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Tailoring the heat transfer on the injection moulding cavity by plasma sprayed ceramic coatings

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Abstract. Inhomogeneous material shrinkage in injection moulding can cause warpage in thermoplastic components. To minimise the deformations of the injection moulding parts, the heat transfer during the cooling phase can be adjusted according to the local cooling demand on the surface of the mould cavity by means of plasma sprayed coatings with locally variable thermal resistance over the surface of the mould. Thermal resistance is a function of thermal conductivity and thickness of the coatings, where thermal conductivity of thermal barrier coatings can be adjusted by altering the chemical composition and the microstructure, which is depending on the thickness. This work evaluates the application of plasma sprayed coatings with variable thickness as thermal barrier coatings in the mould cavity. The thermal resistance of the coating and thereby the heat transfer from the melt into the mould will be influenced locally by varying the coating thickness over the cavity area according to the local cooling demand. Using the laser flash method, the thermal conduction of coatings with different thicknesses will be determined. On the basis of the experimentally determined thermal conduction, the effect of the coatings on the temperature field of the mould cavity will be numerically calculated and the required thickness distribution of the coating for an optimal temperature gradient will be determined.

1. Introduction

Injection moulding is a manufacturing process which allows the production of plastic parts with complex geometries and high reproducibility. During the injection moulding process, plastics granulates are plasticised under high temperatures and shearing stresses. The melt is afterwards injected under high pressure into the mould. As the molten plastic flows from the cavity gate deeper into the mould, it cools down as a result of the heat transfer from the hot molten plastic to the comparably cool cavity walls. Due to the difference in flow length and geometric shapes, this typically results in a non-uniform temperature distribution within the mould cavity. The plastic part is created by the solidification of the molten plastic inside the mould. Due to the inhomogeneous material shrinkage, caused by the non-uniform temperature and pressure distribution within the mould cavity, warpage is induced [1]. Therefore, the avoidance of different shrinkage potentials inside a moulded part is necessary to ensure a dimensionally accurate part. One way to achieve net shape production of the plastic parts is to compensate the warpage by altering the mould cavity geometry. Warpage can also be reduced by maintaining a more appropriate temperature distribution in the mould cavity as the cavity is filled with molten plastic and cooled down. Figure 1 illustrates the warpage behaviour for varying temperatures of the cavity while keeping a constant core temperature. Due to the asymmetric

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cooling, different shrinkages occur locally resulting in warpage. In figure 1 it can be observed, that even low differences in temperature can result in respectively high warpages.

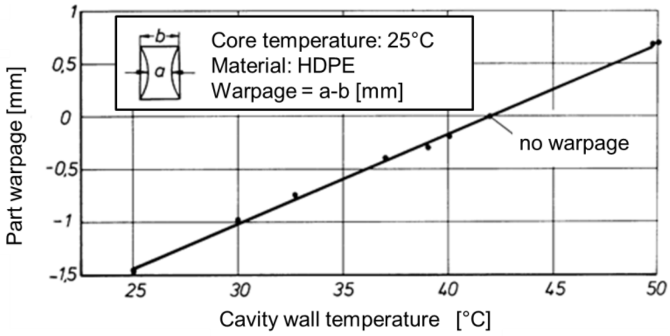

Figure 5: Warpage at constant core temperature and variable cavity wall temperature [2].

To ensure uniform cooling of the part, great effort is spent on the design of cooling channels. Highly complex and conformal cooling channels are implemented inside the injection mould to enable an adequate temperature distribution [3]. New approaches are the inverse thermal mould design, where the location of the cooling channels in the mould is based on the local cooling demand of the plastic part and the use of a self-optimising temperature control to adjust the solidification actively within the process runtime [4]. For both of these techniques, a manipulation of the local specific volume is performed, since the shrinkage potential of the plastics material is directly correlated to its density. This manipulation is achieved by controlling the local temperature by a static tempering layout or an active tempering technique.

This work aims at creating a ceramic coating on the mould cavity to serve as a thermal insulation layer to be used numerous times in production. This paper presents a novel approach for achieving an adjusted temperature distribution on the surface of the mould cavity by employing an air plasma sprayed coating with its thickness adapted to the cooling demand of the given injection moulding process.

