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Methods to improve thin-wall plastic injection molding process

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To my family

Acknowledgments - Ringraziamenti

- I split this text in both languages (Italian and English) in order to allow to everybody to read it.

- Ho diviso il testo in entrambe le lingue (italiano e inglese) in modo da consentire a tutti di leggerlo

English

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Summary – English Version

This thesis has been carried out in the context of the Leonardo da Vinci project that consists of abroad work experience for a six-month time period.
The experience took place in the TECOS which is the main Slovenian institution for research and development created by the Slovenian government to support small, medium and large industries in their own country.
During the whole experience, different issues and relevant projects have been developed, including the international Eoltecco project concerning the design of a micro wind turbine. In any case the choice of the thesis is relapse in the field of injection molding because is the branch most developed and consolidated by the Company.

The aim of this thesis is to use methodologies of systematic problem solving approach, applying them to a particular field of plastic injection molding; the Thin-Wall Injection Molding.
This method involves several disciplines which the main one is the TRIZ.
The purpose of systematic analysis is not to provide a specific solution to the problem, but to give alternative solutions for a future design of a mold-machine system.

First the problem analysis wants to identify main process parameters that intervene in the generic injection molding cycle. This leads to divide them into manageable parameters and not-controllable parameters.

Not-controllable parameters are directly responsible for the botched of Thin-Wall Injection Molding process. Thus the current solutions are shown.

At this point the systematic problem solving approach comes in. It will provide many ideas and solution strategies that are targeted but still on ideal-level. These solutions are the basis for a specific design of a new future system, and must be inspected according to particular needs.
As a result, new design of system based on the results from the investigated TRIZ analysis is now scheduled by TECOS.

In the last phase experiments and simulations are carried out. This phase is "more practical" than the previous one. Purpose of this phase is to primarily validate the claims asserted by the analysis above. Moreover meant to show whether, and how, prediction of the process parameters can be made at the design stage.
The last phase was carried out by the available resources in the TECOS Company that is one of those Companies in each cutting edge about injection molding area.

In this context, the thesis takes an additional validity because various experiments and relative simulations are useful important results for another international project in which the TECOS Company has the leading role.

Sommario – Italian version

Questa tesi è stata portata avanti nel contesto del progetto Leonardo da Vinci che è consistito in una esperienza di lavoro all'estero della durata di sei mesi.
L'esperienza si è svolta alla TECOS che è la principale istituzione di ricerca e sviluppo creata dal governo sloveno per supportare piccole, medie e grandi industrie della propria nazione.
Durante l'intera esperienza sono state sviluppate diverse tematiche e relativi progetti tra cui il progetto internazionale Eoltecco riguardante la progettazione di una micro turbina eolica. In ogni caso la scelta della tesi è ricaduta nel campo dello stampaggio della plastica è il ramo dell'azienda che è maggiormente sviluppato e consolidato.

Obiettivo di questa tesi è l'utilizzo di metodologie di approccio sistematico ai problemi, applicato ad un particolare settore dello stampaggio ad iniezione di componenti in plastica, nominato Thin-Wall Injection Molding.
Questo metodo comprende diverse discipline di cui la principale è quella TRIZ. Questa metodologia non viene attualmente utilizzata dall'azienda.
Lo scopo dell'analisi sistematica non è fornire una soluzione specifica al problema, ma dare diverse alternative di soluzione per una futura progettazione di un nuovo concetto di sistema stampo-macchinario.

Si incomincia quindi con l'analisi della problematica determinando i principali parametri di processo che intercorrono nel generico ciclo di stampaggio ad iniezione della plastica. Questo porta a suddividerli in parametri controllabili e parametri non controllabili.

Una volta appurato che sono proprio i parametri non controllabili i diretti responsabili della malriuscita del processo di Thin-Wall Injection Molding, vengono mostrate le soluzioni attuali.

A questo punto entra in gioco il metodo di risoluzione sistematica ai problemi che fornirà molteplici spunti e strategie di soluzione che sono molto mirate ma tuttavia ideali. Queste soluzioni sono la base per una progettazione specifica di un futuro nuovo sistema, e devono essere ispezionate in funzione delle esigenze particolari.
È ora in programma in TECOS una progettazione di un nuovo sistema basato sui risultati indagati dall'analisi TRIZ svolta.

Nell'ultima fase vengono effettuati esperimenti e simulazioni prettamente "più pratici". Il loro scopo è anzitutto quello di validare quanto affermato dall'analisi svolta in precedenza. Inoltre intendono mostrare se, e come, può avvenire la predizione dei parametri di processo in fase di progettazione.

Questo viene portato avanti tramite le risorse disponibili in azienda che è in ogni caso una di quelle all'avanguardia in questo settore.
In questo ambito la tesi acquista un ulteriore validità poichè diversi esperimenti e simulazioni svolte sono degli importanti risultati utili per un altro progetto internazionale in cui l'azienda TECOS ha il ruolo di leader.

1 Introduction

This thesis is developed in the context of international student exchange program "Leonardo da Vinci Project". This international program allows students to work abroad in their field of study.
The involved partners are the Politecnico di Milano University and the TECOS Company.

TECOS Company

TECOS was established in 1994 by Government of Republic of Slovenia (more precisely Ministry of Science and Technology and Ministry for Education and Sport), Chamber of Commerce and Industry of Slovenia and Municipality Celje (Fig. 1).
TECOS is an institution, established in order to support Slovenian tool-making industry being more competitive on the most demanding markets. Their founders supported them because they saw tool-making as one of Slovenian strategic and primary directions. The main goal of TECOS is to take advantage of its own knowledge and equipment and use it together with equipment and knowledge of both Slovenian universities and other scientifical-research and expert institutions in order to support Slovenian toolmakers.
TECOS is industry-oriented technology center, where industry can find reliable partner in the development of new products, tools and technologies
TECOS has more than 80 industrial and other members the likes of GORENJE.

Fig. 1 TECOS Company

Mi-Nanotech project

The Mi-Nanotech project was one of the several ongoing projects in TECOS Company during the period of international exchange students.
It's an international project which includes also the Ernst Wittner Company and the Department Physical Metallurgy and Materials Testing of the Montanuniversitaet Leoben.

Classical fabrication methods and materials characteristics cannot be transferred directly to micro components with high aspect ratios. This also applies to the injection moulding of micro structured components. That is why the micro-mould characteristic and micro parts production strategy needs to be defined precisely.
For manufacturing of such tools very precise non-conventional machines, know-how and sophisticated fabrication technology are needed. The main problems are achieving required low tolerances, surface qualities and at all fabrication of micro shapes. Secondly, micro-injection moulding production process is also very expensive and difficult to master. Processing cycles usually unacceptable long (in some cases cycle time per part can exceed several minutes) are as consequence of improper or unsatisfying mould tempering (cooling or heating). Unsatisfying tempering can causes insufficient filling the thin walls or ribs, products do not achieve requested tolerances or is too much deformed as consequence of residual stresses. Stressless micro parts are often strongly required.
The technical challenges of production of micro-injection moulds may require non-conventional production concepts. Therefore, the project is focused towards the development and production of specialized miniaturised injection moulds with innovative production technologies using 3D laser removing machine. In order to elongate usage of such moulds nano-coating surface treatment will be determined. The hybrid tempering system will be development by using of Peltier elements and nanocooling fluids. The biggest benefits of so-called hybrid tempering system developed for miniaturised micro-injection mould will be in severe reduction of production cycle time, possibilities to produce even very thin walls and ribs and precise control of process parameters.

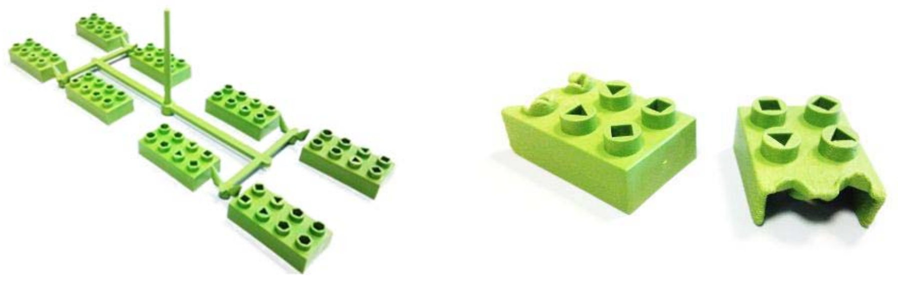


Fig. 2 TECOS nano-coating surface treatment experiments

The project addresses the issue of developing new innovative miniaturized mould with special hybrid tempering system for production specific very precise and complex micro polymer parts. Improving of production process cycle, increasing energy efficiency and satisfying specific functional technical requirements of new emerging micro products will be the main project development priorities. Overall goal of the project is to provide tailored and cost-effective methodologies for production of specific miniaturized injection moulds (micro-injection moulds) for high productivity production of micro polymer parts. Regarding the developments for coatings for micro injection moulds a detailed understanding of wear mechanisms in micro-injection moulding, availability of an optimized coating process and coating architecture for coating moulds with complex 3D geometries and thus moulds with longer lifetime are developed (Fig. 3).

R&D is one of core TECOS activities. They are well aware of the importance of investing into research and development and transfer of the results into industrial practice. Investments into R&D are extremely demanding from the human resources, time and financial aspects. As such they are often hardly feasible, especially for SMEs. TECOS is a bridge between the institutions of knowledge and the industry, while it has been successfully incorporating itself into international projects with a high added value to provide support to small and medium-sized companies.
In the project TECOS will be responsible for the development of optimized tempering system of micro dies and for testing of micro dies in laboratory environment.

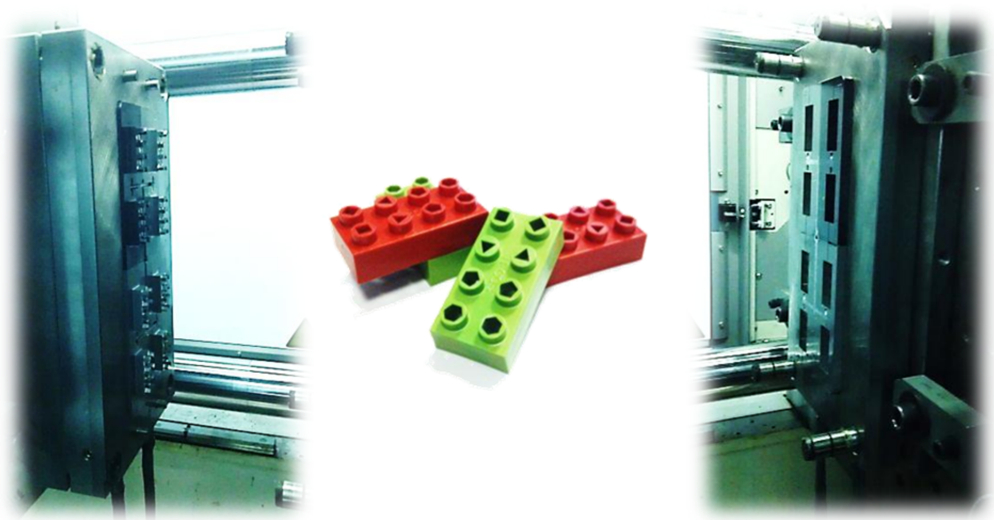


Fig. 3 TECOS' mold for nano-coating surface treatment experiments

Thesis

This thesis was born from idea to support the Mi-Nanotech project from a broader point of view and thinking from the perspective of further development.
The core of the thesis is focused on providing a general method of approach to the problem applied to the field of Thin-Wall Injection Molding Process (Fig. 4).
This type of analysis has never been used by the TECOS Company and it was fully implemented from scratch.
The following skills are those that are used predominantly.

- Methods and strategies for knowledge process representation
- Standard and functional modeling systems: IDEF0
- Techniques for modeling technical systems (functional modeling, event, cause-effect, networking problems, networks of contradictions)
- Methods and tools for systematic problem solving and design inventive (TRIZ, TRIZ-OTSM, GTI, ...)

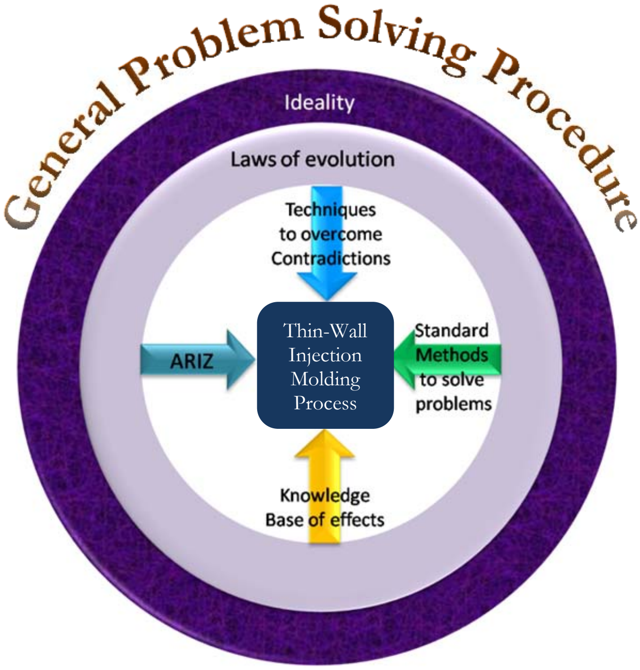


Fig. 4 Problem solving procedure applied to Thin-Wall Injection Molding Proces

The purpose is to give ideas for clarification to the problem without going to the details of a specific solution, which however depends on many other factors.
For this reason, no design is performed.

The validity of the TRIZ analysis will be evaluated in the concluding part through the study of the two main parameters that influence the thin-wall injection molding process. This will be obviously done by the available resources in TECOS Company.
In addition, it is investigated the effectiveness of the current design methodologies in the field of injection molding process for future design based on the statement from the analysis TRIZ.
In this context, some of the Mi-Nanotech project experiments are parallel to the thesis project because they have common goals
These common objectives are the mold filling numerical simulation and the related experiments on the machine.

2 Problem definition

Nowadays the market is characterized by the need for increasing miniaturization, precision, energy efficiency and shortening of the time-to-market for new products. Benefits include reduction in overall component size and weight as well as reducing costs by reducing material use and processing cycle times. Reduction in wall thickness is translatable to larger parts as well. Typical thin wall applications include: cellular phone components, laptop/notebook computer components, hand held devices and medical devices (Fig. 5). The shape, minimal size and properties of the miniaturized parts are at the moment constrained by the capability of technologies for their production. Also production cycle is extremely important with requirement to be shortened and controlled as much as possible. It is expected that production cycles of microinjections parts are short but in reality production cycles are often very long due to improper mould tempering. The project addresses the issue of developing new innovative system for production of micro polymer parts. A definition of thin-wall molding is based on the flow-length to wall-thickness ratios. Typical ratios for these thin-wall applications range are from 100:1 to 150:1 or more. Because of thin-wall parts freeze off quickly, they require high temperature, high injection speed and high injection pressure. Currently main problems are the long process-cycle-time and presence of defects on parts. There are strictly boundary conditions to play with the parameters to avoid defects on parts.

Goal of this chapter is to make a full description of the problem in developing thin-wall plastic parts. Defect description is the first step and it's necessary to determinate what generates them. The causes are explained by the real practical parameters which are extrapolated from the knowledge of the standard injection molding process and by the theory for plastic material.

Fig. 5 Examples of requested thin-wall injection moulding in the field of information technology

2.1 Defects description

The starter point for problem analysis is the result of a current injection molding process. The main harmful problem is presence of defects in final products. The next section is token by bibliography research and describes most of the defects that may arise during the standard injection molding process.

Air traps

An air trap is air caught inside the mold cavity (Fig. 6). It becomes trapped by converging polymers melt fronts or because it failed to escape via the mold vents, or mold inserts which also act as vents. Air trap locations are usually in areas that fill last.
Lack of vents or undersized vents in these last-to-fill areas are a common cause of air traps and the resulting defect. Another common cause is race-tracking (the tendency of polymer melt to flow preferentially in thicker sections), caused by a large thickness too. Trapped air will result in void and bubble inside the molded part. For these reasons it needs to place vents in the areas that fill last and design gate and delivery system in proper way. The last-to-fill areas have to be located at the proper venting locations. Lowering the injection speed will give the air displaced by the melt sufficient time to escape from the vents.
Make sure that the vent size is large enough so that the air present in the cavity can escape during injection. The recommended vent size is 0.025 [mm] for crystalline polymers and 0.038 [mm] for amorphous polymers.

