Differentiated Compression Moulding: A new process innovation creates dramatic cost savings and product improvements for compression moulded applications

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Abstract:

Long glass fibre thermoplastics (LGFT) used in compression moulded applications has grown dramatically due to metal replacement by composites and the derived benefits in both cost and weight savings. In order to make thin walled parts from higher viscosity thermoplastic materials as opposed to thermo setting resins, machine producers have been challenged in terms of clamp size and tooling. In this paper a revolutionary new process called differentiated compression moulding (DCM) is described, and compared with traditional compression moulding. Using new tool designs the process allows for reductions in press sizes of up to 70%. This in turn allows for significant cost savings in machine investment, tooling, and energy consumption. Larger projected areas and thinner walled parts can be made on smaller machines. The paper discusses the physics and rheological conditions that allow for this innovation, and a test case is compared to current technology.

Introduction:

At first the material flow in a compression moulding tool would seem to be intuitively obvious, but computerized finite elemental flow analysis described herein will in fact demonstrate the flow patterns and behaviour is not only unclear, but in fact counter intuitive. This work has led us to visualize the basic problems associated with compression moulding in a new way, and problems being the birth place of innovation have allowed the author to innovate a solution that enables the process to become far more efficient.

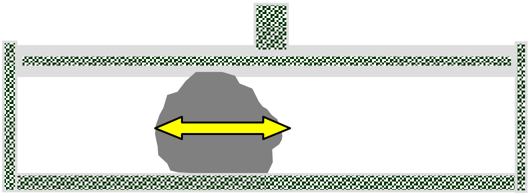
Conventional process:

Compression moulding of plastics has been used commercially for decades, but initially was used for much lower viscosity thermosetting polymers that were better suited to the process. Lately the process is being used more and more with much higher viscosity thermoplastic resins that create a new challenge for the process, especially in larger more complex parts with thinner walls.

To best describe the cause of the challenge, it is illustrative to consider the "spaghetti model" for polymers and what is demanded of the material to form in the tool. One may view the molten blank or cut-off of compound in the tool to be a pile of wet spaghetti with each strand representing the long chain linear molecule. The viscosity of the mass, or its resistance to flow is a function of the length of the strands (molecular weight), the stickiness of the strands to each other (related to the polymer's steric hindrance and polarity) and the stiffness of the strands (function of polymer structure and temperature). These strands must move around and slip over each other in order for the mass to move. This in turn creates the inelastic or non Newtonian nature of polymer's melt flow.

When the blank is dropped into the female or "B side" of the tool, the very first few strands on the outer surface cool immediately and become too rigid to flow. At this point, all flow is from the inside of the blank out, with surface that contacts the tool freezing and creating a coating which does not flow.