Air plasma spraying (APS) is a technological variation of the thermal spraying process which is used to coat various surfaces with a great variety of materials. Electrical energy is converted into heat energy within a plasma generator with the help of an electrical arc, resulting in a highly energetic plasma flame at the nozzle, which can reach temperatures up to 20,000 K. Powder particles are injected into the plasma flame, accelerated and heated up and then impinged on the surface of the part creating a coating. This results in a complex coating microstructure, which does not necessarily exhibit constant porosity throughout the coating thickness. Therefore, the thermal conductivity of the coatings can show slight differences depending on their thicknesses [8, 9].

High temperatures in the APS allow the processing of ceramic powders and manufacturing thermal barrier coatings (TBC). Due to their low thermal conductivity and high melting point, ceramic TBCs are often used for thermal insulation of parts that are subjected to high-temperature environments. In this study, a ceramic coating with varying thickness will be developed to be used in injection moulding. To influence the cooling rate of an injection moulded part, a mould insert can be locally coated to achieve a targeted heat transfer. By adapting the thickness distribution of the coating according to the cooling demand of the plastic part, a more uniform temperature distribution inside the cavity can be achieved. This can enable the reduction of undesirable warping of the plastic components.

The thickness distribution of the coating necessary to achieve a more uniform temperature distribution on the surface of the mould cavity is first determined by simulating the injection moulding process and obtaining the temperature distribution at the mould cavity. Figure 6 illustrates the temperature distribution in the mould cavity which refers to a simulation from a previous work [9], which was further developed in this work. It can be seen that the temperature of the mould cavity decreases along the direction from the gate opening towards the end of the cavity. In order to compensate the heat loss towards the end of the cavity, a linear coating thickness distribution is applied, which has its minimum thickness at the gate opening and maximum at the cavity end.

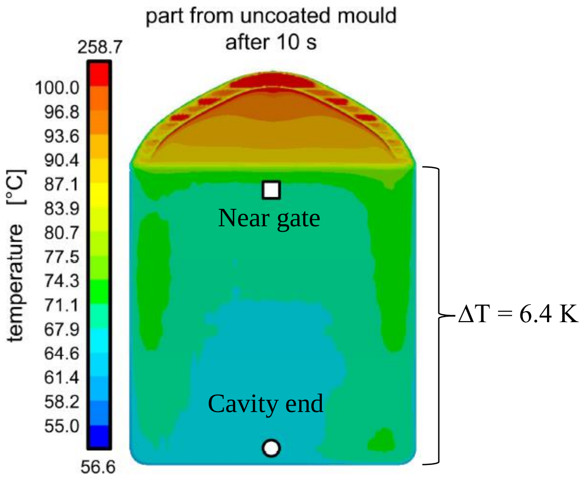

Figure 6: Temperature distribution on the cavity mould after 10 seconds of injection [10]**.**

It should be noted that the thermal conductivity of the coating is expected to be slightly different at different coating thicknesses. This is due to the fact that over the course of the spraying process the substrate is heated, thus influencing the splats formed at the particle impact, which in turn can affect the porosity of the coating. In order to identify the significance of this difference, the thermal conductivity of the coating will be measured for 5 different coating thicknesses. Based on the experimentally determined thermal conductivity of the coating, the injection moulding process will be simulated with the determined thermal insulation of the coating in order to analyse the effect of the coating on the temperature distribution on the surface of the mould cavity. The following section will address the manufacturing process of the TBC with varying thicknesses and the determination of its thickness dependent thermal conductivity. The next section will present the simulation of the injection moulding process and illustrate the effect of the varying thickness TBC on the process. The paper will be concluded with a summary and an outlook to further applications of the varying thickness TBCs in injection moulding process.

2. TBC with variable thickness

Yttria stabilised zirconia (YSZ) powder with particle size of -90+16 µm is used for the coating of an iron-based substrate with the dimensions of 95x20x3 mm with the plasma generator TriplexPro^{TM}-210 (Oerlikon Metco Europe GmbH, Hattersheim, Germany) using the parameters given in Table 2. The varying thickness distribution was realised by adapting the passage numbers to the locally required thickness. The thickness distribution of the coating with varying thicknesses was determined with a 3D laser scanning confocal microscope Keyence VK-X210 (Illinois, USA) and is shown in Figure 7. The thickness distribution at the thinnest part of the coating is not displayed due to the limited measurement range of the confocal microscope. The varying thickness distribution of the coating was assumed to be linear for simplicity. It is possible to achieve a smoother thickness variation by polishing the coating surface, which is a standard procedure depending on the application. The manufactured coating with varying thickness will serve as a basis for the simulation of the injection moulding with coated mould cavity in the following section.