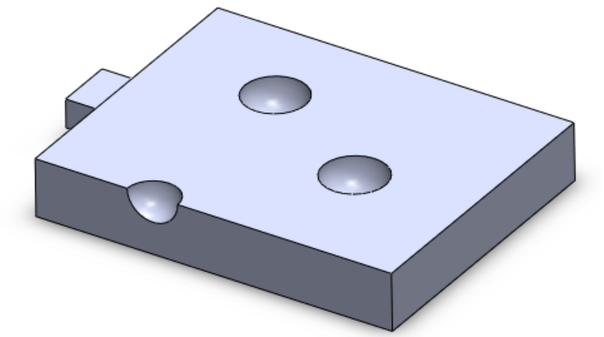


Fig. 6 Air traps

Dimensional variation:

It's a defect characterized by the molded part varying from the batch to the batch or from the shot to the shot while the machine setting remain the same (Fig. 7). It can be caused by unstable material properties or improper molding conditions.

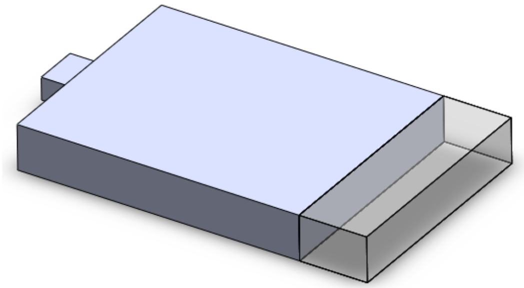


Fig. 7 Dimensional variation

Black specks and black streaks

Black specks and black streaks are dark spots or dark streaks found on the surface or throughout a molded part (Fig. 8). Brown specks or streaks refer to the same type of defect, except the burning or discoloration is not as severe. It's a defect caused by overheated material. Material that stays in the nicked rough surfaces of the barrel wall and screw surfaces for a prolonged period of time after heating will degrade, resulting in the defect. Material degradation can result from a high melt temperature so it suggests to low down the barrel and nozzle temperature. Contaminants in the air or in the material like dirty regrind, foreign material or different color material are what most often lead to black specks and black streaks. It's better to avoid recycling rejected parts with black specks and black streaks.
The typical machine shot size should be between [20-80] percentages of machine injection capacity. For temperature sensitive materials, the range should be narrowed down more. If the range is too big the material remains for prolonged periods of time inside the barrel and it becomes degraded.

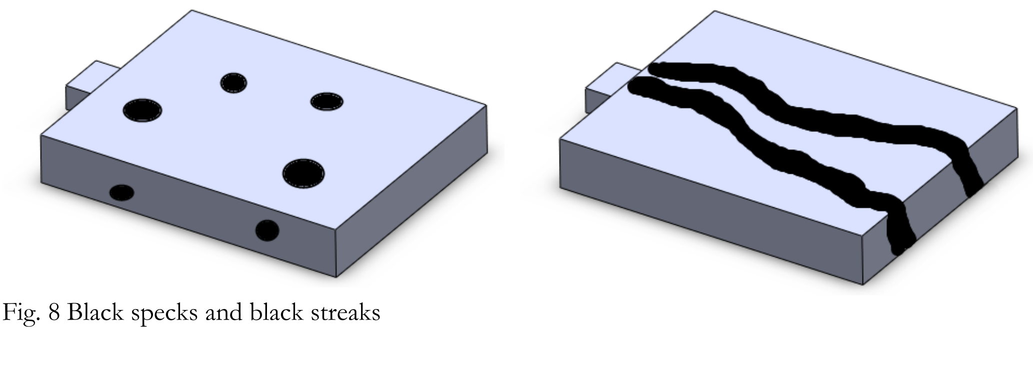


Fig. 8 Black specks and black streaks

Burn marks:

Burn marks are small, dark, or black spots that appear near the end of the molded part's flow path or in the blind area where an air trap forms (Fig. 9).
If the injection speed or injection pressure is too high, the air trapped in the runner system and cavity cannot be released to the atmosphere through the venting system properly within a very short filling time. Air traps also occur in improperly vented system when race-tracking behavior is significant. Consequently, the air will be compressed, resulting in a very high pressure and temperature, which will cause the polymer to degrade on the surface near the end of the flow path or the blind area. Burn marks can also result from the degraded materials being carried downstream and the appearing on the surface of the molded part or near the venting areas. It needs to decrease the barrel temperature and the screw rotation speed because if it's too high, during the plasticization period, it will create too much frictional heat, which could degrade the material. Another solution is to increase the dimensions of the flow path and use the recommended venting system dimension.

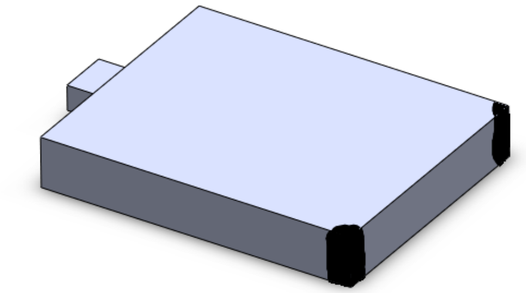


Fig. 9 Burn marks

Discoloration:

It's a color defect characterized by a molded part's color having changed from the original material color (Fig. 10). The material stays in the barrel too long or the barrel and nozzle temperature is too high. Another cause of this problem can be the presence of contaminants.

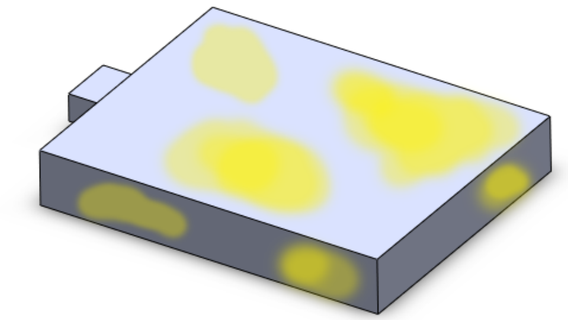


Fig. 10 Discoloration

Fish eyes:

Fish eyes are a surface defect that results from not melted materials being pushed with the melt stream into the cavity and appearing on the surface of a molded part (Fig. 11). If the barrel temperature is too low to melt the materials completely, the unmelted pellets will merge with the melt stream, marring the surface of the part. Too much regrind material can cause the problem. The shape and size of regrind is irregular compared with original material, which can trap more air and cause the material to blend unevenly. If a high-melt-temperature material is blended into the original one, the blended material may stay in pellet form and cause fish eyes during the molding process. If the screw rotation speed and the back pressure settings are too low, there might not be enough frictional heating to melt the material completely.
It's better to limit or eliminate regrind for practical molding, depending on part quality requirements and limiting to 10% of regrind is a good start but only when regrind is allowed.

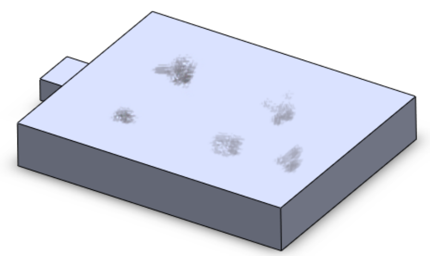


Fig. 11 Fish eyes

Brittleness

It's a result from material degradation leading to shorter molecular chain length (thus lower molecular weight) (Fig. 12). Brittleness can be caused by excessive drying time or drying temperature. A brittle molded part has a tendency to break or crack. Restrictive runner, gate or even part design cause excessive shear heating that aggravates an already overheated material, causing material degradation.
Reduce the barrel and nozzle temperature, back pressure, screw rotation speed or injection speed to avoid overheating. While not overheating the material increase melt temperature, mold temperature or injection pressure if the weld line has a tendency to crack.

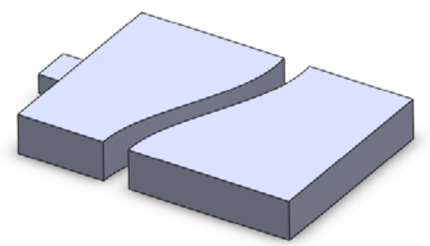


Fig. 12 Brittleness

Delamination:

It is also called lamination or layering and it's a defect in which the surface of a molded part can be peeled off layer by layer (Fig. 13). Delamination can be caused also by blending incompatibles materials together or it's possible that too much mold release agent being used during the molding process. It would be good to increase the barrel temperature and the mold temperature. If the melt temperature is too low, layers of material are formed because they can't bond to each other, when ejected or subjected to stress, they separate from each other. Another cause of delamination is excessive moisture or the presence of sharp corners at the gate and runner.

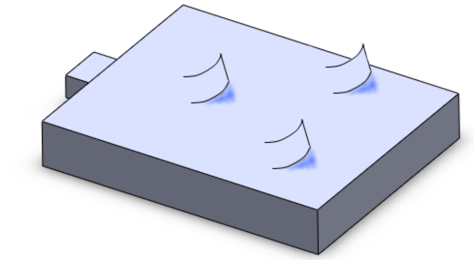


Fig. 13 Delamination

Short shots:

A short shot is a molded part that is incomplete due to insufficient material has been injected into the mold (Fig. 14). In some cases, short shots are intentionally produced to determine or visualize the filling pattern. Problematic shots occur when the polymer melt cannot fill the entire cavity and this most commonly occurs at thin sections or extremities. Any factor that increase the resistance of polymer melt to flow or prohibit delivery of sufficient material into the cavity can cause a short shot. Examples of these factors include: Insufficiently-sized restrictive-flow areas such as gates, runners, and thin walls. Lack of vents cause air trapped inside the cavity, low melt and mold-wall temperature could be other reasons. Short shots can also be due to an insufficient machine injection pressure or ram speed, or volume, premature solidification of the polymer melt due to hesitation, poor filling pattern or prolonged injection time.

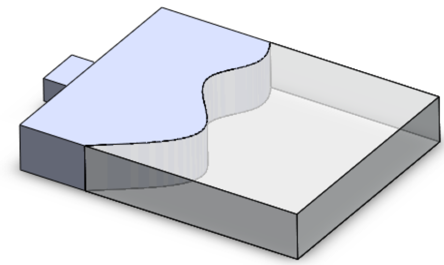


Fig. 14 Short shots

Ripples:

Ripples are the wavelets or small fingerprint-like waves near the edge or at the end of the flow (Fig. 15). Flow-front velocity and mold temperature have a stronger influence on the formation of ripples compared to the shape of the gates and the melt temperature.

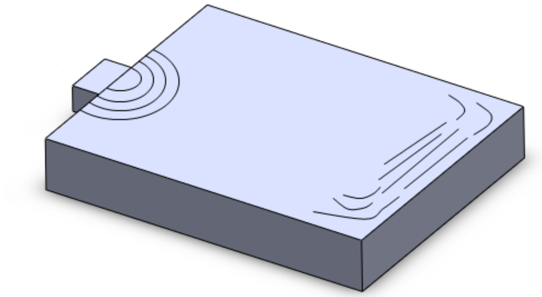


Fig. 15 Ripples

Flow marks:

It's a surface defect which circular ripples of wavelets appear near the gate (Fig. 16). Flow marks are caused by cold material near the gate or lack of compensated material during the packing stage. The problem usually can be attributed to the low melt temperature, low mold temperature, low injection speed, low injection pressure, small runner stem and gate. Accord to recent visual analysis using a glass-inserted mold, the flow mark defect can also be caused by cooling of the flow front portion on a cavity wall and the repeated phenomena of "getting over" and cooling with the subsequent melt.

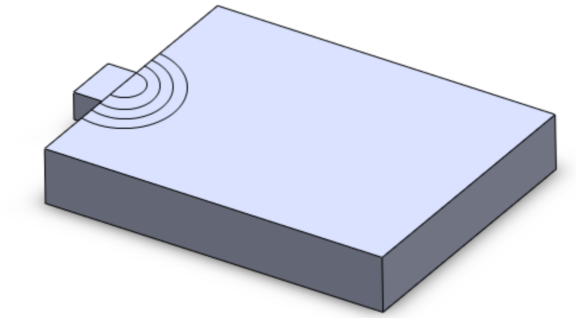


Fig. 16 Flow marks

Jetting:

Jetting occurs when polymer melt is pushed at high velocity through restrictive areas, such as the nozzle, runner, or gate, into open thicker areas without forming contact with the mold wall (Fig. 17). The bucked, snake-line jetting stream causes contact points to form between the folds of melt in the jet, creating small-scale "welds". It's better to use overlap gate to avoid jetting. It's also possible to slow down the melt with a gradually divergent flow area. A tab or fan gate provides a smooth transition from the gate to the cavity. If it's possible use an optimized ram speed profile so that melt-front velocity is initially slow when the melt passes through the gate, then increases once a dispersed and tongue-shaped material is formed near the gate.

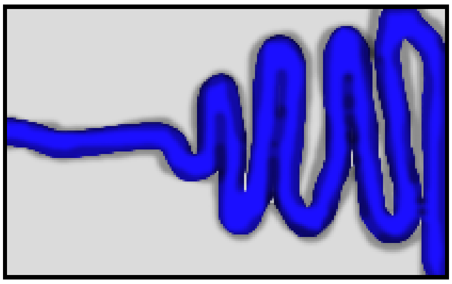


Fig. 17 Jetting

Flash:

Flash is a defect characterized by excessive material found at locations where the mold separates, notably the parting surface, movable core, vents, or venting ejector pins (Fig. 18). If the clamp force of the injection machine is too low to hold the mold plates together during the molding process, flash will occur. Flash will also occur if the parting surface does not contact completely, due to a deformed mold structure, parting surface defect, improper machine and mold set up, or flash or foreign material stuck on the parting surface. High melt temperature (which makes a thinner melt) or high injection pressure will cause flash. An improperly designed venting system and a very poor venting system or a venting system that is too deep will cause flash.

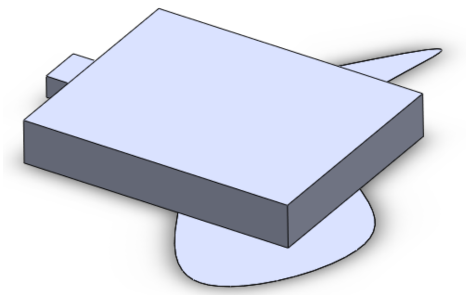


Fig. 18 Flash

Hesitation:

Hesitation is a surface defect that results from the stagnation of polymer melt flow over a thin-sectioned area, or an area of abrupt thickness variation (Fig. 19). When polymer melt is injected into a cavity of variable thickness, it tends to fill the thick and less resistance areas. As a result, polymer melt may stagnate at thin sections until the rest of the part is filled and the stagnated polymer melt starts moving again. However, if the duration of hesitation is significant, polymer will solidify prematurely and a surface defect such as a hesitation mark occurs.

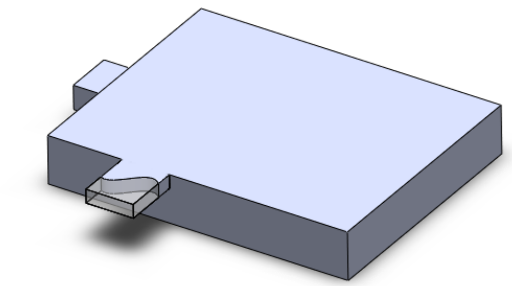


Fig. 19 Hesitation

Sink marks and voids:

A sink mark is a local surface depression that typically occurs in injection moldings with thicker sections, or at locations above ribs, bosses, and internal fillets (Fig. 20). A void is a vacuum bubble in the core, not visible from the surface.
Sink marks and voids are caused by localized shrinkage of the material at thick sections without sufficient compensation when the part is cooling. A sink mark almost occurs on a surface that is opposite to and adjoining a leg or rib. This occurs of unbalanced heat removal or similar factors. After the material on the outside has cooled and solidified, the core material starts to cool. Its shrinkage pulls the surface of the main wall inward, causing a sink mark. If the skin is rigid enough, as a engineering resins, deformation of the skin may be replaced by formation of a void in the core.