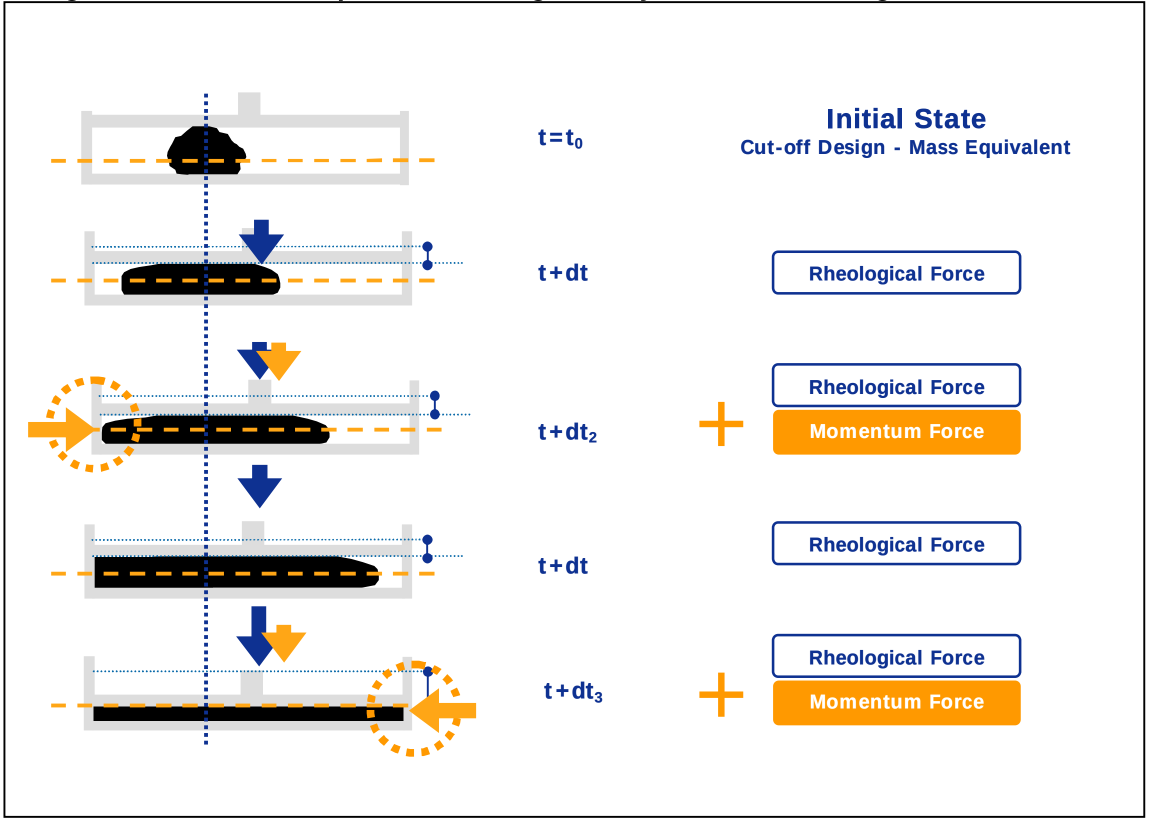
Figure 1. Simple schematic of compression moulding tool



Stepping back to a macroscopic view of the process, in what we will label as phase 1 of the moulding process, the material flows three dimensionally in all directions parallel to but constrained by the walls of the closing tool. Any force back against the A and B sides of the tool is only a function of the polymer's resistance to deformation. This phase is from the initial state to process state $dt_{2.}$

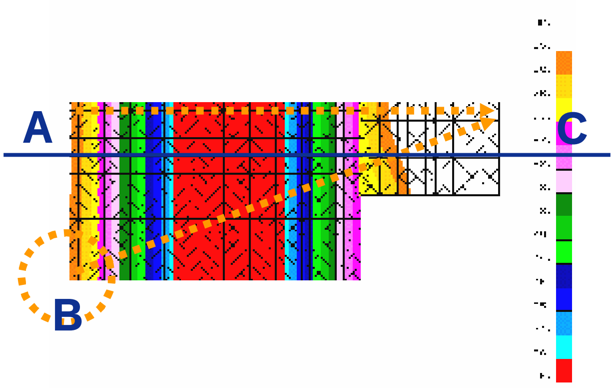
Eventually at process time t= dt_2 the polymer will make contact with one or more tool walls. As the tool is immovable and elastic it imparts a force against the polymer melt front which can be seen as a reflection of the momentum of the polymer melt. This will be seen as a pressure spike (additional Momentum Force) in the process which we label as phase 2 of the process. It can be demonstrated that the melt now flows in the opposite direction with the material flowing from the outer edge to the inside of the mass (left to right).