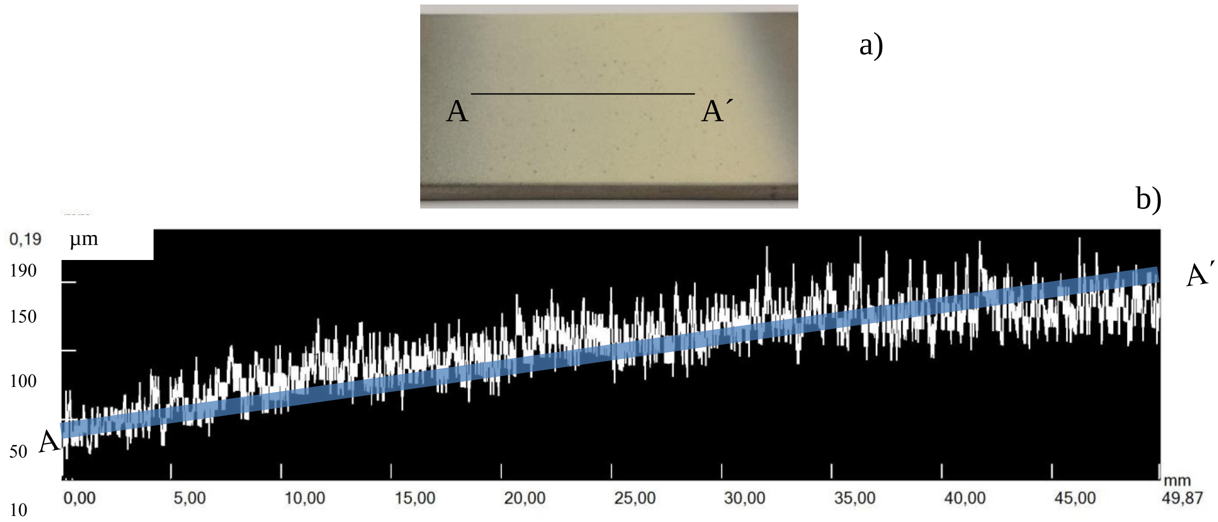

Figure 7: YSZ coating with varying thickness and its thickness distribution measurement the line AA´.

In order to take into account the deviations in the thermal conductivity of coatings with different thicknesses, coatings with uniform thicknesses of 24, 48, 72, 120 and 170 µm were sprayed with the same process parameters as the coating with the varying thickness. An example of a cross-section image of the coatings is illustrated in Figure 8. The coating illustrates a fairly homogeneous thickness distribution over its length and a homogenous porosity distribution over its thickness.

Table 2: Spraying Parameters.

Parameter	Value
Current	450 A
Argon	60 SLPM
Nitrogen	8 SLPM
Spraying distance	120 mm
Nozzle	9 mm

The thermal diffusivity of each coating is determined according to the laser flash method with a Flashline^{TM} 4010 (Anter Corporation, PA, USA) at 80˚C which is a typical temperature during the cooling phase in the injection moulding. Each of the 5 coatings with different thicknesses and an uncoated substrate were prepared as specimens with a dimension of 10 mm x 10 mm x 3.1 mm. The top and the bottom faces of the specimens were sprayed with a thin layer of graphite suspension in order to improve the absorbance of the laser. The laser flash method consists of shooting a laser beam at the top surface of the probe and measuring the temperature on the bottom surface. Thermal diffusivity of the probe is then calculated by means of the time to the half maximum of the temperature of the bottom face and the thickness of the probe. Thermal conductivity was calculated using the measured thermal diffusivity, the density and the specific heat capacity of the material [11]. The effect of the substrate was taken into account with the help of the measurement of the uncoated substrate. Thermal conductivities of the coatings with different thicknesses did not show a significant correlation with their thicknesses because the scattering of the measurements was rather high in comparison to the slight variation in thermal conductivity values that was expected for the coatings with different thicknesses. The average value of the measured thermal conductivities for all measurements was determined to be $\lambda_{coating}$ = 1.1 W/mK. This value corresponds well with porous YSZ coatings sprayed by air plasma spraying by Schlichting et al. [12] and is used in the simulation of the injection moulding process, which is described in the following section.