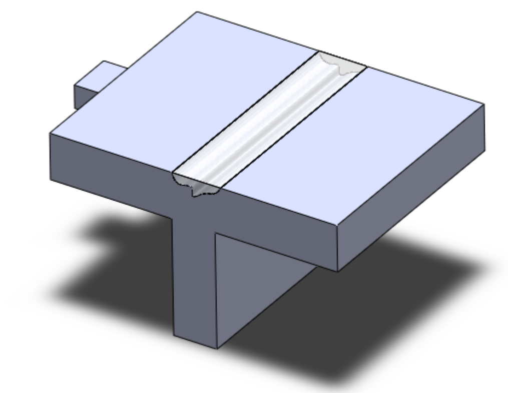


Fig. 20 Sink marks

Weld lines and Meld lines:

A weld line (also called weld mark or knit line) is formed when separate melt fronts traveling in opposite directions meet. A meld line occurs if two emerging melt fronts flow parallel to each other and create a bond between them (Fig. 21). Weld and meld lines can be caused by holes or inserts in the part, multiple gates, or variable wall thickness where hesitation or race tracking occurs. If weld or meld lines cannot be avoided, position them at low-stress and low-visibility areas by adjusting the gate position. Improve the strength of weld and meld lines by increasing the local temperature and pressure at their locations. Traditionally, the meeting angle is used to differentiate weld lines and meld lines. If the angle is smaller the 135° it produces weld line else it produces meld line. Normally, weld lines are considered to be lower quality than meld lines, since relatively less molecular diffusion occurs across a weld line after it is formed.

Weld lines are generally undesirable when strength and surface appearance are major concerns. This is especially true with fiber-reinforced material, because the fibers do not bridge the weld lines and often are oriented parallel to them. The exact strength of weld line depends on the ability of the flow fronts to weld to each other. The strength of the weld area can be from 10 to 90% as strong as the pure material used. With such a wide range possible the conditions that are favorable to better weld line quality are worth examining: high injection pressure and speed, high melt and mold-wall temperature, formation of the weld lines closes to the gate, a temperature difference of less than ten degrees between the two emerging flow fronts. If a weld line forms before the filling is complete and is immediately subject to additional packing pressure, the weld line will typically be less visible and stronger.

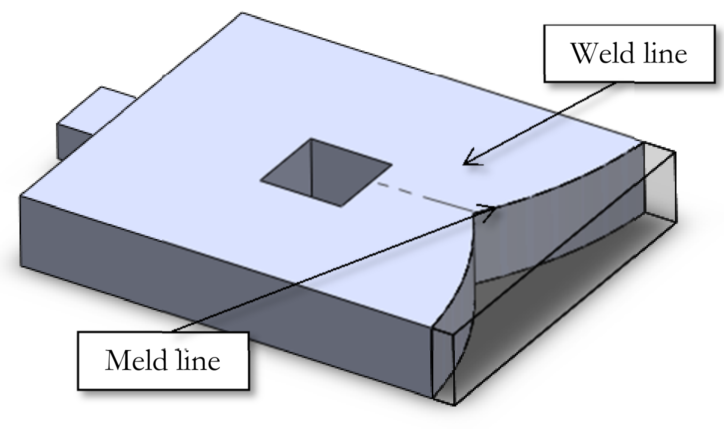


Fig. 21 Weld lines and Meld lines

Silver streaks:

Silver streaks are the splash appearance of moisture, air, or charred plastic particles on the surface of a molded part, which are fanned out in a direction emanating from the gate location (Fig. 22).

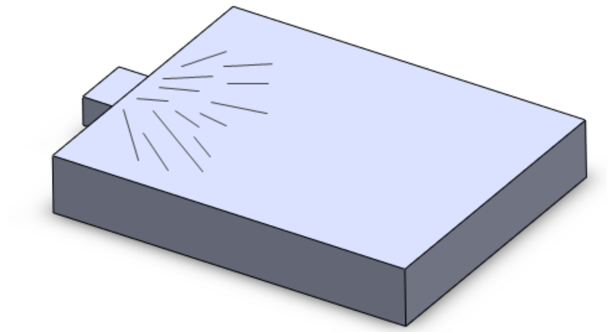


Fig. 22 Silver streaks

2.2 Standard process description

The IDEF0 context diagram fast allows the sharing information among members in engineering context. It is used to make a functional model that represents the structure of functions, activities or process involved in the system.
The main popular features are: completeness, expressivity, consistent, easy to create, immediately recognizable and widely validated.
TECOS Company still not exploits IDEF techniques so this is the first occasion to show how to implement them in a specific context.

2.2.1 IDEF0 description for standard injection molding process

The standard injection molding process can be easily described with the IDEF0 techniques as follows.

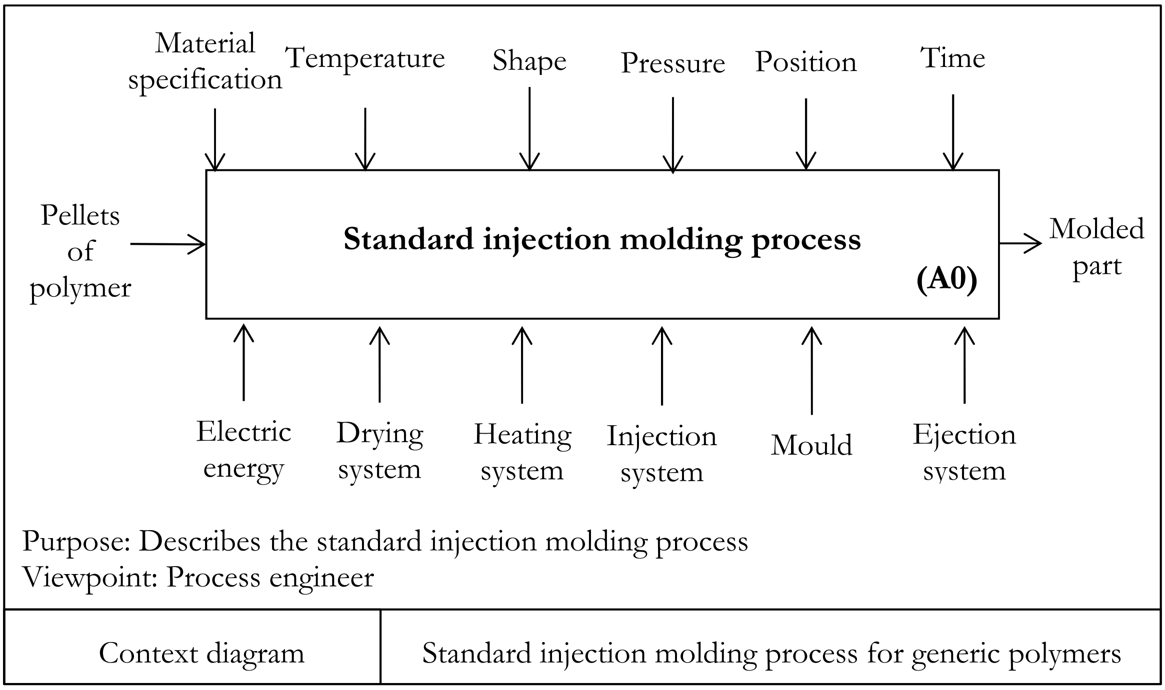


Fig. 23 IDEF0 Context diagram for standard injection molding process

The previous picture (Fig. 23) shows the context diagram for the whole process. The left side represents the input. Here it's pellets of polymer. On the right side output are displayed. At the end of the process, pellets of polymer become molded part. From the bottom of the scheme resources start instead on the top there's the presence of the controls.
The whole process is made by one machine; an example of this machinery is show below (Fig. 24).

Fig. 24 Plastic injection molding machine

The context diagram is not fully explanatory; it's thought to have a first view of the full process, without details. The A0 is the main diagram, and as expected, it increases the degree of detail for the process (Fig. 25). Standard injection molding process can be divided into four phases. The input material changes properties after each phase till becoming molded part.
Some resources and controls are common to more than one phase, like electric energy or position. Others are specific only for one phase, like the drying system.

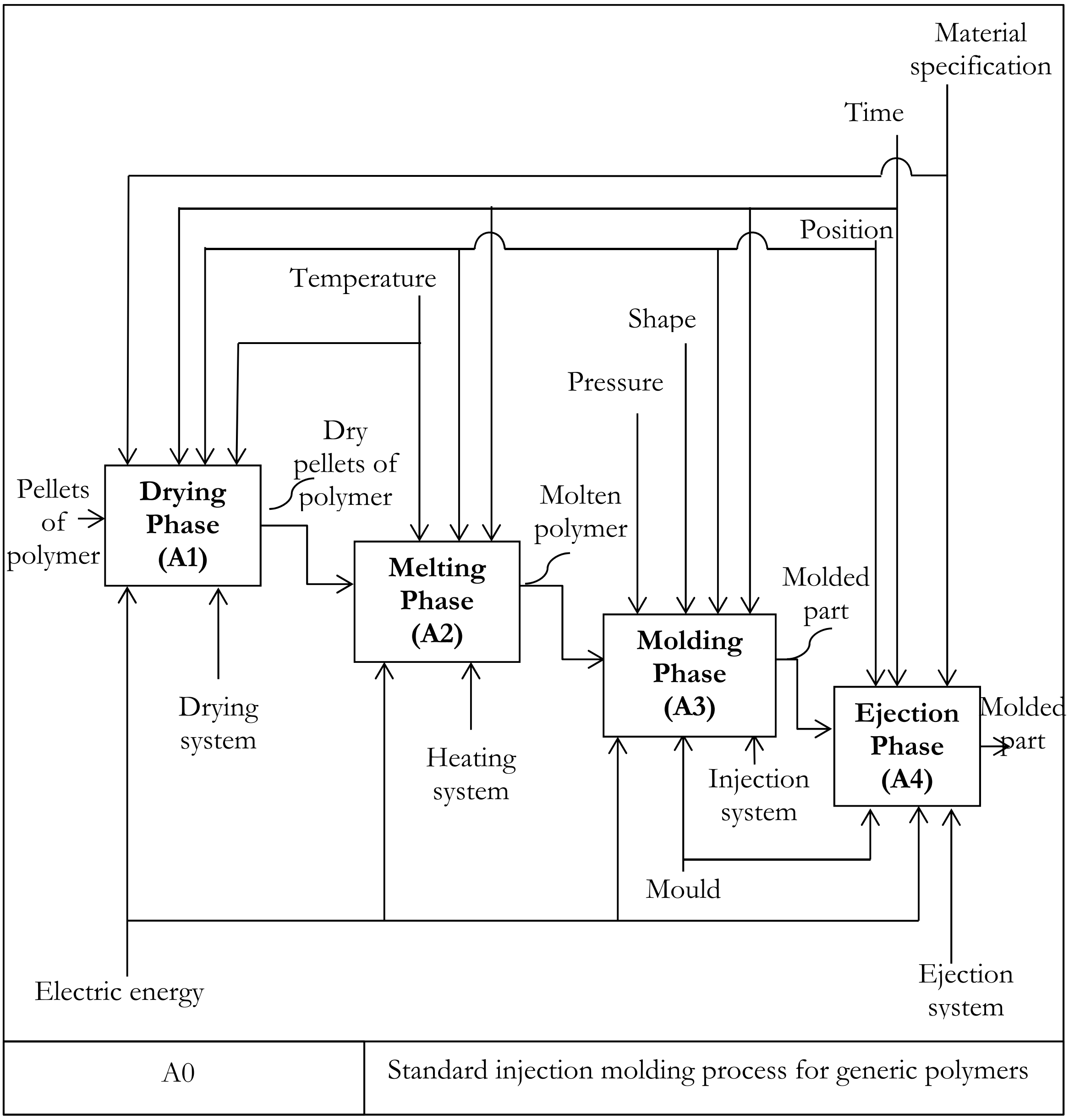


Fig. 25 IDEF0 A0 diagram for standard injection molding process

The A3 diagram is like a magnifier pointed on the molding phase. It's possible to increase the level of detail as much as it needs. Molding phase requires to be described more accurately, that's why a focus is necessary (Fig. 26).

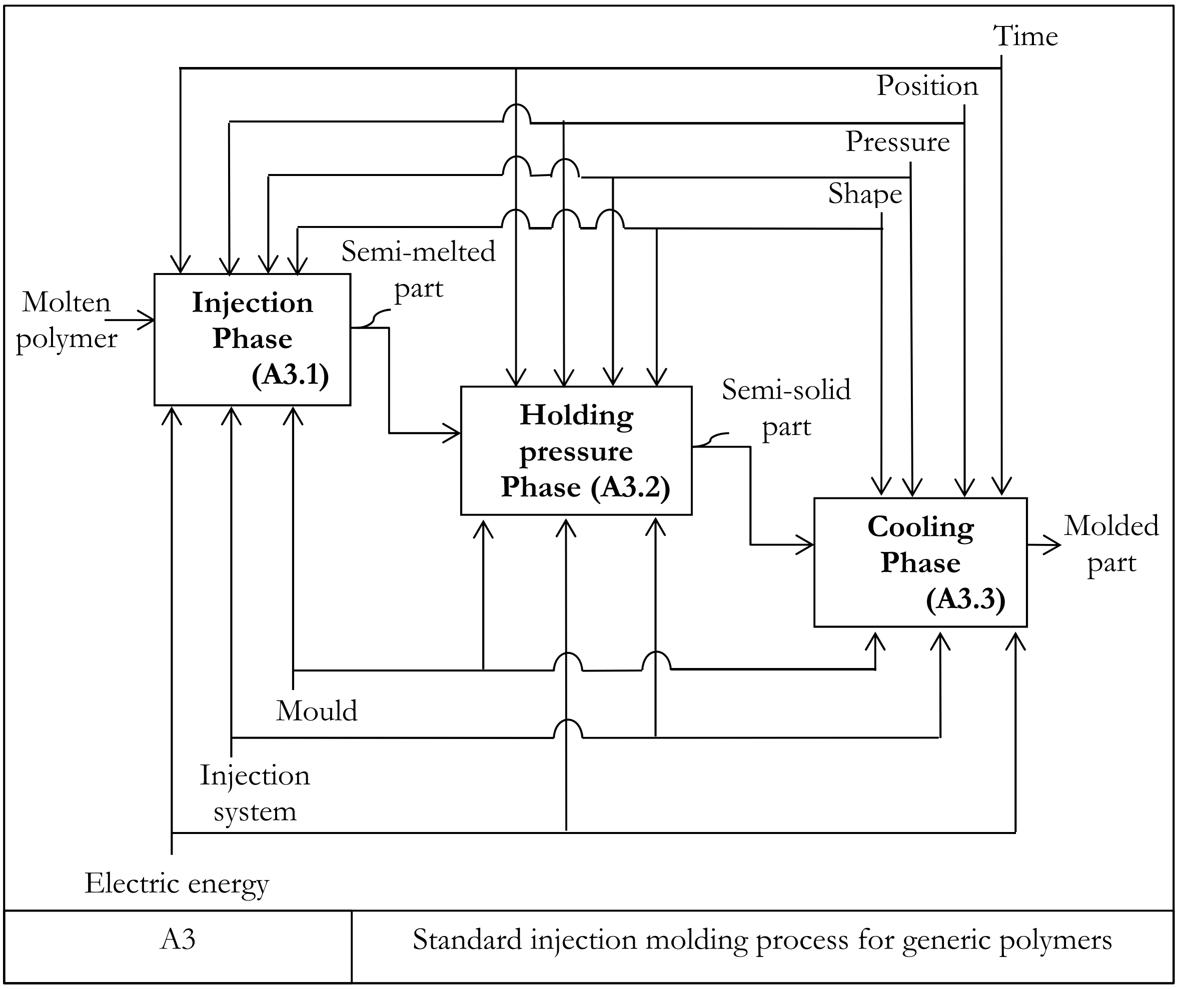


Fig. 26 IDEF0 A3 diagram for standard injection molding process

It has been reached a sufficient degree of detail of the process that allows to describe it in an accurate manner since were explained the main elements that characterize it.

