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IMPROVEMENT OF THERMOFORMING PROCESS AIMING HIGHER PRODUCTIVITY

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Abstract. *Thermoforming is a widely used polymer processing technique capable of producing in high production rates. In this process, an extruded polymer sheet is heated to its softening temperature and then deformed against a mould to reach a final shape. However, to achieve high productivity associated to an adequate tool and machine life, thermal managing and geometric compliance are key issues. This paper describes four optimization approaches applied to improve the performance of a high productivity thermoforming machine for polypropylene cups production. The use of a PID controller for the sheet heater produced a well-defined and uniform temperature distribution. The cold water flow management through the mould block also produced a well-defined and uniform temperature distribution. The optimization of the mould geometry enhanced the heat transfer. The manufacturing and assembly tolerances allowed a more precise machine operation. After the modifications, the machine showed to be more robust and efficient.*

Keywords: *Thermoforming, Thermal management, Mould geometric compliance, Thermoforming productivity*.

1. INTRODUCTION

Thermoforming is a manufacturing process to produce plastic parts by preheating a flat sheet of plastic to its softening temperature, then bringing it into contact with a colder mould to achieve its shape. To guarantee the contact between the plastic sheet and the mould, in a first stage mechanical stretching is carried out using a plug and then air pressure finishes the task. The sheet is held against the mould surface until become cooled enough to make possible to trim out the formed part from the sheet (Ilig, 2001).

In industrial scale, thermoforming is carried out in automatic machines running - in cycles to reach the expected productivity. This cycle frequency depends on the designed machine operation dynamics and its capability to manage the machine thermal distribution and heat transfer. During use, the machine productivity is also affected by moulds and trimming tool wear. When the machine thermal management is not well done and / or the moulds and trimming tools are not well adjusted or sharp enough, the result is the failure in the trimming stage of the process. Figure 1 shows the occurrence of failure in the trimming stage when producing plastic cups.

Figure 1. Failure in the trimming stage of plastic cups production

Figure 2 shows a schematic magnification of the trimming action. Key factors here are the geometric relation between the knife and the mould and the physical condition of the plastic sheet during the trimming action.

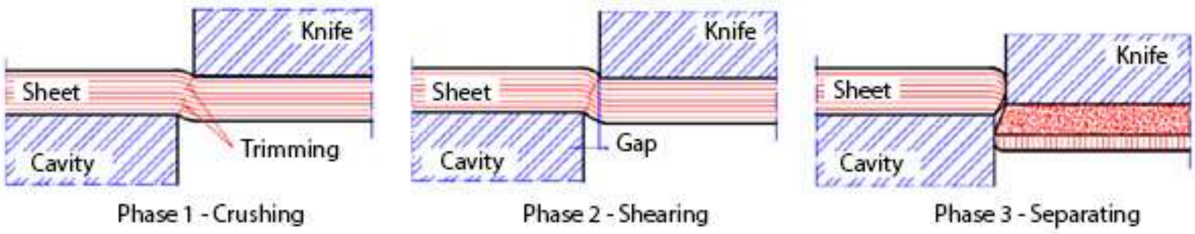

Figure 2. Schematic magnification of trimming action

The gap between the knife and the mould must be uniform around the perimeter in each mould cavity, must stay within a dimensional tolerance to effectively trim the part and must be sharp enough to produce a quality trim.

During the trim action, the plastic sheet cannot stay anymore softened. The contact between the sheet and the mould must provide sufficient heat transfer to cool down the region of interest where the trim action is done over the plastic sheet. This particular factor is the key issue to determine the machine cycle frequency in continuous processing.

As moulds and knifes become worn, the gap increases. Bigger gaps demand harder (or colder) plastic sheets to make possible to produce quality trims. There is a direct correlation between gap conformity and plastic temperature to produce suitable trims.

The ability of plastic material to be shaped by the thermoforming process depends on the rate of change in its mechanical properties due to the change in temperature (Dharia, 2006). Thus, different material behaves differently when submitted to a change in temperature. Each material demands a unique heating and/or cooling cycle to properly be processed by thermoforming. In this project, the thermoforming machine must be able to process both Polystyrene (PS) and Polypropylene (PP).

2. DESIGN PROCEDURE

Based on a design methodology (Back, 2008), the main aspects and functions of the thermoforming machines were evaluated and it was possible to identify four critical aspects of the current machine design that would need to be redesigned aiming to improve the performance of this high productivity thermoforming machine for polypropylene cups production. The four critical aspects are:

- The use of a PID controller for the sheet heater to produce a well-defined and uniform temperature distribution;
- The cold water flow management through the mould block to also produce a well-defined and uniform temperature distribution;
- The optimization of the mould geometry to enhance the heat transfer at the trimming region;
- The redefinition of manufacturing and assembly tolerances to allow a more precise machine operation and working life.