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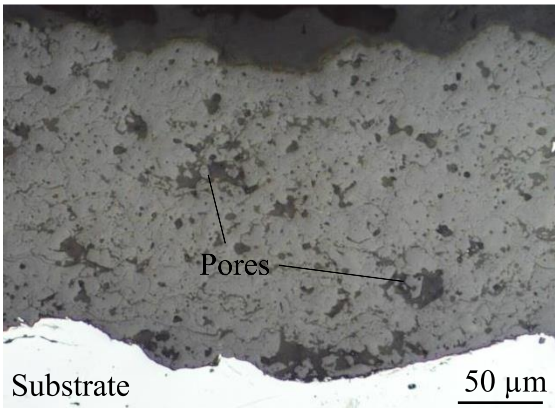

Figure 8: Cross-section picture of the coating with a thickness of 120 µm.

3. Effect of variable thickness coating on the cavity temperature

The manufactured coating with varying thickness was taken as the basis for the simulation of the injection moulding process with a coated mould cavity. In the simulation, the thickness of the coating is zero at near the gate opening and increases linearly in 10 steps up to 170 µm at the cavity end. Its thermal conductivity was set to $\lambda_{coating}$ = 1.1 W/mK according to the measurement with the laser flash method.

To analyse the effects of the coatings on the processing of injection moulded parts, simulations have been performed using injection moulding simulation software SIGMASOFT by SIGMA Engineering GmbH, Aachen. Modelling extremely thin elements with finite element and finite volume methods leads to a high element count as well as numerical precision issues. This is due to the mapping of the elements to a standardised element, which is used for the discretisation of the governing differential equations. To avoid both issues, the impact of the resulting thermal conductivities is modelled by a representative heat transfer coefficient (HTC). At first, a representative HTC was chosen to model a macroscopic contact without the coating. The initial heat transfer coefficient was chosen in a range recommended by the simulation software. For the first trials, a heat transfer coefficient of $\alpha = 1{,}000\ \mathrm{W}/m^2\mathrm{K}$ has been used for the whole contact area between part and mould. The heat transfer occurring as a result of the employed HTC value is translated into a reference thickness for a hypothetical insulation layer made of air. Figure 9 shows the geometric approach, which has been used to describe the heat transfer between part and mould. The representative HTC between the part and the mould steel should include the effect of the air layer and the coating. This is achieved by coupling in series the thermal resistances of the air layer and the coating, and then translating the combined thermal resistance into locally varying representative HTC values.

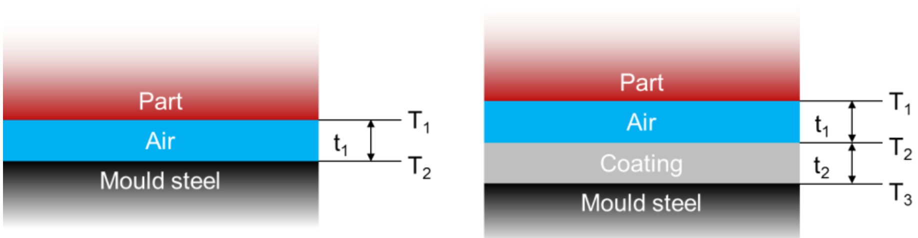

Figure 9: Geometrical simplification for the determination of heat transfer coefficients.