Figure 2. The different phases of filling a cavity and forces acting



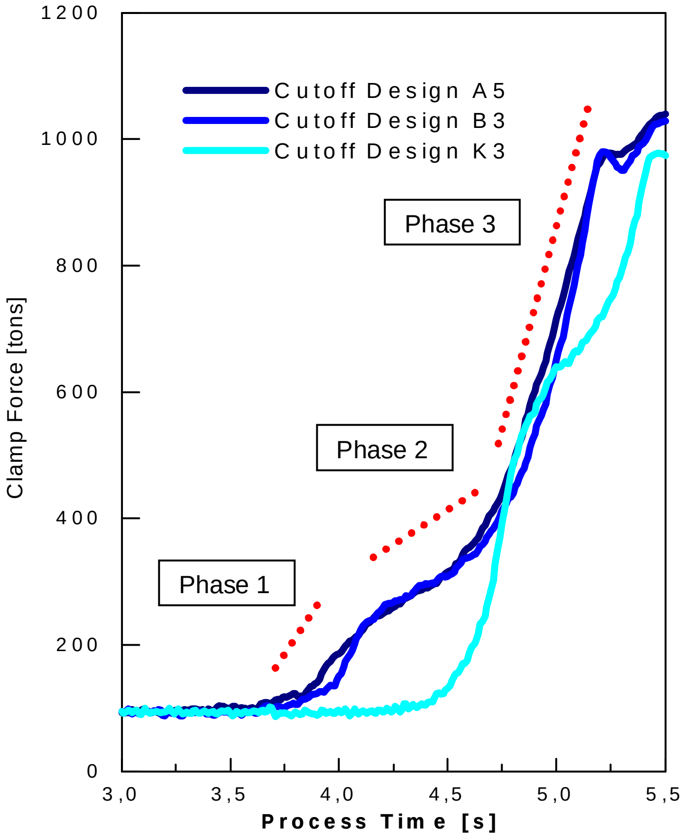
Finally at time dt_3 the material must flow to the final boundaries of the tool. We have labelled this phase 3 for the compression moulding process. The maximum pressure developed here is a function of the maximum flow length in the tool. Note this is not the maximum distance from the initial positioned cut-off to the tool wall, but is a measurement from one end of the tool to the other. As illustrated in figure three it is not the distance **AC** but rather **BC**. It is rather important to mention, that defined relevant distance BC is only related to tool dimensions and not to the position or dimensions of the cut-off design. Due to this matter the clamp force required filling the tool is dependent on the maximum tool dimensions and the material viscosity, but independent of the cut-off position and design (geometry), that is used in the a specific compression moulding process.

Figure 3. Material flow in simple tool illustrating maximum flow length.



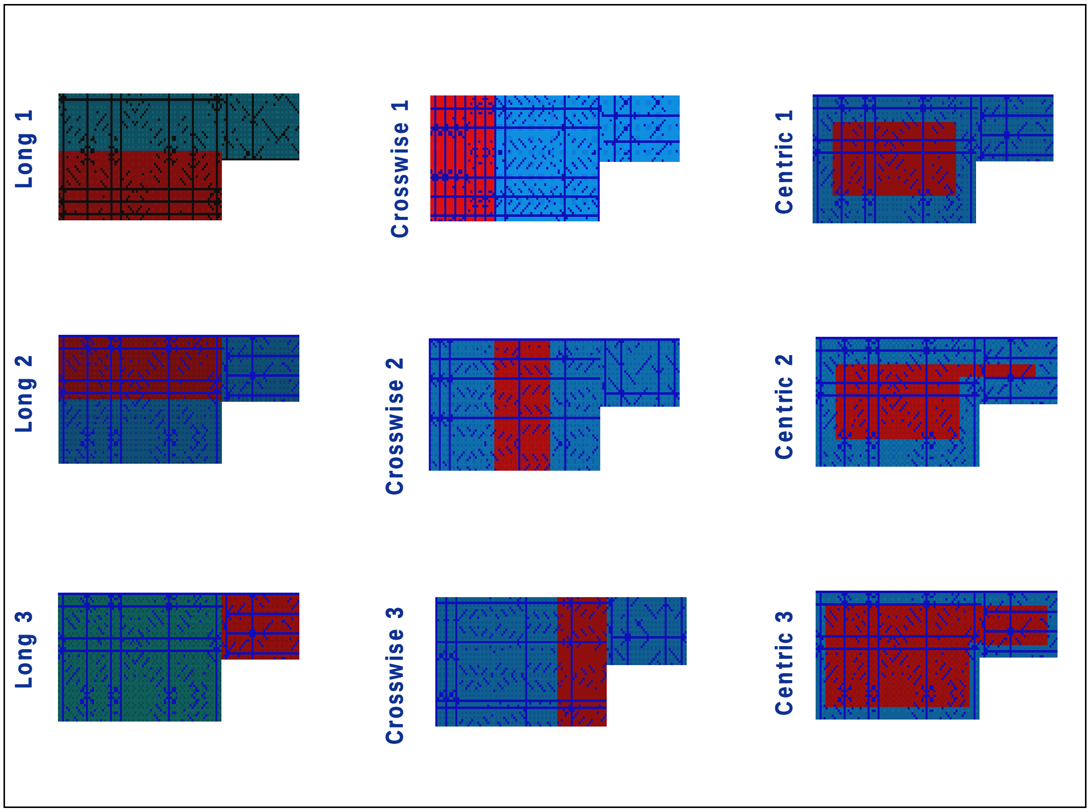
The forces in these three phases are depicted below in figure 4 with the red dotted line representing the process phases we are describing. The momentum force additions are quite significant relative to simple reological forces.