2.3 Parameters definition:

It's necessary to identify the origin of defect to avoid it. Thus it needs to establish which parameters are controllable and which are not. Next paragraph make a correlation between standard injection molding process and defects procreation.
By current knowledge of plastic molding process it's possible to trace the cause of a defect and allocate it on a specific resource and the relative parameter.
The next guide can easily help to manage the presence of defects.

❖ ***Drying system***

- **Contamination of polymers** ***(CP= Material specification):***
  - **High** ->Black specks and black streaks, Delamination, Discoloration, Fish Eye, Silver streaks
- **Drying condition** ***(CP= Temperature):***
  - **Improper** ->Brittleness, Silver streaks, Dimensional variation

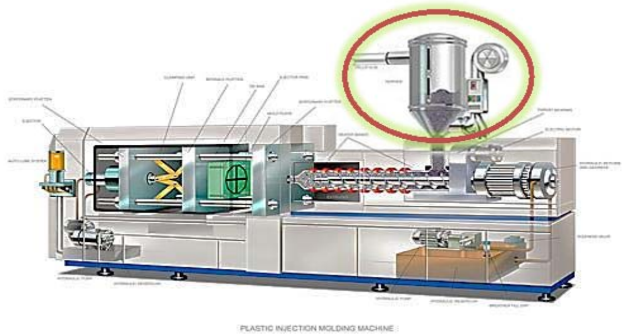


Fig. 27 Drying system and its place on the machinery

- ***Heating system***
  - **Barrel and nozzle temperature *(CP: temperature):***
    - **High** ->Black specks and black streaks, Brittleness, Burn marks, Discoloration, Flash, Silver streaks
    - **Low** ->Black specks and black streaks, Brittleness, Delamination, Fish eye, Flow marks, Hesitation, Ripples, Short shots
  - **Time of material inside barrel *(CP: Time & Position):***
    - **High** ->Black specks and black streaks, Discoloration, Silver streaks

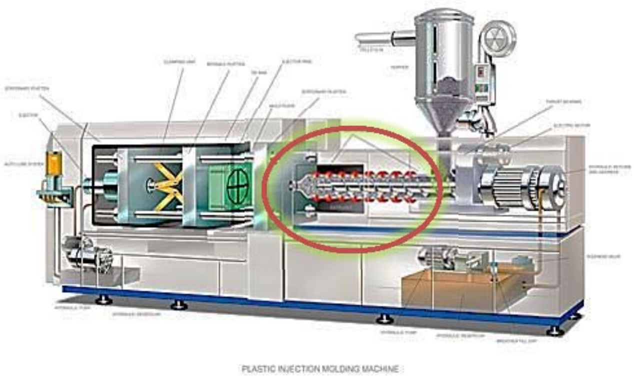


Fig. 28 Injection unit (heating system)

- ***Injection system***
  - **Injection Volume *(CP= Position):***
    - **Low** ->Short shots
  - **Injection speed *(CP= Position):***
    - **High** ->Air traps, Brittleness, Burn marks, Flash, Silver streaks
    - **Low** ->Flow marks, Ripples, Short shots, Weld lines and meld lines
    - **Even** ->Jetting
  - **Injection pressure *(CP= Pressure):***
    - **High** ->Burn marks, Flash, Silver streaks
    - **Low** ->Brittleness, Flow marks, Hesitation, Ripples, Short shots, Sink marks and voids, Weld lines and meld lines

- **Packing pressure** ***(CP= Pressure):***
  - **High** ->Flash
  - **Low** ->Flow marks, Sink marks and voids, Weld lines and meld lines
- **Hold time** ***(CP: Time):***
  - **Low** ->Sink marks and voids
- **Cooling time** ***(CP: Time):***
  - **Low** ->Sink marks and voids
- **Back pressure** ***(CP: Pressure):***
  - **High** ->Brittleness, Fish eye, Flash
  - **Low** ->Silver streaks
- **Machine shot size** ***(CP: Position):***
  - **Big** ->Black specks and black streaks
  - **Small** ->Air traps, Silver streaks
- **Screw rotation speed** ***(CP: Position):***
  - **High** ->Brittleness, Burn marks
  - **Low** ->Fish Eye
- **Clamp force** ***(CP: Position):***
  - **Low** ->Flash
- **Cushion stroke** ***(CP: Position):***
  - **Low** -> Sink marks and voids

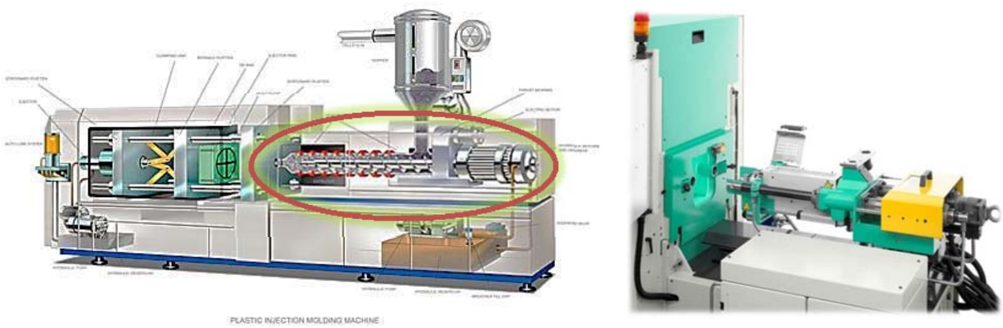


Fig. 29 Injection system

- ***Mould***
  - **Runner system type *(CP: Shape):***
    - **Cold** ->Flow marks
  - **Runner dimension *(CP: Shape):***
    - **Small** ->Brittleness, Burn marks, Short shots, Silver streaks, Weld lines and meld lines
  - **Gate position *(CP: Shape):***
    - **Incorrect** ->Air traps, Hesitation, Ripples, Sink marks and voids, Weld lines and meld lines, Dimensional variation
  - **Gate dimension *(CP: Shape):***
    - **Small** ->Brittleness, Burn marks, Flow marks, Short shots, Silver streaks, Sink marks and voids, Weld lines and meld lines
  - **Gate shape *(CP: Shape):***
    - **Incorrect** ->Jetting
  - **Vents position *(CP: Shape):***
    - **Incorrect** ->Air traps, Short shots, Silver streaks, Weld lines and meld lines
  - **Vents dimension *(CP: Shape):***
    - **Small** ->Air traps, Short shots, Silver streaks, Sink marks and voids
    - **Big** ->Flash
  - **Part Thickness ratio *(CP: Shape):***
    - **High** ->Air traps, Ripples, Short shots, Weld lines and meld lines
    - **Not even** ->Hesitation, Short shots
  - **Part dimension *(CP: Shape):***
    - **Thick** ->Brittleness, Burn marks
  - **Presence of mold release agent *(CP= Material specification):***
    - **High** ->Delamination
  - **Mold Injection temperature *(CP= Temperature: NOT AVAIBLE):***
    - **Low** ->Brittleness, Delamination, Flow marks, Ripples, Short shots, Weld lines and meld lines

- **Mold Ejection temperature *(CP= Temperature: NOT AVAIBLE):***
  - **High** ->Ejection problem, Deformation, Sink marks and voids

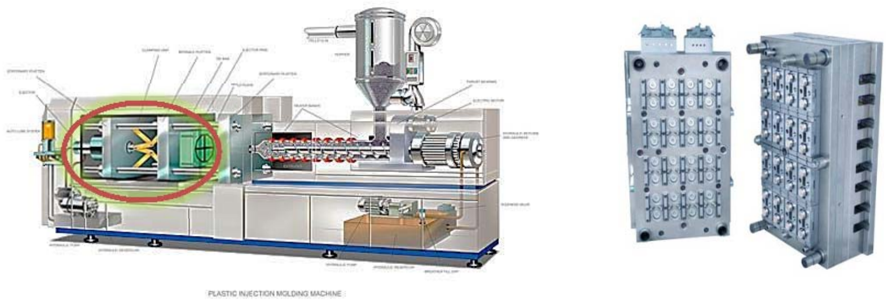


Fig. 30 Mould and relative position inside the machine

With the standard injection molding system it's not possible to avoid every kind of defect because there's no way to control the mould temperature during the process.

Currently there are few and insufficient systems to solve this problem. The goal is to find, at least in theoretical way, the best solution.

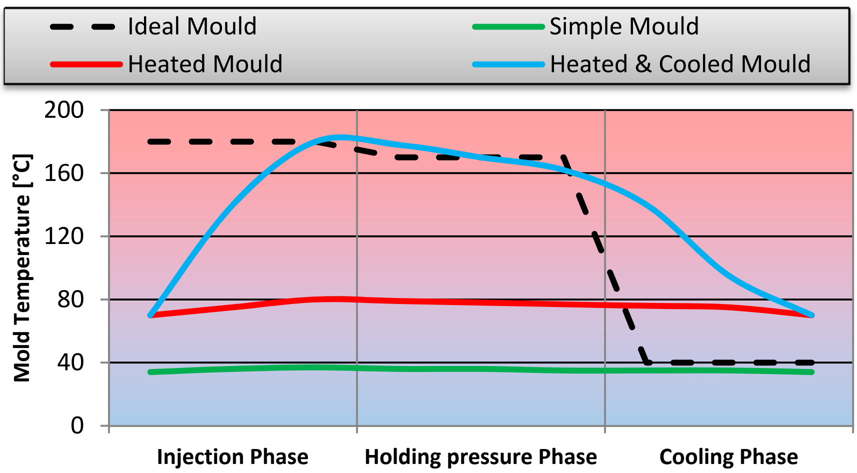


Fig. 31 Mold temperature system comparison

The standard injection molding process works with a simple mould. The temperature in this case is not controllable by the user; it's only possible to measure it.

The mould temperature increases just by few degrees during the injection phase because of polymer temperature and then it decreases during the cooling phase because of environment temperature.
The first solution is a temperature control during the injection phase, increasing it with a heater system. However in this way the mould temperature remains too high during the ejection phase or it needs big cooling time to reach the ejection temperature.
Another and preferable solution is to heat up the mold during the injection phase and then to cool down the mold during the cooling phase. The objective of this solution is to reach the ideal mould temperature that is shown in the graph minimizing the cycle process time.
An idea of different situations is shown on the previous graph (Fig. 31).

2.4 Thin-wall process description

A more advanced process must be described. To control temperature during the cycle some devices have to be introduced. IDEF0 diagrams fast allows the localization of that controls on the phases. New resources are necessary otherwise controls cannot be applied.
The thin-wall injection molding process has two more available resources respect to the standard one: the mould heating system and the mould cooling system (Fig. 32).
Most of the process remains the same.

2.4.1 IDEF0 description for thin-wall injection molding process

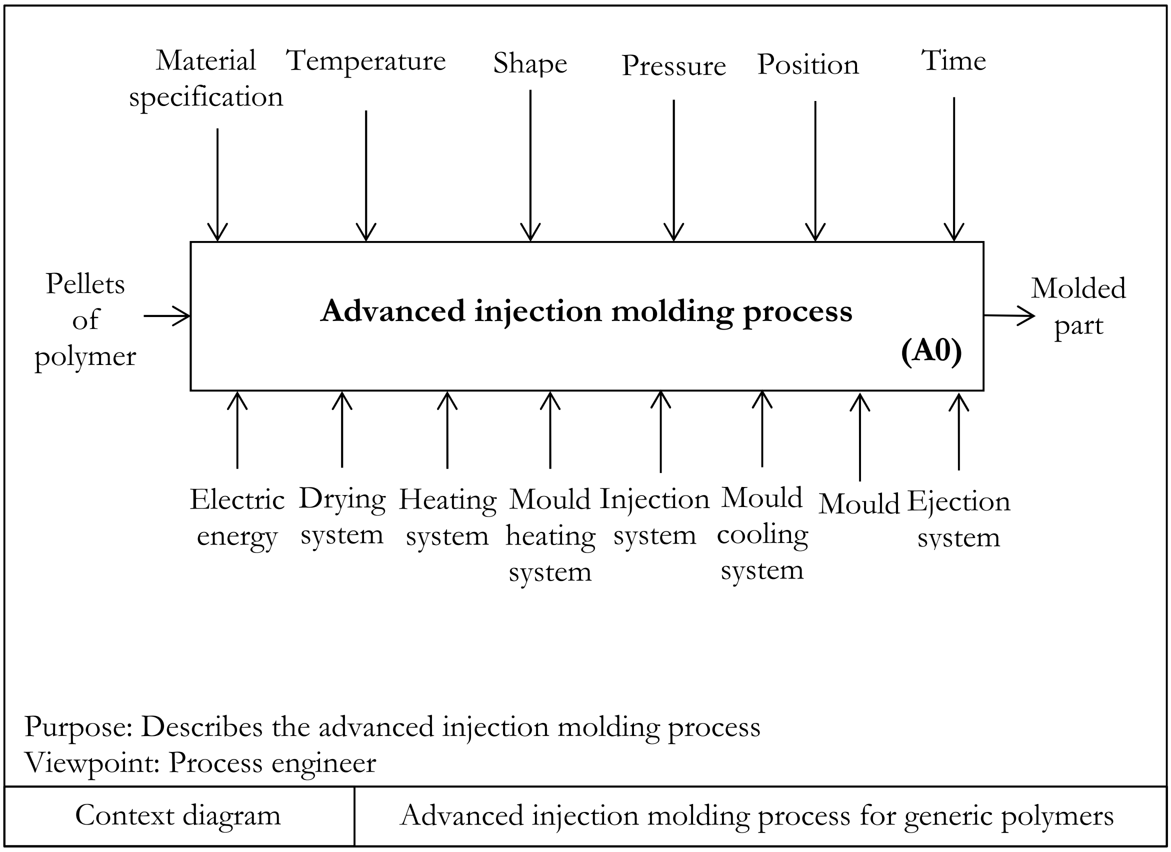


Fig. 32 IDEF0 Context diagram for advanced injection molding process

The A0 diagram shows the temperature control introduction on the molding phase. It shows also the presence of the mould heating system and mould cooling system on the same phase (Fig. 33).

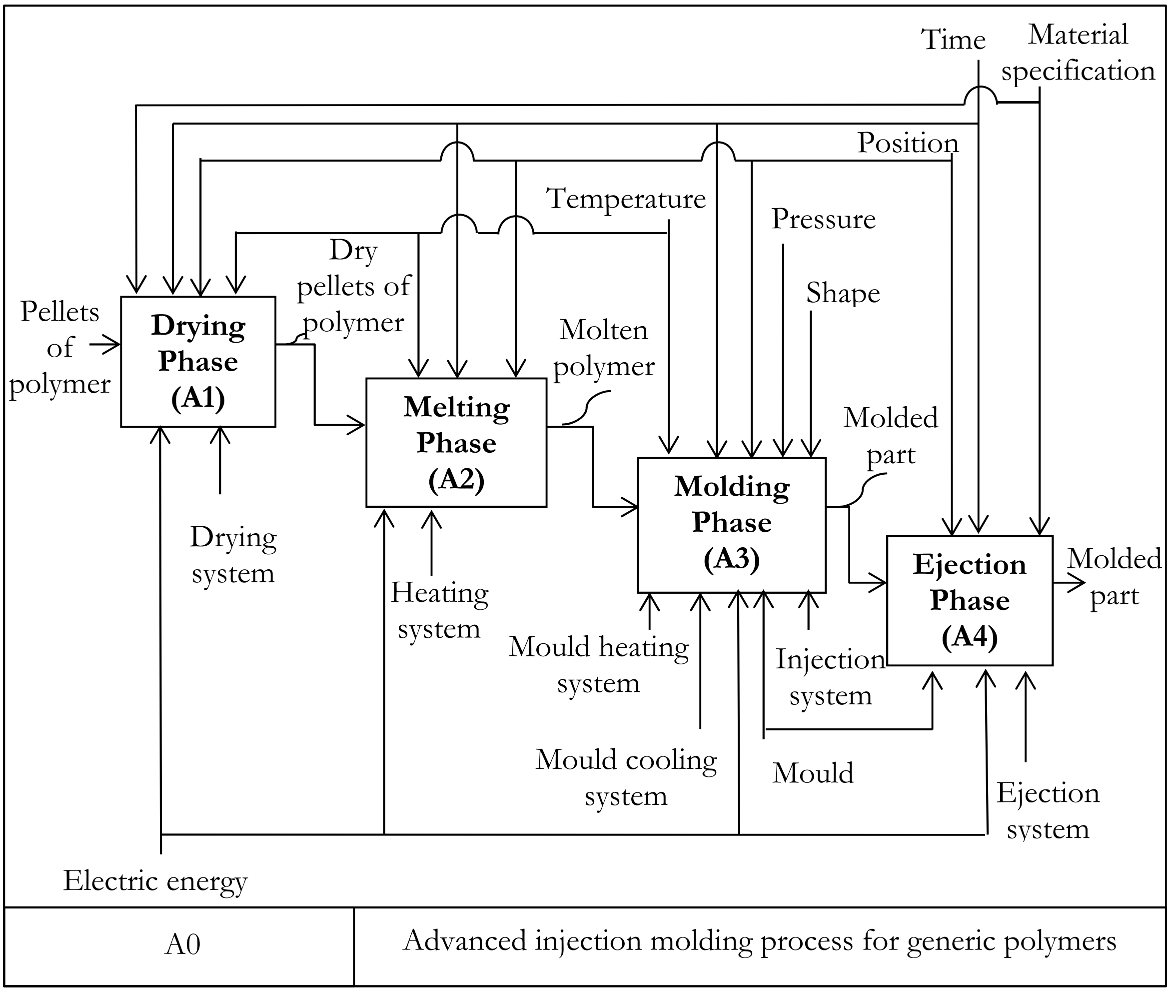


Fig. 33 IDEF0 A0 diagram for advanced injection molding process

To be more precise the A3 diagram shows exactly their working areas (Fig. 34).