3. RESULTS AND DISCUSSION

The path to improve the thermoforming machine productivity, as presented, involves an adequate thermal control of the machine and a high quality dimensional and form level of the tooling. Each aspect was detailed discussed and will be presented as follow.

3.1 Thermal control of the heating oven

The heating oven is responsible for delivering a thermal load that allows obtaining a uniform temperature range in the sheet of polymer material to ensure optimal conditions for the softening and conformation of this sheet during the process.

The sheet heating should ensure an optimum temperature throughout the volume of the material, thus avoiding significant differences in temperature, for example between the edges and the center of the sheet. The local temperature and humidity conditions can also influence the attainment of this equilibrium, as well as changes in the processing speed of the machine. Therefore, a strict control of the heating radiation emission is necessary.

In order to evaluate the effectiveness of the oven temperature control, as well as the heating time, an oven with the same size and in real conditions of operation was set up to test different heating control strategies. A proportional-integral-derivative (PID) controller was modeled and tested also as a P (proportional) and PI (proportional-derivative) controller, and the results obtained based on a target temperature with an error lower than 1ºC showed different results of response time and capacity of control, as can be observed in Figure 3.

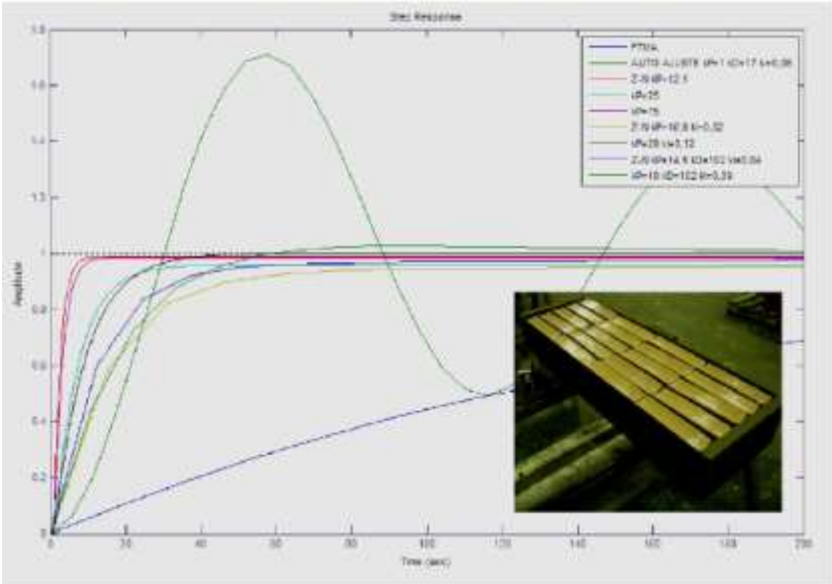

Figure 3. Modelling of the oven response based on different control parameters

In most cases, the use of PID control modules in resistance heating elements banks is efficient because there is no sheet temperature feedback in the control parameters. Instead, only the resistance heating elements temperature feedback is achieved from thermocouples installed in specific resistance heating elements called pilots. A typical organization of the resistance heating elements bank in the heating ovens can be seen in Figure 4.