Figure 4. The force to fill for different blank geometries.

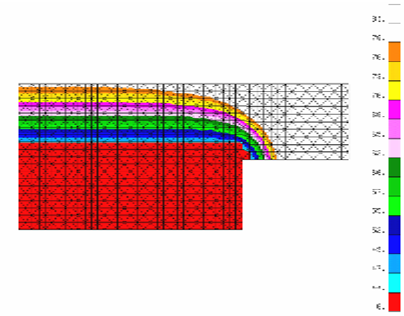


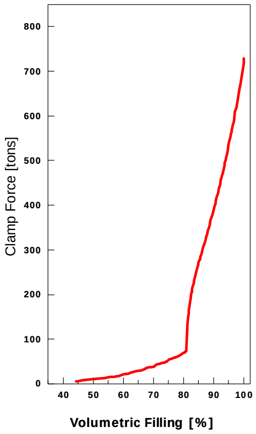
In order to validate that the cut-off position and geometry do not create significantly different required clamp forces for filling the tool cavity, we looked at modifying the cut-off or blank position and geometry, and then running the mould filling analysis with similar process parameters. Those cut-off positions and geometries (red fringed areas) can be seen in figure 5. We have shown here the analysis for four of the nine different geometries. However, in all cases we saw that the maximum required clamp force to fill the cavity was similar, the fill relationship to volume fill was similar, and used about 1/8th of the maximum pressure to achieve 80-90% of the volumetric fill. The idea that blank geometry had very little effect on the overall clamp force and energy consumption to fill was again quite surprising and counter intuitive.

Figure 5. Cut-off geometries with the model based on the material being the red part of the tool in the initial state as well as several models