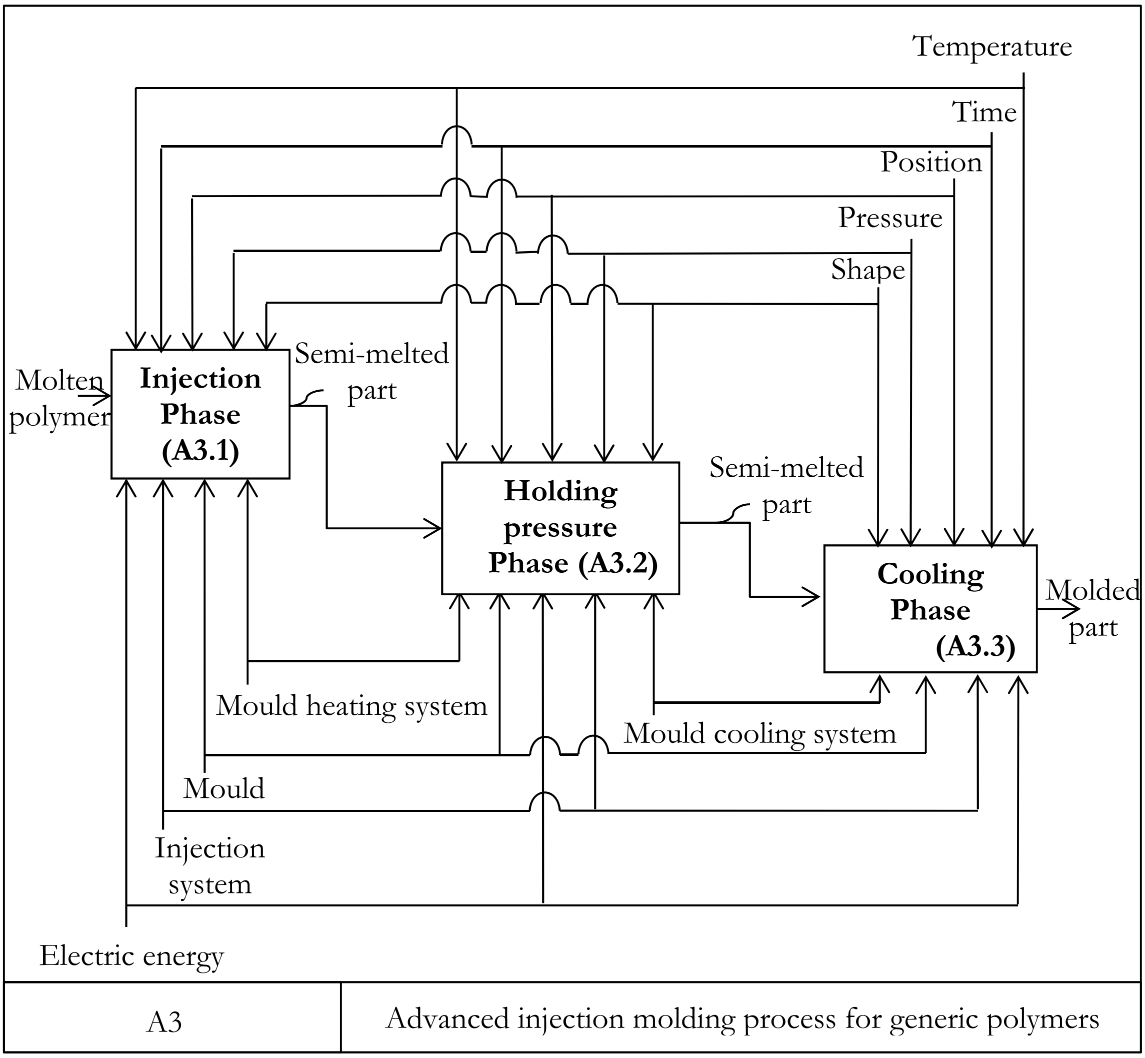


Fig. 34 IDEF0 A3 diagram for advanced injection molding process

In conventional injection molding when the molten polymer comes into contact with the relatively cool surface of the steel mold tool an instantaneous skin layer of frozen or highly viscous material is formed. The advanced injection molding process wants to delay the layer creation till the cooling phase allowing additional material to be injected.

2.4.2 Side benefits

Other benefits in heating the cavity were found by lots of Company that works in the plastic field. A collection of these benefits is beneath listed:

- less injection pressure and longer holding pressure
- less clamping force is required
- lower internal stress
- better quality of reproduction of surface structures
- smoother glossy surfaces with piano finish even with normal resins
- less likely occurrence of flow marks and silver streaks
- more homogenous orientation of glass fibers
- less likely occurrence of weld lines
- lower risk of warpage caused by shrinkage
- better dimensional stability and consistency

Pictures below show some of these benefits (Fig. 35 and Fig. 36).

Fig. 35 Weld line studied on ABS polymer at Swansea University for GIWW Ltd

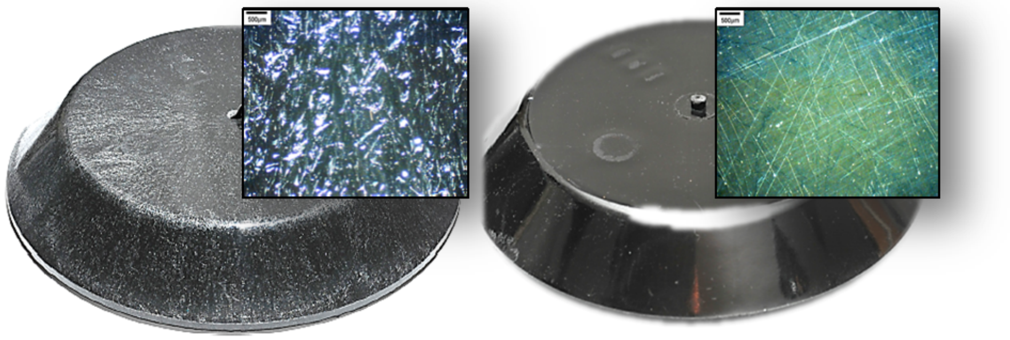


Fig. 36 Surface roughness studied on LGS PP polymer at Swansea University for GIWW Ltd

Thus there are many reasons to implement solutions on existing machinery.

2.4.3 Physics of the process

The previous pictures shows an incredible improvement of the part quality. The reason for these big differences lies in the physics of the process as it is demonstrated by differents studies (Fig. 37) but these aspects will be not deeply examinated.

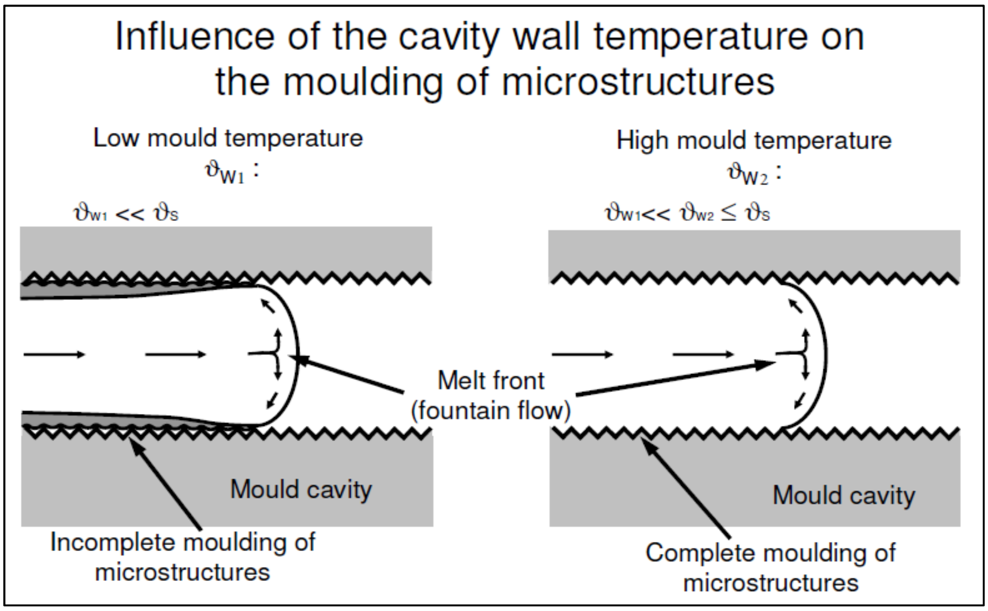


Fig. 37 Influence of the cavity wall temperature on the moulding of microstructures shows by the Institute of Plastics Processing (IKV) at RWTH Aachen University

Melt shear viscosity is a material's resistance to shear flow. Usually, polymer melts are highly viscous because of their long molecular chain structure.

$$Viscosity = \frac{Shear\ stress}{Shear\ rate} \qquad Shear\ stress = \frac{Force}{Area} \qquad Shear\ rate = \frac{Velocity}{Height}$$

For non-Newtonian f1uids, which include most polymer melts, the viscosity varies with temperature and with the shear rate. The shear rate depends in turn from the velocity and a typical cavity velocity profile with the conforming shear rate distribution is shown below (Fig. 38).

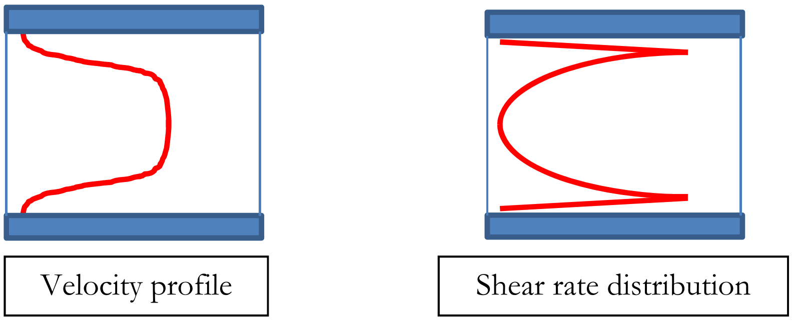


Fig. 38 Velocity to shear rate correlation

Since the mobility of the polymer molecular chains increases with increasing temperature, the flow resistance of polymer melt also depends on the temperature. The melt viscosity increases with decreasing shear rate and temperature because of the alignment and mobility of the molecules. It also depend on the pressure, the lower the pressure the less viscous the melt becomes (Fig. 39).

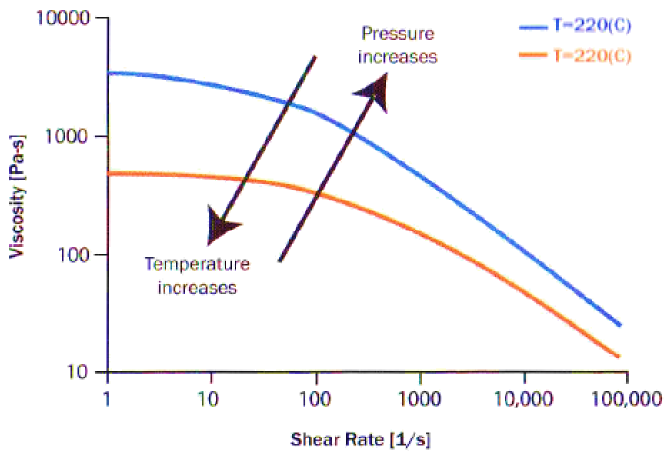


Fig. 39 Influence of temperature and pressure on the viscosity

During injection molding, the distance that the material can flow with certain processing conditions and wall thickness, depends on the thermal properties and shear properties of the material. This behavior can be characterized by the melt flow length (Fig. 40).

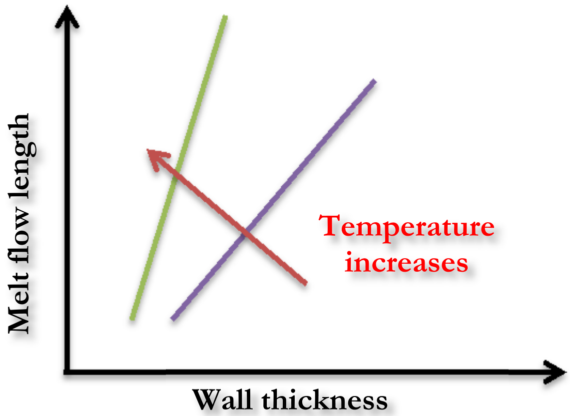


Fig. 40 Melt flow length versus wall thickness with temperature effects

Due to the high velocity and shear rate in thin-wall molding, orientation occurs more readily. To help to minimize anisotropic shrinkage in thin-wall parts, it is important to pack the part adequately while the core is still molten

Thus the procedure to adopt prior to injection is to heat up cavity wall to above the glass transition temperature of an amorphous material or near to the melting point of a semi-crystalline material. Then after cavity filling, switchovers to mould cooling just long enough to reach the ejection temperature for demoulding.

3 Current solutions

This chapter shows the state of the art regarding heating systems, cooling systems and other micro-moulding solutions. Each method has pros and cons in terms of costs and efficiency. Most of next solutions are already available on the market although not in a massive way.
There are systems designed just for heat up the mould and systems developed just for cool down the mould. Some systems can be used for both situations, lastly other solution totally want to revolutionize the micro plastic moulding process.

3.1 Resistance heaters

Cartridge heaters

They are structured of a resistance shrouded that is covered by a tubular sheath made of very conductive material (Fig. 41). This is the cheaper way to heat up the mould because this kind of heaters need only cylindrical drilled holes on the mold and a controller device.

Fig. 41 Cartridge heaters

Tubular and Microcoil heaters

They are based on the same principle of the previous solution however they can assume all kind of shape is required, obviously at the expense of a higher cost (Fig. 42). Microcoil heaters are designed to solve critical heating problems, in particular where little area is available.

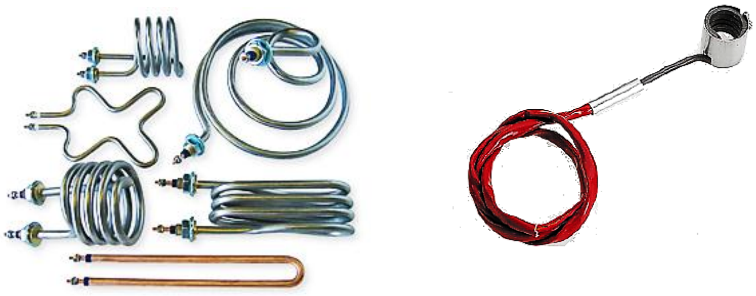


Fig. 42 Tubular and microcoil heaters

3.2 Fluid circuits

There are various circuits but for all of them the time to reach the required temperature mainly depends from: the channel design, the flow rate obtainable from the pump and from the fluid heat exchange capacity.