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In a first step, based on the prescribed heat transfer coefficient of 1,000 W/m^2K and equations (1) and (2), resulting from the Fourier's law and the definition of the heat transfer coefficient, a representative air layer thickness of 0.0262 mm is determined.

$$\dot{q} = \alpha \cdot (T_1 - T_2) = \frac{\lambda_{\mathrm{air}}}{t_1} \cdot (T_1 - T_2) \tag{1}$$

$$t_1 = \frac{\lambda_{\mathrm{air}}}{\alpha} \tag{2}$$

where $\dot{q}$ denotes the heat flow, λ thermal conductivity, t_{air} the thickness of the air layer and $T_1 - T_2$ the temperature difference. In a second step, using Equation (3) and (4), the heat transfer is defined with the help of the total thermal resistance R.

$$\mathrm{R} = \sum \frac{t}{\lambda} = \frac{t_1}{\lambda_{\mathrm{air}}} + \frac{t_2}{\lambda_{\mathrm{coating}}} \tag{3}$$

$$\alpha_{total} = \frac{1}{R} \tag{4}$$

To include the heat transfer coefficients into the injection moulding simulation the mould surface has been separated into 10 discrete regions. Each region with different theoretical coating thicknesses is assigned with corresponding heat transfer coefficient. The theoretical coating thicknesses have been selected to be linearly increasing along the direction from the gate opening up to the end of the cavity. The corresponding position, coating thicknesses and calculated HTCs are given in Table 3.

Table 3: Discretised coating thickness and heat transfer coefficient.

Distance from P near the gate opening in Figure 10 [mm]	Coating thickness [µm]	Heat transfer coefficient [W/m^2K]
8.5	8.5	992.33
25.5	25.5	977.34
42.5	42.5	962.80
59.5	59.5	948.68
76.5	76.5	934.98
93.5	93.5	921.66
110.5	110.5	908.72
127.5	127.5	896.13
144.5	144.5	883.89
161.5	161.5	871.98

For the injection moulding simulation, a plate shaped sample geometry has been used, which is covered by two mould inserts. The plastic material used for the simulation is polypropylene "Sabic PP505P". For the discretisation of the coating layer, one of the mould inserts is split into 10 elements. Afterwards, for each part of the insert, the previously defined heat transfer coefficient is prescribed for the contact between the part and mould insert. Additionally, to cover the whole part, a solid mould is added. The geometric setup of the injection moulding simulation is illustrated in Figure 10.

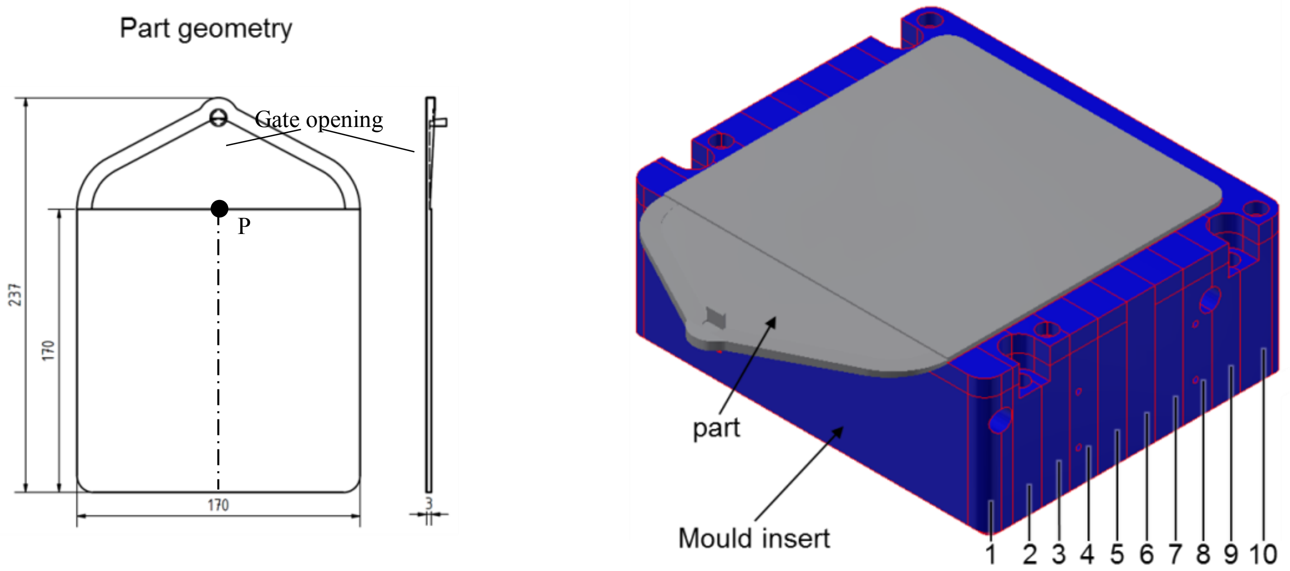

Figure 10: Geometric setup for the injection moulding simulation.