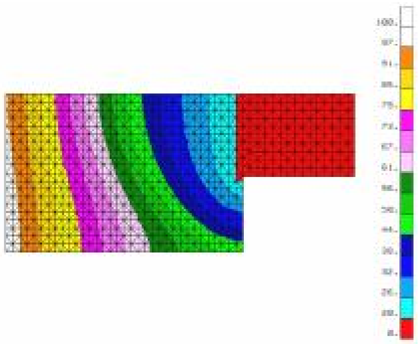


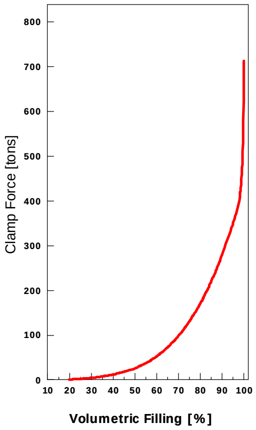
Filling forces of Long 1



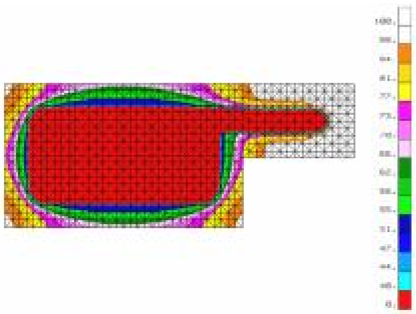


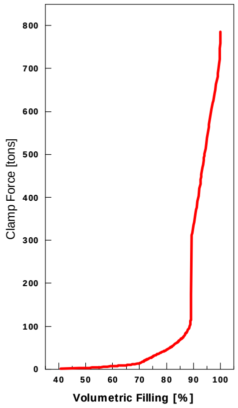
Filling Forces for long 3



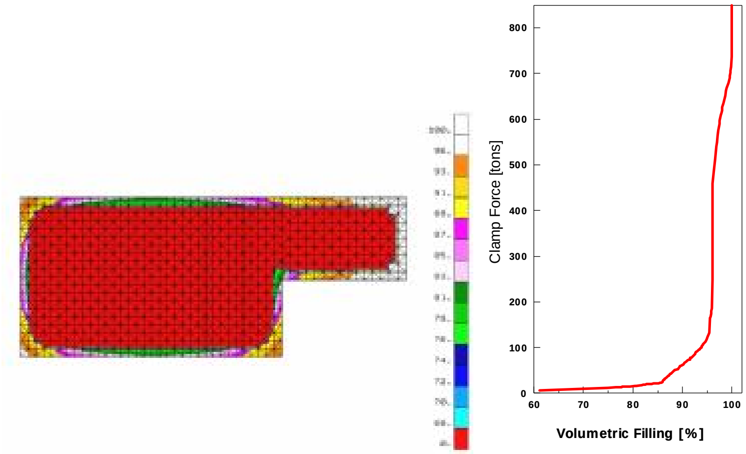


Filling forces for Concentric 2





Filling forces for Concentric 3



This information allowed us to draw several conclusions about the conventional compression moulding process at its current state of the art:

- The clamp force required for pure Rheometric flow is very low relative to the total clamp force required.
- Momentum forces come additionally into existence any time a flow front dynamically strikes a cavity boundary. These momentum forces are required to force the material flow to another (opposite) flow direction. These momentum forces are quite high, and are the ultimate challenge for required press size of moulding machines.
- Clamp forces (machine size) are related to the positions of the cavity sections which are last filled by the polymer melt. Required clamp forces (machine size) of different cut-off positions or designs will not matter significantly.
- Due to the momentum forces and the change of the polymer flow directions the conventional compression moulding process is not is not energy efficient, and is difficult to control.

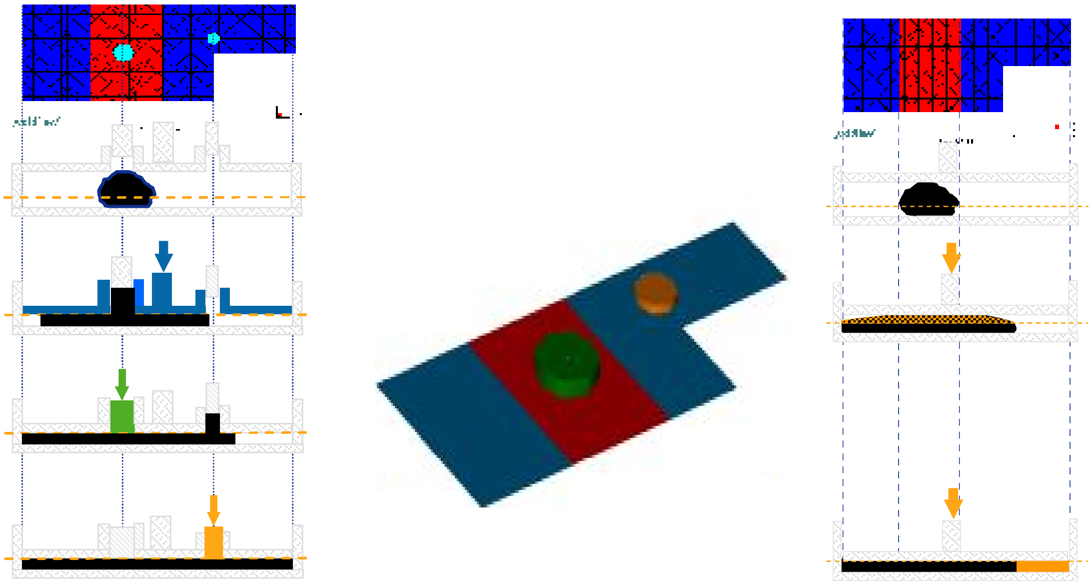
Processing problems are mainly caused by the existence of momentum forces and due to the “incompatibility” of the polymer flow. The incompatibility of flow defines all required flow direction changes of the conventional compression moulding process until the cavity is totally filled.