Water circuit

Water is the most common fluid used to cool down the mould. Mold cooling can account for more than two-thirds of the total cycle time in the production of injection molded thermoplastic parts. An efficient cooling circuit design reduces the cooling time, which in turn increases overall productivity. Moreover, uniform cooling improves part quality by reducing residual stresses and maintaining dimensional accuracy and stability.

A cooling system typically consists of the following items (Fig. 43).

- Temperature controlling unit
- Pump
- Supply manifold
- Hoses
- Cooling channels in the mold
- Collection manifold

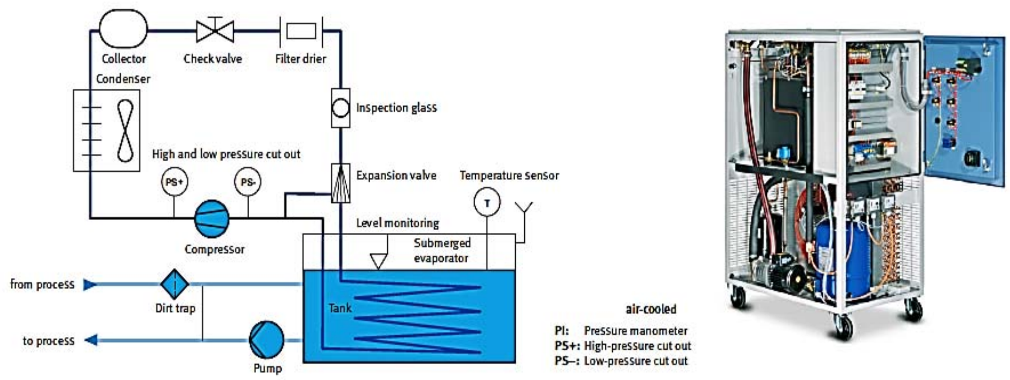


Fig. 43 Cooling systems and chillers with integrated cooling circuit

The mold itself can be considered as a heat exchanger, with heat from the hot polymer melt taken away by the circulating coolant.
A good design of the cooling channels is the main problem of this system. The fluid circuit must be as close as possible to the interested cooling surface (Fig. 44).

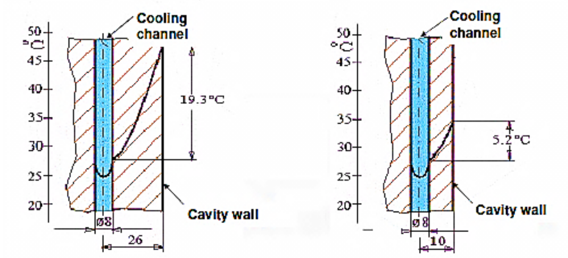


Fig. 44 Effect of the thermal conductivity of the mould steel

An efficient cooling circuit has a very complex design and it should take into account thermal expansion of various mold components.
Another typical problem is to create channels as a single loop instead of multiple channels.

- Parallel cooling channels are drilled straight through from a supply manifold to a collection manifold. Due to the parallel design flow characteristics, the flow rate along various cooling channels will be different because of each individual channel's flow resistance differences. These varying flow rates in turn cause the heat transfer efficiency of the cooling channels to vary from one to another. As a result cooling of the mold will not be uniform with a parallel cooling-channel configuration.

- Cooling channels connected in a single loop from the coolant inlet to its outlet are called series cooling channels. By design, if the cooling channels are uniform in size, the coolant can maintain its turbulent flow rate through its entire length. Turbulent flow enables heat to be transferred more effectively. However you should take care to minimize the temperature rise of the coolant because the coolant will collect all the heat along the entire cooling-channel path.

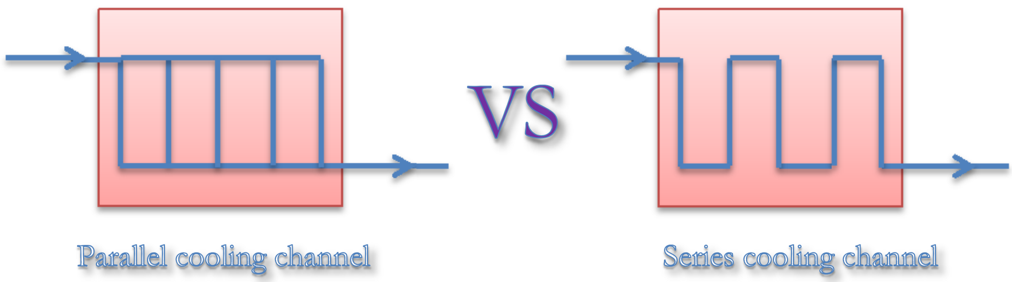


Fig. 45 Parallel versus series cooling channel

An example of well-designed water channel is expressed on the next picture (Fig. 46).

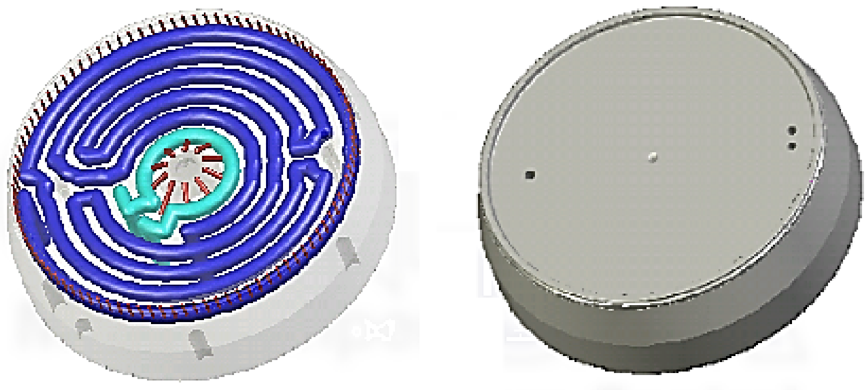


Fig. 46 Thin wall application with water cooling channel by CONTURA

Water channel can be used not only for the cooling phase, but for the heating phase too. Thus it's possible to assist the previous solution with the next one (Fig. 47).

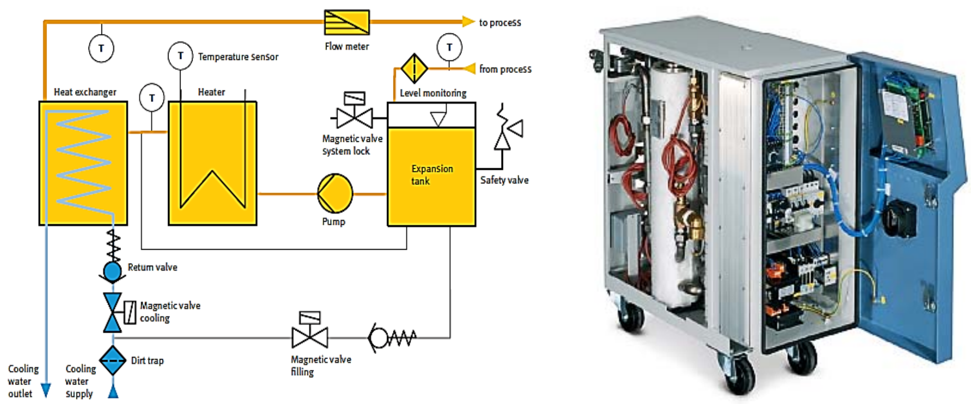


Fig. 47 Water-operated control units for high temperatures

Some industrial company already thought fully integrated systems that mix both solutions.
The result of this mix is the next (Fig. 48).

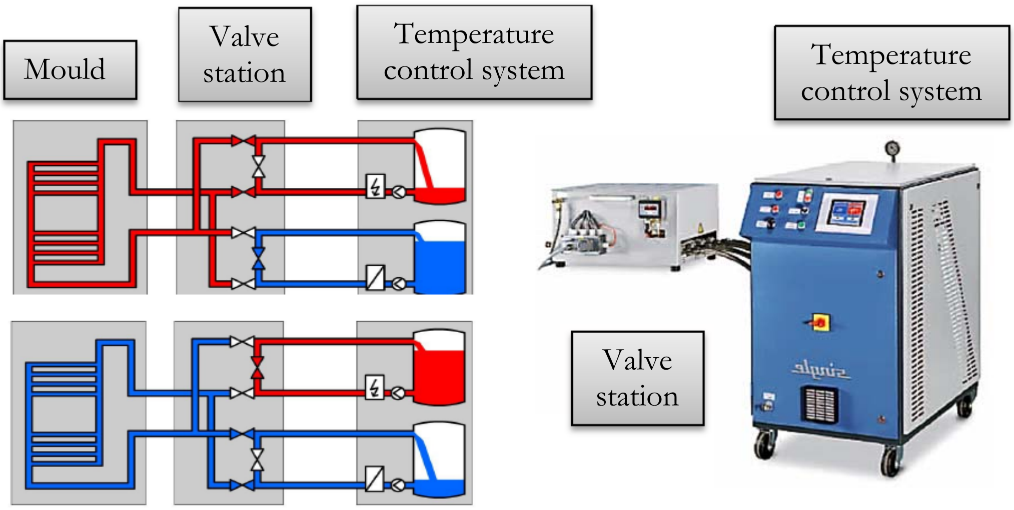


Fig. 48 Water heating and cooling system

CO_2 circuit

Water is easy to manage but it isn't the best choice in terms of cooling capacity. Other fluids can be employed; a very new implemented method works with the carbon dioxide. But auxiliary channels for the heating phase must be added.
The benefits using CO_2 instead of water is just detectable in term of temperature by the next picture (Fig. 49).

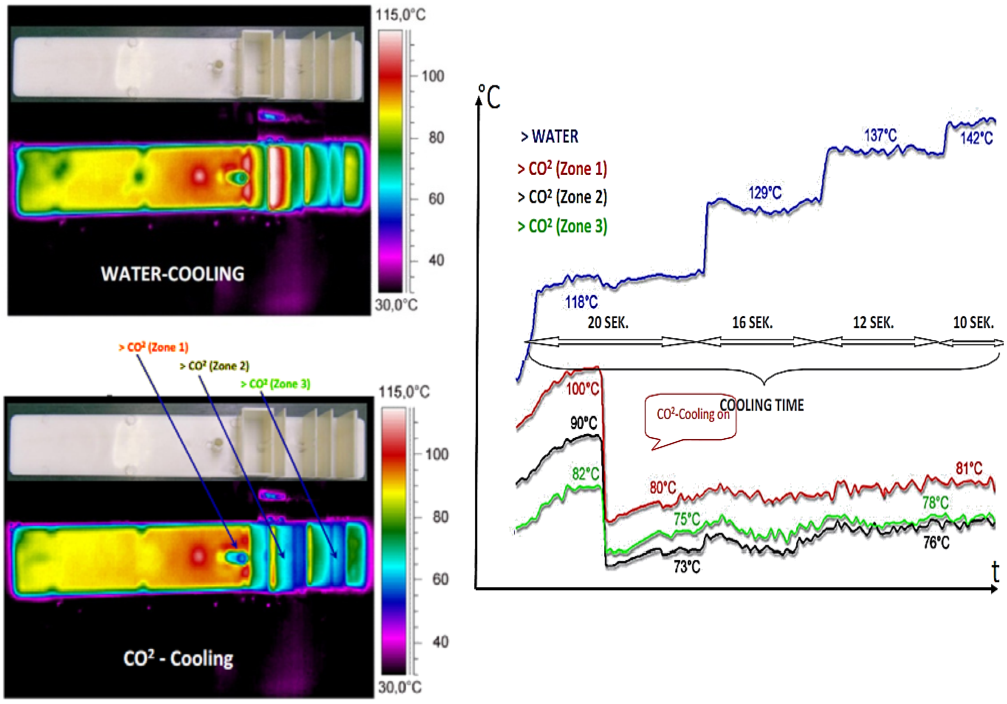


Fig. 49 Carbon dioxide cooling effects shown by RMK group

Oil circuit

Water is a perfect trade-off to heat up and cool down the mould temperature keeping the same channels. But like the cooling phase can be improved by using specific fluids the heating phase can be improved on the opposite side introducing oil (Fig. 50).

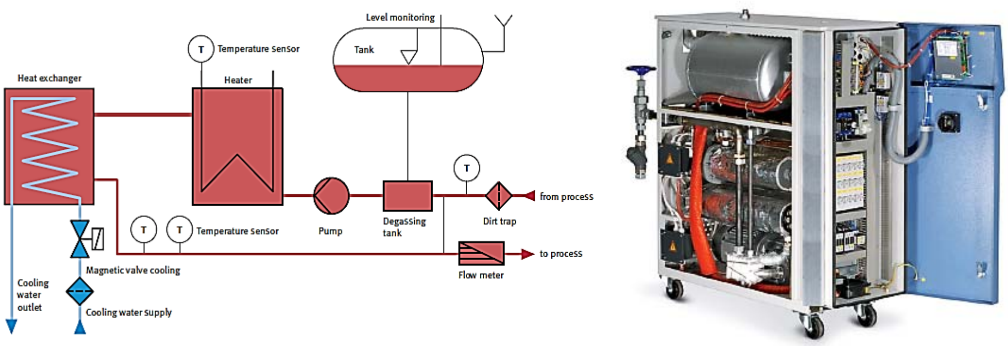


Fig. 50 High-temperature oil-operated temperature control units

Steam circuit

These systems are a good compromise due they allow keeping the same channels for both the heating phase and the cooling phase. While the cooling phase is water characterized, the heating phase is very fast because of the heat capacity of the steam.

The complex scheme of a steam-water system is shown below (Fig. 51).

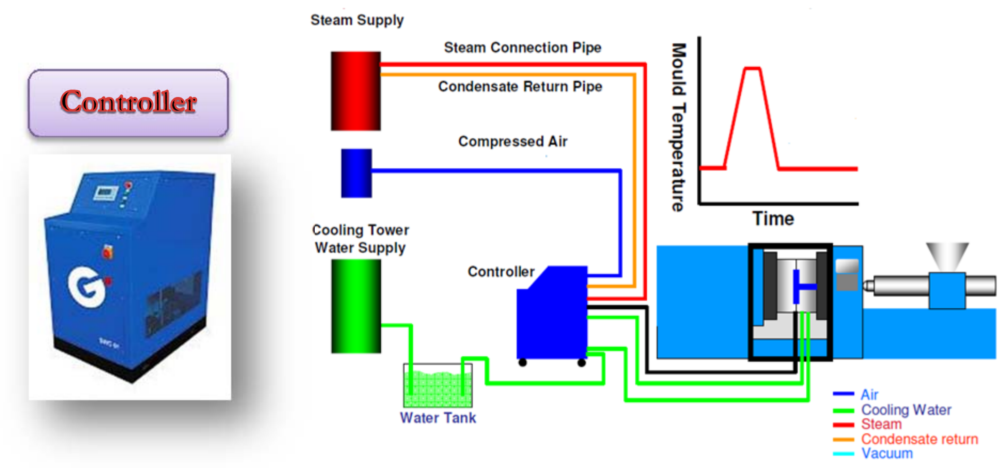


Fig. 51 Steam heating system with water cooling system assisted

TECOS Company now starts working with this kind of technology as result first experiments are made. Picture (Fig. 52) shows the first elementary steam experiment made in TECOS. This experiment has been necessary to show benefits of the steam use respect to the water use then to convince to invest money in this field.

