as higher resistance to abrasion and

higher temperature stability.

RHC blanks can be ground, eroded and

polished to order. This makes it possible

for them to be integrated in molds and

mold elements as heating or cooling ele-

ments quite simply, often even retroac-

tively. In addition to considerable energy

savings, they offer numerous advantages:

Start-up scrap is reduced thanks to rel-

atively rapid achievement of quasi-sta-

tionary thermal equilibrium in the

mold.

The short heat-up times and reduced

cooling times allow rapid cyclical tem-

perature curves (variothermal process

technology), thus significantly reduc-

ing cycle times compared to the known

variothermal tempering methods.

The entire cavity surface can be heat-
ed uniformly with RHC, thus notice-
ably improving molded part quality.

Very fine surface structures can be shaped

better, thin-walled parts are easier to fill,

and weld marks and flow lines can be re-

ing element, this newly developed high-

performance material has the following

advantages:

- Its contour-adapted geometry effects
  rapid, dynamic tempering of molds
  and mold elements.
- Its high heating power relative to area
  results in a high level of efficiency.
- Due to its hardness and the resulting
  resistance to pressure and wear, it can
  be employed for close-to-contour in-
  direct heating.

The material is, of course, rather difficult
to cut, but erosion, grinding and polishing have proven to be passable machin-
ing methods. Integrating it into molds and mold elements is relatively simple – even in already existing mold designs.

One approach that even allows exist-
ing molds to be retrofitted, is to integrate it in an indirect heating element directly beneath the cavity. Presuming that the mold itself has been designed with suffi-
cient stiffness, the distance between the heating element and the shaping mold wall can be reduced to 2 mm to achieve maximum temperature dynamics.

One interesting possibility resulting from its hardness and good polishability is to utilize the ceramic material directly as a mold wall that simultaneously heats and shapes. Investigations have shown that heating dynamics improve over in-
direct heating due to the elimination of

heating line losses.

Rapid Temperature Change and
Regulated Mold Cooling

In additional test runs, RHC heater/cool-
er inserts were compared with an isother-
mal tempering design. The mold inserts

with the integrated cooling system were provided by gwk – Gesellschaft Wärme

Kältetechnik mbH of Kierspe, Germany. One of the mold inserts investigated pro-
duces polycarbonate lenses with a maxi-
mum wall thickness of 6 mm (Fig. 4).

The isothermal process ran at a con-
stant mold wall temperature of 100 °C,

whereas in the variothermal process the
top mold wall temperature was 140 °C

and the lowest 60 °C (Fig. 5). Heat-up was

consigned to secondary processing times.

In concert with the cooling system, cycle,
i.e. cooling time was thus reduced by

more than 20% (Fig. 6).

The temperature curve inside the
molded part depends in part on mold

wall temperatures. In the variothermal
process, 295 °C hot molding compound
hits a cavity wall that is 40 °C hotter than

in the isothermal process. For this reason,
the cooling rate is slower at the start of
the cooling phase. From the point of view
of polymer engineering, however, this is
an advantage, since initially slower melt
cooling is freer of stress and good for
quality. The molded part later exhibits less
internal stress and only minimal warping.

As the cooling phase progresses, mold

wall temperature remains constant at

100 °C in the isothermal process, thereby

slowing down the cooling process no-

ticeably. In the variothermal process,

however, the cavity is cooled to less than

reference temperature. Thus the average

mold wall temperature during a cycle is

lower in the variothermal method than

the corresponding average temperature

in the isothermal process. In the end, this

leads to shortened cooling time.

In order to realize correspondingly
short cooling times in concert with dy-
namic heating, an efficient cooling sys-
tem is required, e.g., one which is based

on liquid and/or gaseous media. These
can be fed in during the cooling phase

through contoured tempering channels

inside the mold insert or directly through

tempering channels created in the ce-

ramic. Simply by putting the cooling

channels close to the cavity increases the

heat exchange surface as much as three-

fold compared to conventional boring
techniques, thereby reducing cooling time by 50% and more. The indirect en-

ergy savings thus achieved are also con-

siderable.

Fig. 6. Cool-down curves in iso and variothermal processing, each at the center of the molded part

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duced by using heating elements made from the new material. Last but not least, being able to exercise creativity when designing heating elements holds untapped potential for polymer processing, such as for processing reactive systems and crosslinked molding compounds such as duroplasts and elastomers or for combining hard and soft materials in multi-component technology.

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