Differential Compression Moulding Process (DCM)

With these problems in mind the question was how to minimize the momentum effects and reduce the force requirement to fill a cavity. Problems in effect are opportunities to innovate, and it was determined that there is a better way to move the material to the last sections to fill rather then attempting to drive the motion throughout the entire mass. The process has been patented under patent number EP 1 019 232 BI, and we believe offer the processor the chance to make a step change in the performance of their equipment, and to offer better part solutions to OEMs.

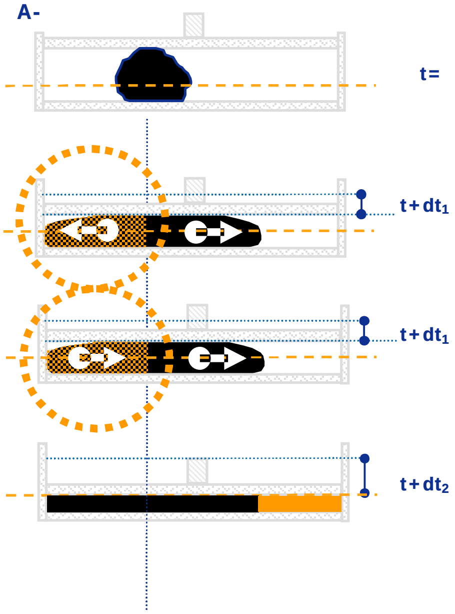
The innovation is to simply make available molten material at precisely where it is needed and when it is needed in order to minimize the final flow distance without depending on forcing the flow though the rest of the cavity. In Figure 6. We illustrate in a drawing the concept using a simple part geometry. Basically what is proposed is locating material reservoirs temporarily in the A or B side of the tool (cavity). The reservoirs or “shot pots” are filled from the blank during phase 1 and or 2 of the moulding process automatically. At the appropriate time the resin is pressed from the reservoir by pistons. Preferably this will happen at a time when the melt front reaches a cavity boundary. The pistons that drive the resin from the reservoirs may be activated by mechanical means (i.e. levers, slides) or hydraulics in conjunction with springs or other timing devices. Ejector plates may be used effectively for this purpose as well. The reservoirs are used to avoid momentum forces during the process and guarantee a final defined maximum flow length for filling the cavity, which are lower then the maximum dimension of the cavity.

Figure 6 shows a compression mould built for the DCM process on the left as opposed to a conventional tool (process) on the right



The blue sections of figure 6 illustrate the cavity (part), while the red fringed areas illustrate the initial cut-off design in both processes. In the conventional compression moulding process (right figure), the forced movement of the A side of the tool (clamp force) forces the flow of melt until the cavity is totally filled. At the time in the process when the flow front hits the cavity boundaries, the melt is forced to change its direction of flow as illustrated below in figure 7.

Figure 7 Flow directional changes on boundary contact (conventional process)



The orange coloured area illustrates the melt volume, which is forced by momentum to change the flow direction for totally filling the cavity. However, this matter of fact is avoided by the patented DCM process. The first step of the DCM process closes the tool in a manner, by which the melt does not reach any cavity boundary (no momentum forces), but by design fills the first temporary reservoir (green piston). The following process step is performed by the green piston, which empties the temporary reservoir for filling the next section of the cavity (right side) as well as filling the next temporary reservoir further managed by the yellow piston. In this example the controlled movement of the yellow piston guarantees the final filling of the last sections of the already closed cavity. The flow length for this process step is thus minimized.