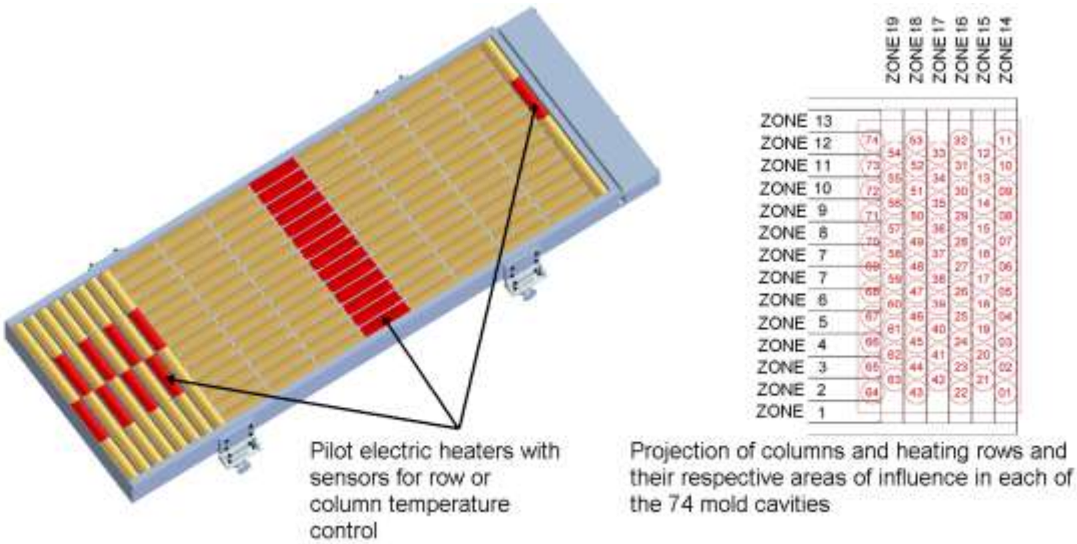

Figure 4. Resistance heating elements banks and configuration of heating zones

The number of pilot resistance heating elements and their arrangement in the oven depends on the dimensions of the tooling and the thermal stability of the heating oven. The modeling of the oven's thermal behavior proved to be quite faithful to its actual behavior. With efficient control, the machine is able to maintain optimum operating characteristics under any manufacturing environment conditions.

3.2 Thermal control of the tool cooling circuit

The temperature control for the tool cooling is made by the temperature control of the coolant passing inside the cooling channels. A pump feeds the circuit and the water is cooled in an external chiller, which maintains a constant temperature in the tank. As the thermal demand increases, so does the cooling load on the liquid chiller. Figure 5 shows the cooling circuit subdivided into lines or extensions, where each branch refers to a longitudinal row in the tooling.

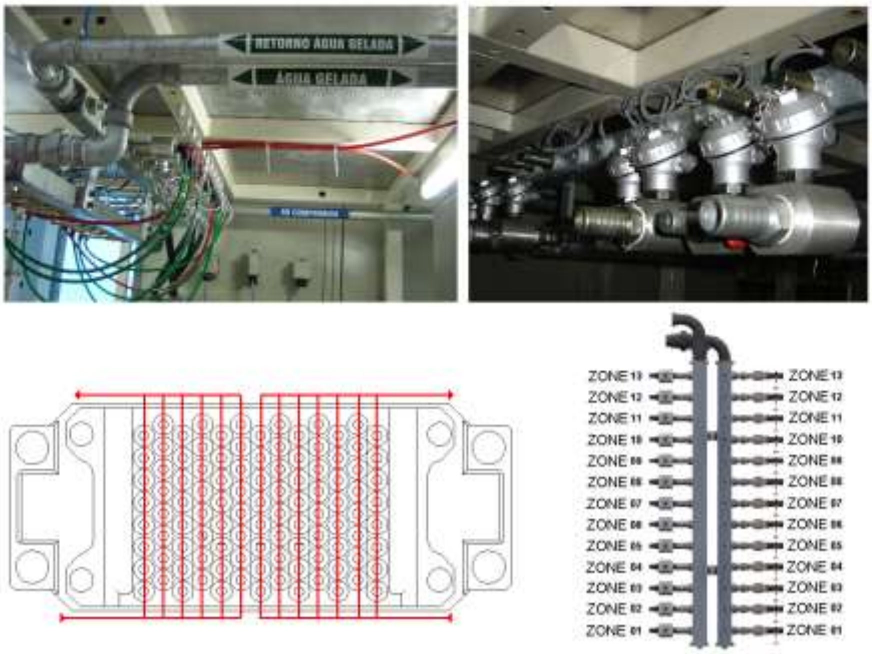

Figure 5. Circuits e cooling zones monitored by sensors and controlled by valves

Valves control the flow of coolant through each channel and this flow has its temperature monitored by thermocouples. The system proved to be efficient after manual settings of the coolant flow. An experienced operator performed these settings, but the ultimate goal is to have a specific automatic controller to ensure temperature uniformity in all regions of the tooling from valves controlled electrically.

3.3 Mould geometry optimization

The search for temperature uniformity in all regions of the tooling ensures controlled and steady operation in all available cavities, but does not guarantee the proper rate of heat withdrawal in the most critical region of the mold, which is the cutting cavity, responsible for the trimming and correct separation of the processed material.

Aiming to make the cutting edge cooling more efficient, a study based on finite elements was carried out to identify the real conditions of heat exchange in this region of interest, as well as the possible improvements to be implemented in the geometry of the cavity, its cutting edge and its interface relationship with the other components of the tooling. A demonstration of the obtained results can be observed in Figure 6, where the boundary conditions used (Figure 6a) and the obtained base result (Figure 6b) are presented for the geometric condition tested.