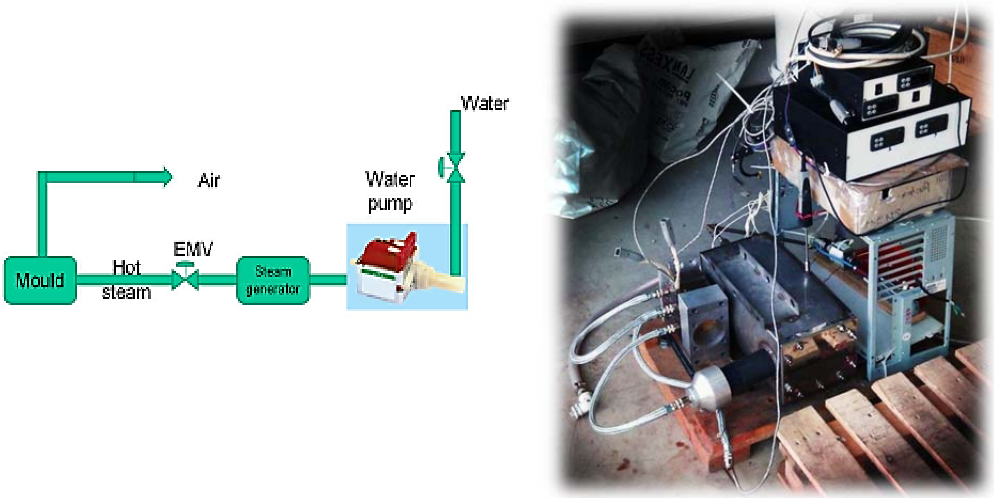


Fig. 52 First TECOS experiment with a steam generator

3.3 Heat transfer and heat stopover solutions

Isolation materials vs conductive materials

Thermal insulation provides a region of insulation in which thermal conduction is reduced. The insulating capability of a material is measured with thermal conductivity. Low thermal conductivity is equivalent to high insulating capability. Vice versa the higher thermal conductivity the good heat transfer. Metals (e.g. copper, platinum, gold, etc.) are usually good conductors of thermal energy.

Fig. 53 Isolation plates and copper tubes

Thermal pin

A heat pipe or thermal pin is a heat-transfer device that combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two solid interfaces. It's a sealed cylinder filled with a fluid. The fluid vaporizes as it draws heat from the tool steel and condenses as it releases the heat to coolant (Fig. 54). The heat transfer efficiency of a thermal pin is almost tem times as great as a copper tube.

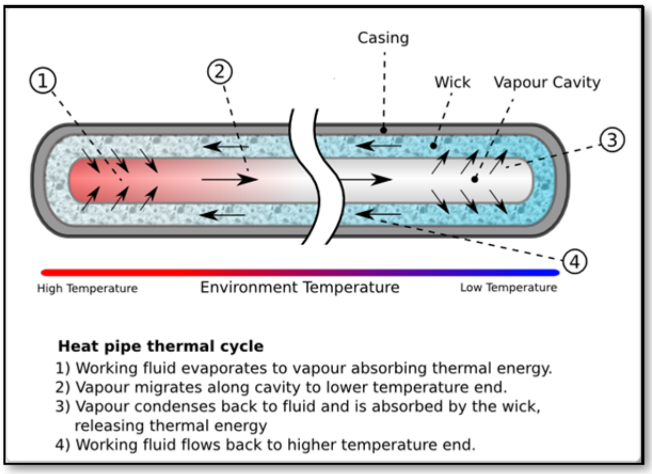


Fig. 54 Thermal pin working cycle

3.4 Inductive heating system

An electromagnetic field is created in close proximity to a conductive coil referred to as the 'work coil', preferably formed with copper tubing along which high to very high alternating electric current is passed. When electrically conductive metal, preferably steel, is positioned within the magnetic field the steel is heated rapidly. The heat transfer is controlled from a single state 'inverter', connected to thermocouples positioned in and monitoring the temperature of the steel component.
For this technology the work coil is formed in copper tubing and shaped to match the profile and configuration of the mould surface to equalize the magnetic field and therefore distribution of heat. The design of the coil is critical for the uniform temperature control of the mould surface within a range of ±5 [°C] of the set temperature. Chilled water is flowed through the copper coil in order to avoid overheating of the copper.
The system can be internal of external to the mould (Fig. 55).

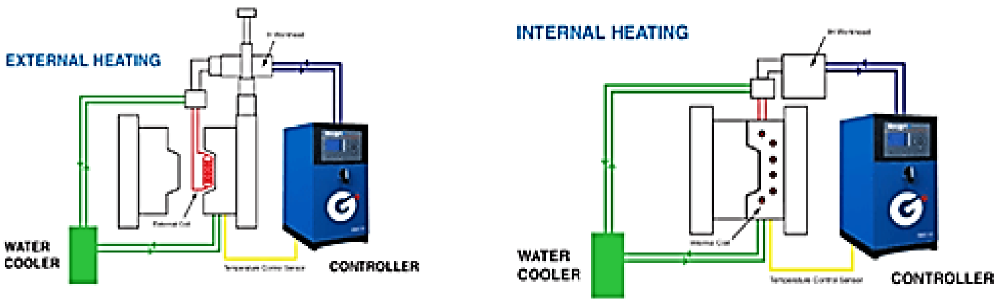


Fig. 55 Configuration for the inductive heating system

This system is a viable and competitive solution for moulding which is comparatively flat, medium to small size. Another benefit is the very efficient energy conversion and transfer compared with other alternatives.
In the case of external heating the process cycle is shown below (Fig. 56).

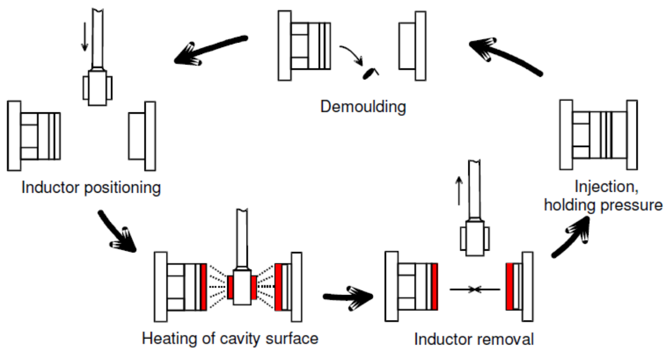


Fig. 56 External inductive heating process scheme

3.5 Integrated laser optic system

Another solution to heat up the mould quickly is the use of laser. A laser is a device that emits light (electromagnetic radiation) through a process of optical amplification based on the stimulated emission of photons. Respect to the inductive heating, laser can be up to five times faster but a special mould must be designed (Fig. 57). In addiction there are no limitation regarding the heatable mould material moreover tridimensional surfaces can be heated.

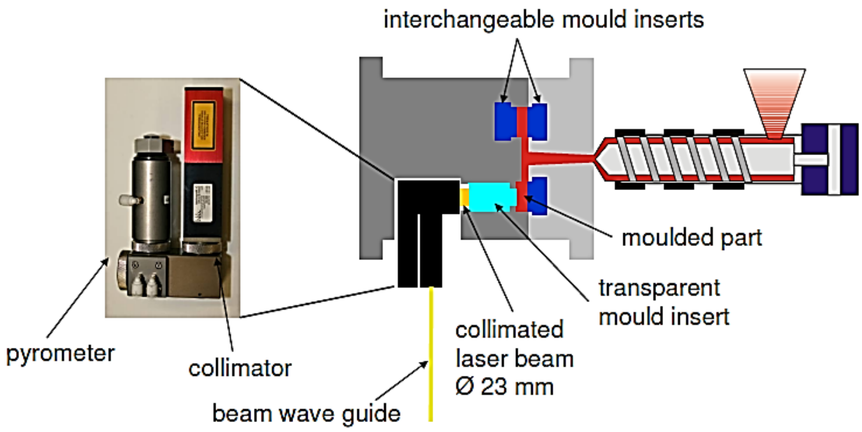


Fig. 57 Integrated laser optic system

3.6 Radiation heating

Infrared is electromagnetic radiation, similar in nature to light but in a longer wavelength range. Infrared heaters are generally classified into 3 categories according to the peak energy or peak emission wavelength of the element: ceramic elements, quartz elements and quartz tungsten elements (Fig. 58). The last emitters heat up and cool down within seconds making them particularly suitable for systems requiring short cycle times.

Fig. 58 Infrared heaters

3.7 Peltier elements

A Peltier heater or cooler is a solid-state active heat pump which transfers heat from one side of the device to the other, with consumption of electrical energy, depending on the direction of the current. The main advantages of a Peltier heater or cooler are its lack of moving parts or circulating liquid, and its small size and flexible shape. Its main disadvantage is that it cannot simultaneously have low cost and high power efficiency. Many researchers and companies are trying to develop Peltier heaters and coolers that are both cheap and efficient. TECOS is one of the first companies that attempt to implement the use of Peltier element in the field of plastic injection molding. The picture shows a mold with embedded Peltier element (Fig. 59).

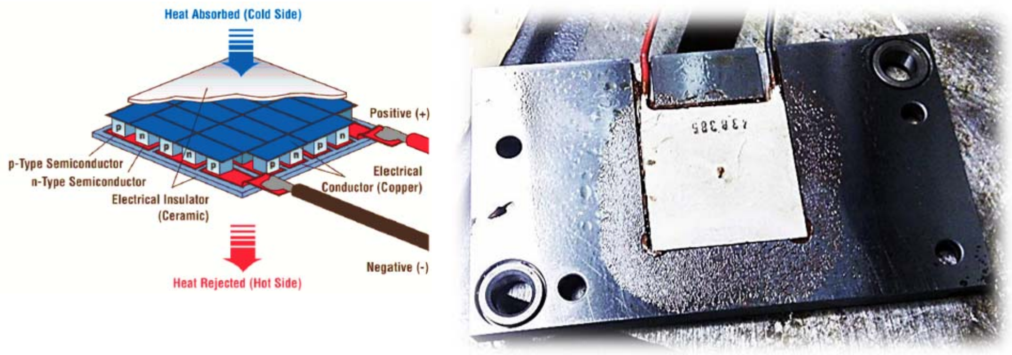


Fig. 59 Scheme of Peltier device and relative real TECOS application

3.8 Ultrasound molding

All methods shown up to now maintain unchanged the concept of injection molding process. Ultrasound molding is a new revolutionary plasticizing and molding conception using ultrasound as primary energy source, replacing traditional plasticizing idea of tempered screw and molding by high pressure.
Ultrasound is cyclic sound pressure with a frequency greater than the upper limit of human hearing. They are mechanical vibrations: acoustic waves higher than 20[KHz].
Every thermoplastic material is suitable to be molded by ultrasound technology. It allows reproducing very thin walls without warpage. Moreover the specific energy consumption is two orders of magnitude lower than the traditional one.
Ultrasound molding is especially used for the micro injection molding (Fig. 60).

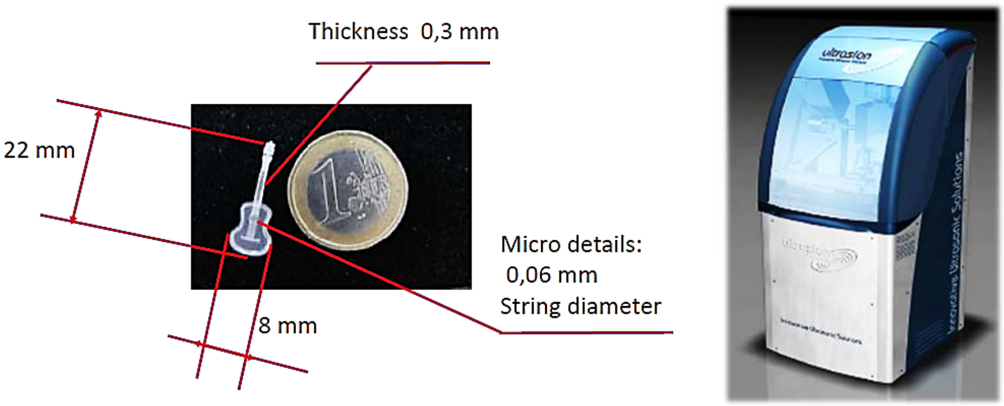


Fig. 60 Example of micro injection molding powered by Ultrasion S.L

4 Application of the systematic problem solving procedure

During the previous chapter were shown the modern solutions to the thin-wall injection molding problem. The purpose of the next analysis is to show how to provide other possible solutions starting and keeping most of the standard injection molding process. The fastest and efficient way to find the excellent solution is to apply part of the custom procedure developed by through the integration of TRIZ, OTSM-TRIZ and GTI.
TRIZ techniques are poorly known in TECOS Company therefore they are not normally used to solve problems.
This method can provide feasible solutions without time losses because it identifies the correct direction of solution. The next picture (Fig. 61) represents different approach to the problem. The brainstorming process randomly proceeds along the space of possible solutions. The TRIZ method is thought to be directed to the solution.

Fig. 61 Brainstorming versus TRIZ approach

The TRIZ path includes lots of scheme and model needed to increase the level of abstraction of the problem, in this way general and easy solution can be found. At the end, more specific solution must be thought. In any case during this chapter specific solutions will be not explored but lots of cues will be available.
The problem solving process can be symbolized with a hill as in next picture (Fig. 62). What has been written so far is just the first step of the analysis.

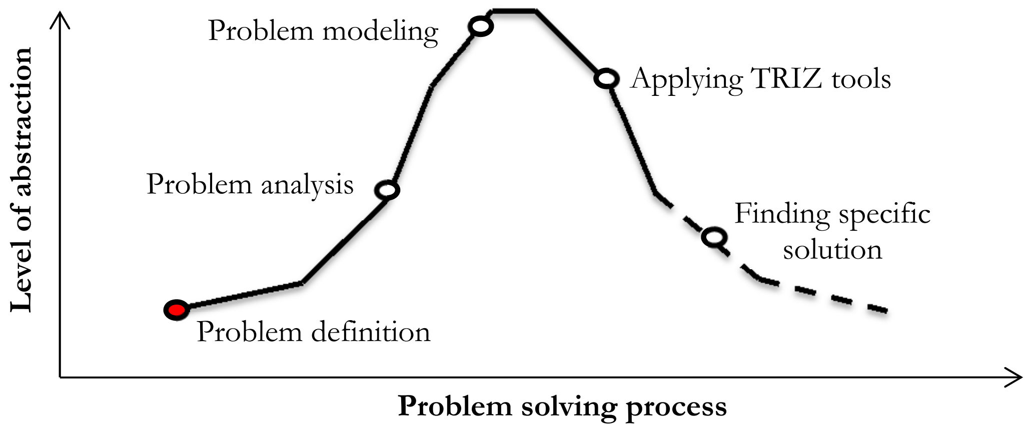


Fig. 62 Hill diagram for the problem solving process

4.1 Multiscreen analysis:

This step serves to show a larger point of view of the problem. It's part of the problem analysis.
The next table is organized by two axes. Along the X axis, time is shown instead of the Y axis that is like a magnifier. A matrix of the multiscreen analysis is commonly based on a cause-effect model. Applying these rules to the thin-wall injection molding process the next table can symbolize the problem.

Super System	What should the • **Molding machine** • **Environment** • **External devices** do in order to avoid the polymer flux stopping ?	What should the • **Molding machine** • **Environment** • **External devices** do in order to avoid the polymer cooling with a presence of defects?	What should the • **Molding machine** • **Environment** • **External devices** do in order to remedy to defects on the molded part ?
System	What should the • **Mould with semi-melted polymer** do in order to avoid the polymer flux stopping ?	What should the • **Mould with semi-melted polymer** do in order to avoid the polymer cooling with a presence of defects?	What should the • **Mould with molded part** do in order to remedy to defects on the molded part ?
Sub System	What should the • **Mould shape** • **Mould material** • **Polymer composition** do in order to avoid the polymer flux stopping ?	What should the • **Mould shape** • **Mould material** • **Polymer composition** do in order to avoid the polymer cooling with a presence of defects?	What should the • **Mould shape** • **Mould material** • **Polymer composition** do in order to remedy to defects on the molded part ?
	Past	Present	Future

Fig. 63 System operator based on cause-effect model

The scheme (Fig. 63) shows the mould with polymer as the central system. Usually prevention is better than cure, which means to look before at the past scene of the scheme.

Another possible expression of the multiscreen analysis applied to this specific problem is based on a time model and referring to the A3 IDEF0 diagram of the advanced injection molding process (Fig. 64), the axis time can be divided by three phases.