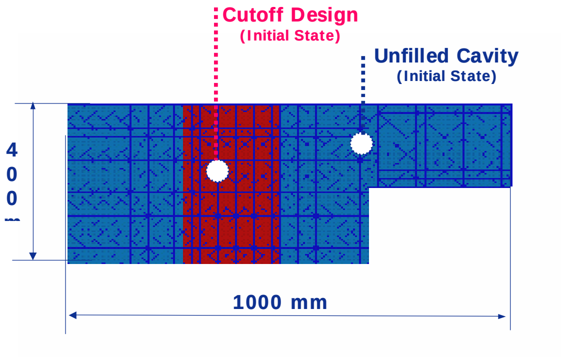
A model was run on the referenced part in Figure 8 considering a conventional compression process and a DCM process with the following conditions:

Material: ***Borealis PPGF30 (30% glass fiber reinforced)***

<u>Process</u>
Melt Temperature: 210 [°C]
Tool Temperature: 70 [°C]
Tool const.Closing speed: 10 [mm/s]

<u>Engineering</u>
Done by: Harald Herbst
Software: Express 4.0
Hardware: HP J200

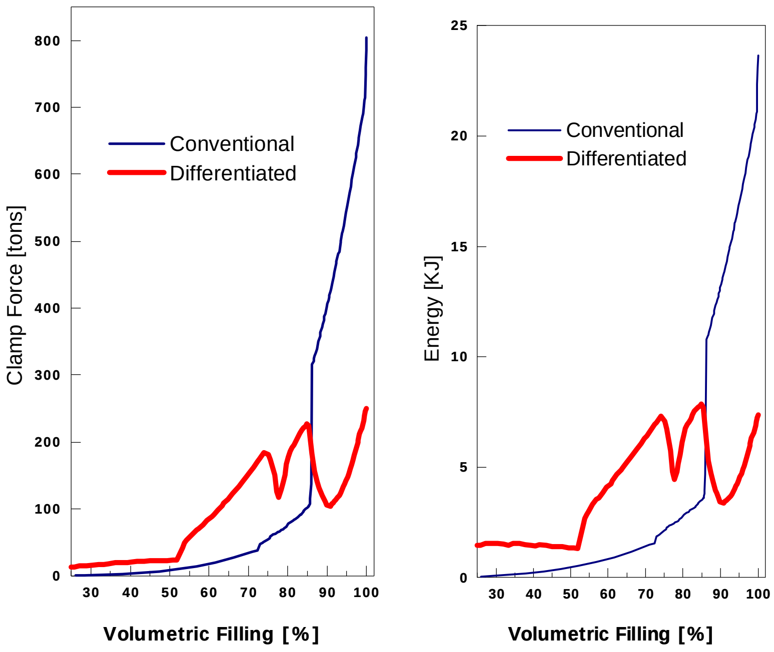
Figure 8 reference part



Thickness: 3 [mm]
Projected Area: 0,34 [m2]
Volume: 1E-3 [m3]
Mass: about 1,0 [kg]

The flow analysis showed maximum clamp force dropped from 803 tons to 248 tons or a 70% reduction in required machine size. Energy consumption dropped from 23.6 KJ to 7.8KJ or a 67% reduction in energy.

Figure 9 shows the required force filling the cavity and energy for DCM in contrast to the Conventional Compression Moulding of illustrated part.