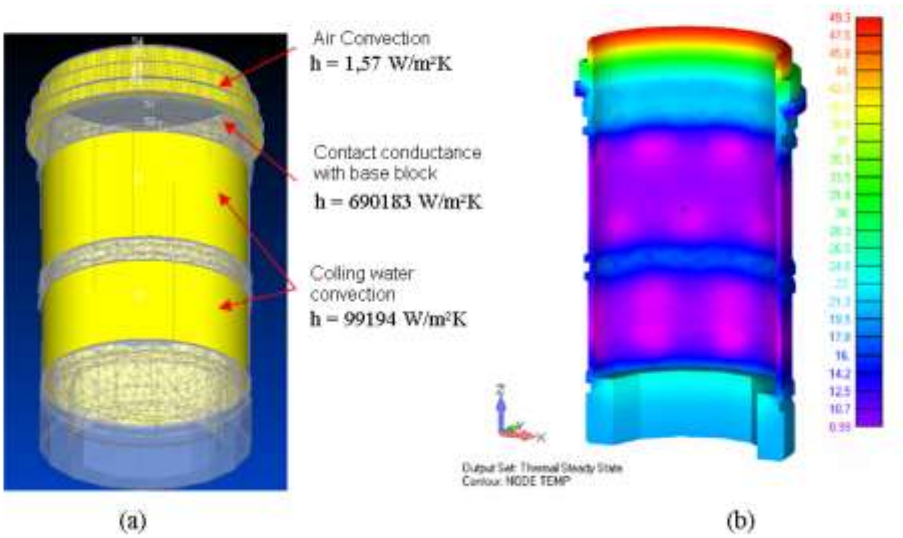

Figure 6. Numerical simulation of the tooling thermal behavior. (a) Boundary conditions, (b) Base result

The successive simulations with different geometries led to the definition of a more appropriate geometric condition of the tooling, which allows a better efficiency in the heat exchange at the cutting edge and, consequently, a higher productivity of the machine.

3.4 Dimensional management

Large-sized tooling, such as that used by high productivity machines, undergoes larger temperature gradients during the process. Therefore, in addition to the need for temperature uniformity of the tooling, both its design, manufacturing and assembly must comply with narrow quality parameters aiming at a smooth operation and the longest lifetime as possible during its continuous operation.

The definition of clearance between the cavity and the knife should ensure efficient shear cutting. In addition, the shape error on the two relative cutting surfaces must be small enough to ensure that this clearance remains constant throughout the perimeter of the tool. This leads to the definition of very narrow design tolerances in the critical tooling regions.

Setting these tolerances alone does not guarantee the quality of operation and long machine life. It is necessary that the manufacture and subsequent assembly comply with these tolerances and, above all, ensure that the individual cavities have an adequate geometric relationship so that the products result in the desired quality.

In order to obtain this final quality, the tooling was all designed based on GD & T tools to ensure appropriate references for the manufacturing, assembly and dimensional control of each component. In addition, component fixture solutions were developed during its manufacture in order to reduce distortions caused during machining and to obtain some degree of repeatability in the successive pieces produced for the tooling encompassing all the machining steps from roughing to finishing steps. Finally, specially developed mounting templates aided in the assembly process by ensuring faster operation and minor relative positioning errors between the parts.

All these actions contribute to ensure less machine stresses during the operation and a longer tool life.

4. CONCLUSIONS

The failure in the separation between the thermoformed product and the polymer sheet significantly impairs the efficiency of the process and the quality of the products obtained. A detailed study of the main causes for this failure in separation led to the definition of thermal management and dimensional control as the main factors that influence this problem.

The detailed heating conditions of the material sheet and the cooling of this sheet together with the tooling made it possible to propose suitable control solutions to guarantee uniformity in the thermal changes during the process. In addition, significant improvements were achieved in the tool cutting edge cooling through finite element simulation of different tooling geometries in this critical region.

An adequate treatment of the geometric and shape tolerances of the tooling, associated to a more rigid control and with better defined references for manufacturing and assembly of its components, allowed the tooling to reach a global geometric condition more adequate for the operation and the increase of the life of machines.

These solutions indicate an important path for the optimization of the thermoforming process for the manufacture of disposable cups, but it does not exhaust the possibilities of improvement. New tool geometries, the use of more efficient technical materials and the possibility of cavity instrumentation for real monitoring of the conditions encountered during the process are ways that can still be better explored to further improve the process.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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