4. Results of the injection moulding simulation

The simulation shows a positive impact on the temperature distribution of the part. In the area where the coating was applied, a more homogeneous temperature distribution is achieved. Figure 11 illustrates the temperature distribution on the part surface, where the coating was applied to the mould insert. The simulation results for the modified mould exhibit a more homogeneous temperature profile. Implementation of linearly rising heat transfer coefficient allows a targeted manipulation of the heat transfer resulting locally at the part surface. As illustrated in figure 1, reducing the temperature difference, which is occurring locally by 2.5 K can lead to significant reductions of warpage, especially considering manufacturing of high precision parts.

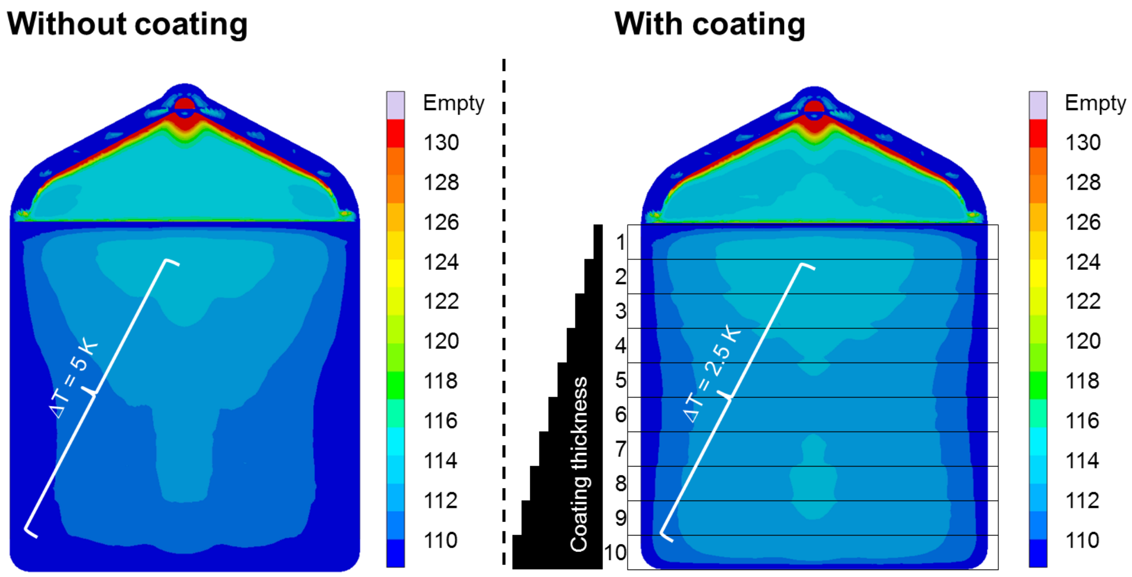

Figure 11: Simulated temperature distribution of the part after 10 s cooling.

5. Summary and outlook

A novel concept for varying thickness TBC for the application in injection moulding was presented in this work. Production of such a coating was presented and the thickness dependent thermal conductivity values for the presented coating were determined by the laser flash method. The contribution of the varying thickness TBC on the heat transfer coefficient in injection moulding process was numerically determined with the help of the experimentally determined thermal conductivity value. Employing the varying thickness TBC influenced the injection moulding process positively by helping to achieve a more uniform temperature distribution on the surface of the mould cavity, thus promising a reduction in warpage of plastic parts. In the future, validation experiments will be performed for these insulation coatings within the injection moulding process. The focus of these investigations will be the analysis of the resulting temperature distribution at the part thickness as well as the durability of these surface coatings with respect to the high temperature and pressure loads occurring in this process. Furthermore, coatings with a more complex thickness distribution will be developed, that will be able to reflect the cooling demand of more complex mould geometries. Due to the local application possibility, only critical positions have to be treated using air plasma spraying. Therefore, when only addressing cold temperature regions, the overall cycle time is not influenced, such that an efficient process with the same cycle time is still given.

Acknowledgments

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