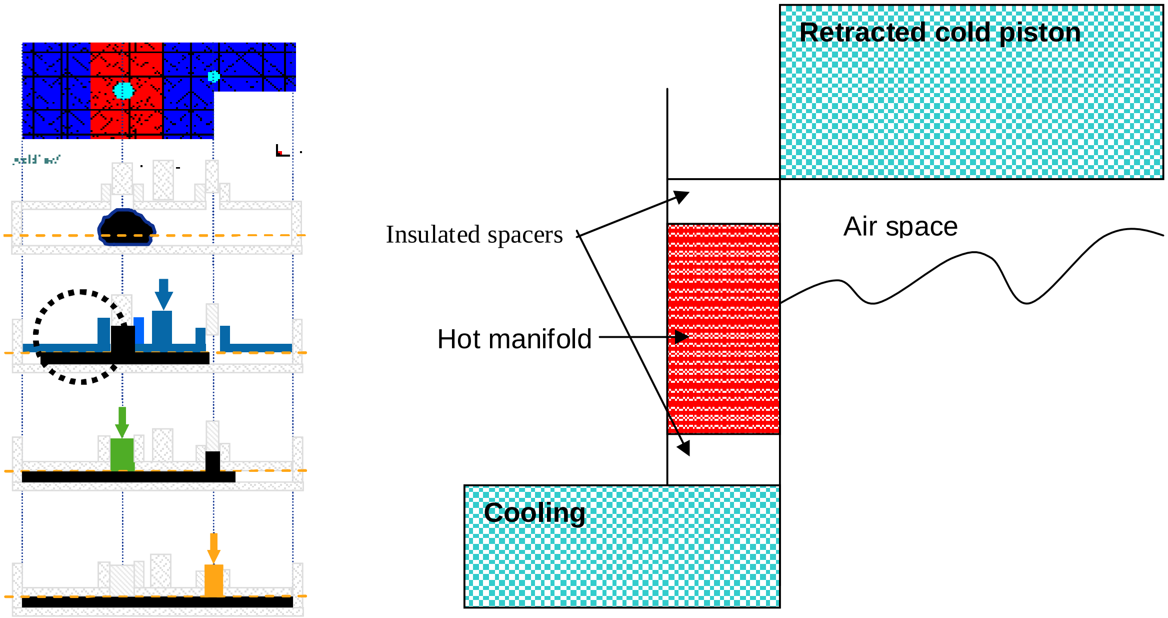


Tips and Traps:

The DCM process promises tremendous potential benefits for processors and designers, but in order to make commercial parts the user will need to run a mould flow analysis to ensure the reservoirs are properly located, and the filling and actuation is properly timed.

Further, the reservoirs may require special attention in tool design. The reservoirs must be warm enough to keep the material in a molten state, and yet the piston becomes a section of the final tool surface, and thus must be cooled to allow full freezing of the part. This can be accomplished by using hot runner/manifold technology to heat the reservoirs and cool the piston. It may be required that the piston surface is deep enough in the retracted position so as to not contact the molten polymer and prematurely cause its freezing. In Figure 10 we illustrate one possible design to consider for a reservoir. There are certainly other tooling possibilities, and these will depend on material properties as well as part geometry.

Figure 10. Possible piston design detail



Conclusion and benefits of DCM:

In principle, the DCM process offers more freedom to control filling of the tool cavity then using a conventional compression or injection compression moulding process. The critical process determining variable (material flow) is controlled directly in the unfilled sections of the cavity instead of being controlled through the entire blank. Due to the temporary establishment of melt reservoirs, the incompatibility of flow no longer creates any negative impact on the process nor the creation of excessive momentum forces. These facts lead to capital cost savings of using reduced machine sizes and may benefit in achievable part qualities. In the example illustrated in current paper, the same part is producible on a compression moulding machine by the use of the DCM process, which is just one third of the current machine size and which additionally may be produced with less then half the energy consumption. Common known industrial process problems such as unfilled cavities may be eliminated. Also, due to the greater freedom to control flow in the cavity, there are additional benefits in the DCM process that are much less obvious and should be considered:

1. Higher viscosity polymers (greater molecular weight) may be used that previously would not be possible for the conventional compression moulding process. These materials will have better properties, particularly impact, and give the OEM greater design flexibility.

2. The pistons, directly positioned in the cavity may better control packing of the material and thus give better control of part dimensions and reduce tendency for part warpage.

3. Freedom to control flow inside the cavity allows the producer to define the orientation of fibre reinforcements of a part, so that the fibre reinforcement is most efficiently used.

4. Freedom to control flow inside the cavity may also be used to move or possibly eliminate welding lines and enhance final part performance.

5. Lower required pressures may allow better use of inserts such as foams and soft surface skins. The process may now be able to compete with low pressure injection moulding in applications such as door and instrument panels.

6. Finally, the freedom of designing parts is increased. Part designs and sizes previously impossible for the conventional compression moulding process may now be possible. Applications that heretofore were moulded by thermoforming or blow moulding such as boats, pallets and load floors may now be suitable for the DCM process using existing machine capacity without modification. This may be the greatest single benefit and should open the way for further innovations in new applications.