Super System	How can the • **Molding machine** • **Environment** • **External devices** keep the polymer in a liquid-state?	How can the • **Molding machine** • **Environment** • **External devices** keep the polymer in a liquid-state?	How can the • **Molding machine** • **Environment** • **External devices** convert the polymer in a solid-state?
System	How can the • **Cold mould with molten polymer** keep the polymer in a liquid-state?	How can the • **Cold mould with molten polymer** keep the polymer in a liquid-state?	How can the • **Cold mould with molten polymer** convert the polymer in a solid-state?
Sub System	How can the • **Mould shape** • **Mould material** • **Polymer composition** keep the polymer in a liquid-state?	How can the • **Mould shape** • **Mould material** • **Polymer composition** keep the polymer in a liquid-state?	How can the • **Mould shape** • **Mould material** • **Polymer composition** convert the polymer in a solid-state?
	Past : Injection phase	Present : Holding pressure phase	Future : Cooling phase

Fig. 64 System operator based on process phases model

4.2 Problem modeling

Functional problem:

As can be seen from the previous scheme there are nine different situations however not all of them are problematic situations. The functional analysis directed by the OTSM-TRIZ model identifies tools and objects then it connects them with actions. The actions can be declared using only four verbs: change, increase, decrease and stabilize. After the verb a feature is displayed and in order to avoid misunderstandings, this feature must match with the controls of the IDEF0 diagram. Only in the case of not available control then a new one can be added.
A solid line means useful action. A dashed line means useful action too though with insufficient effect. Then waved lines indicate harmful actions. Harmful actions should be defeated, not compromised at the expenses of useful actions however sometime this kind of solution it's really hard to find.
The multiscreen operator analysis has shown that problems arise into two separate frame of time. This is due to different functions performed by subjects during the injection cycle.
The standard mould roughly measures the environment temperature as a result the polymer freezes as soon as it gets into the cavity (Fig. 65).

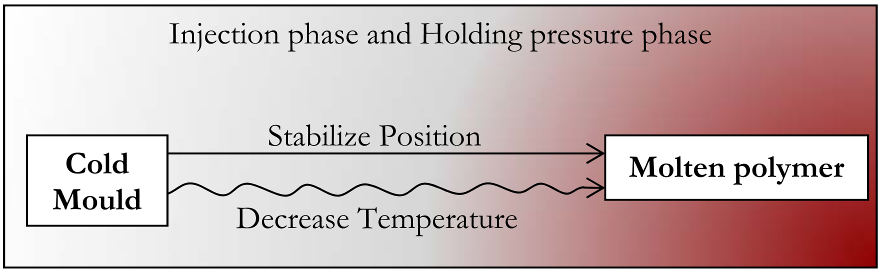


Fig. 65 Functional problem of the injection and holding pressure phases

Therefore a solution to solve the previous scheme can be: heat up the mould. Nevertheless the heated mould has the followed defined problem (Fig. 66).

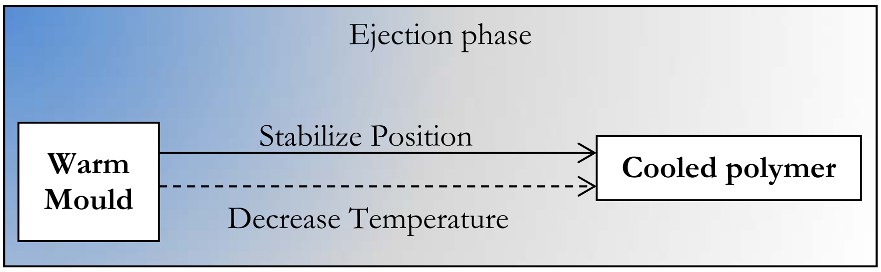


Fig. 66 Functional problem of the ejection phase

Namely the heated mould hinders the cooling period and interferes with the ejection.

Technical/Physical Contradiction Model:

From the previous path a problem has been defined. That problem has a partial solution however it generates a new problem. How to reach the contradiction model from the problem flow network is described below.
There are two visible contradictions on the same spatial location but placed on different time frame. However, what causes the contradiction is the same control parameter for the two separate cases: the mould temperature.
Variation of the Control Parameter (CP) causes effects that are measurable by Evaluation Parameter (EP).

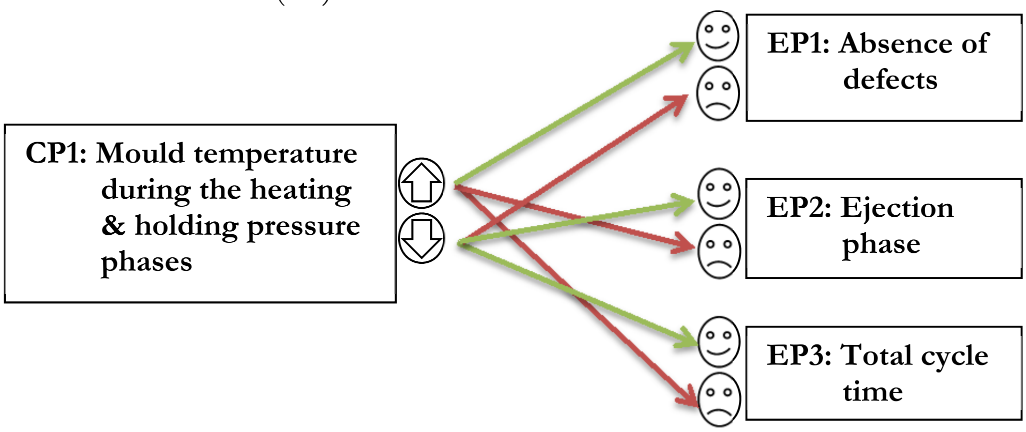


Fig. 67 Contradiction model for the control parameter number one: CP1

The first contradiction (Fig. 67) shows that increasing the mould temperature during the injection and holding pressure phases there's one benefit through two collateral effects. The contradiction on the evaluation parameter number two can be solved during the cooling phase introducing the next contradiction model (Fig. 68).

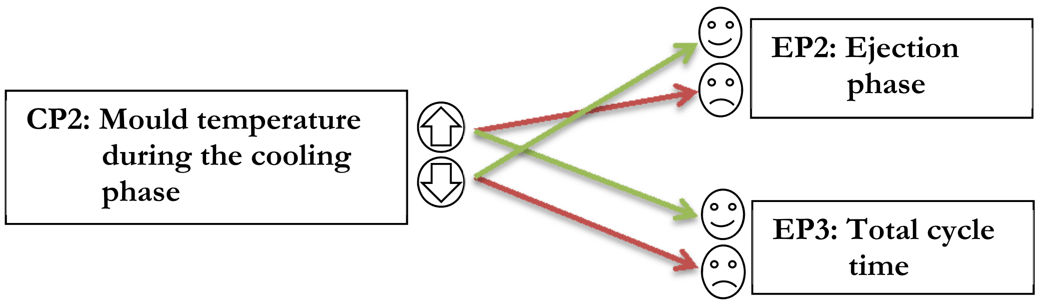


Fig. 68 Contradiction model for the control parameter number two: CP2

Overlapping both models, two benefits won at the expenses of the total cycle time by acting on the mould temperature.

4.3 Applying of suitable TRIZ tools

At this step of the analysis, the ideality peak of the problem solving process has been reached (Fig. 69). Descending down the hill means finding solutions that gradually become more practical and suitable for the real problem starting from theoretical one.

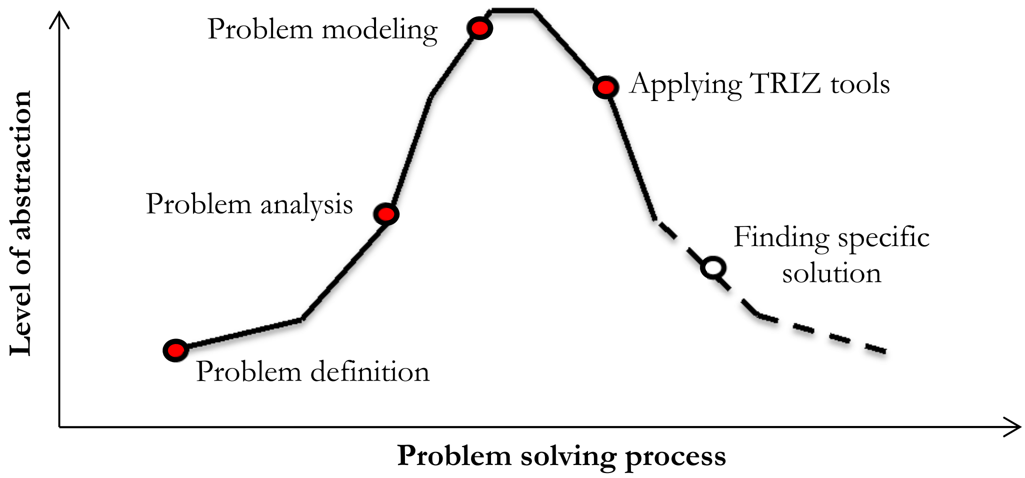


Fig. 69 Problem solving scheme: applying TRIZ Tools

4.3.1 Analysis of the contradiction

This step consists of a short procedure whose aim is finding simple direction of solutions.

- Identify the Operational Zone
- Identify the Operational Time
- Exaggerate the Contradiction
- Search for resources which could play the role of further control parameters for the same contradiction
- Apply the appropriate Inventive Principle

Solution can be found by the using of forty inventive principles that are provided by TRIZ theory. There are four main action categories where all principles can be divided: In space, In time, On condition and Macro-micro level.

Operational Zone and relative Separation in Space

The operational zone is the place where the conflict occurs. Thus it needs to identify the functions directly related to the conflicting evaluation parameters (EP). It's necessary to clarify the zone of each function as the region of interaction between the tool and the object, and then the union of these zones is the operational zone for the whole contradiction (Fig. 70). If different functions have diverse operational zone then Separation in Space is a candidate direction of solution.

Fig. 70 Operational zone

Four functions were previously found by the problem modeling (Fig. 70).

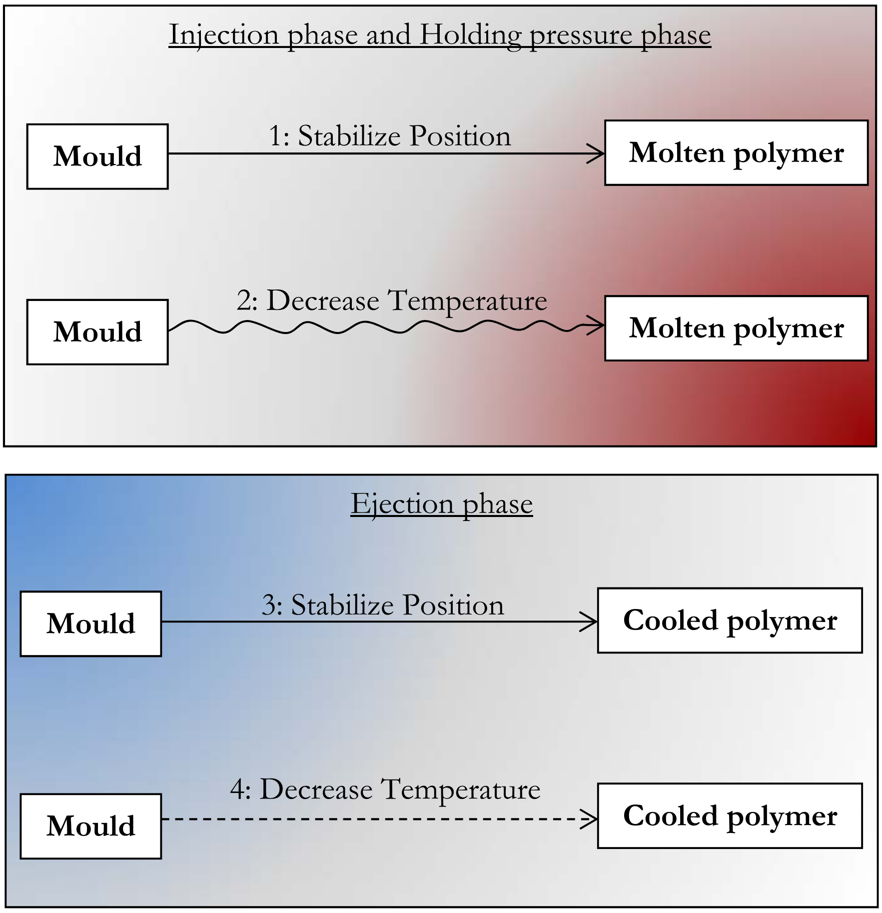


Fig. 71 Operational zone applied to every function

All functions apparently share the same operational zone: the surface containing the shape to be molded. A real sample is shown below (Fig. 72), the rest of the mold is completely irrelevant with considering functions described above. Thus it would be better to heat up and cool down only this little area rather than total mold.

Operational zone includes also mold position. The first function (1: Stabilize Position) works during injection phase and holding pressure, namely when high pressures are applied in order to avoid defects. Thus during this phase the mold has to be on the machine. On the other hand, regarding the cooling phase, not a big pressure is applied on the injection channel so machine is not strictly necessary in this phase. It's only important that the mold remains tight closed, but this situation can happen also far from the injection system.

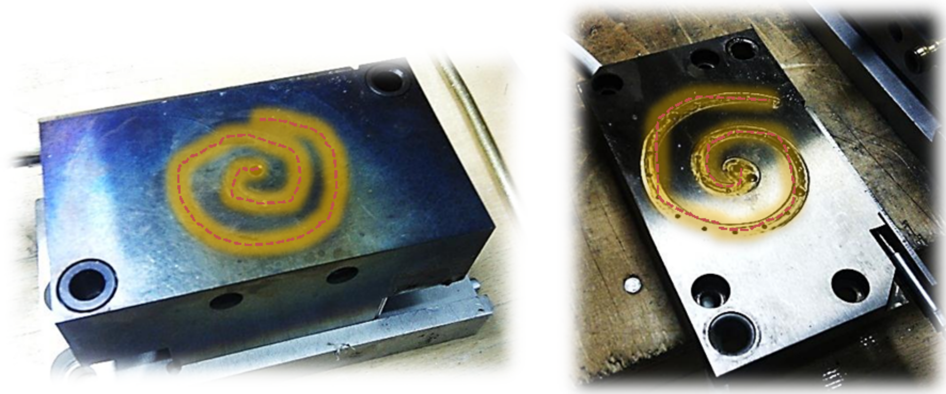


Fig. 72 Operational zone applied to a real mold

Operational Time and relative Separation in Time

The operational time is the time which the conflict occurs. Same reasoning saw for the space can be applied for the time. In this case time has already been divided into two separate moments. But then something else can be done. Total operational time can be split into 3 instants: time before conflict, time of a conflict and time after a conflict. Therefore watching at the problem from this point of view it clearly appears that the mold surface, identified by the operational zone, can be heated before the injection phase; whereas it should be able to remain warm only for few seconds. Thus function of stabilization and function of heating acts separately.
Unfortunately, the second contradiction cannot be further separated from the point of view of time because the useful action (3: Stabilize Position) and the insufficient one (4: Decrease Temperature) act in the same period. However as it seen if it acts with a heating and a cooling in two separate time instants, remain only benefits at the expense of a longer cycle time.

Problem reformulation

Before proceeding, the problem must be reformulated according to what has been discovered.

1. Prior the injection the mold can be heated. During this phase contact between mold and injection unit is not necessary. Mold cavity doesn't contain polymer, thus it can be heated by internal or external systems (Fig. 73).

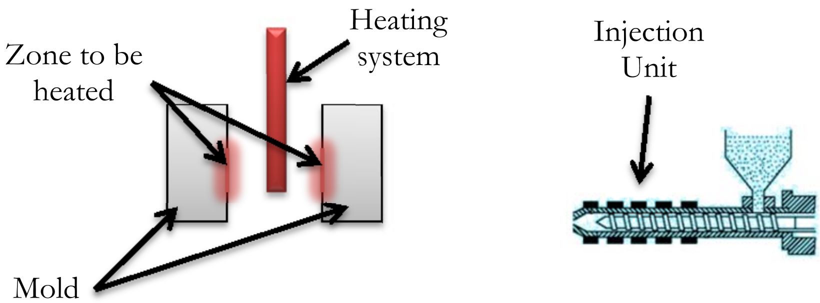


Fig. 73 Mold heating scheme

2. During the injection the mold must withstand high pressures and the cavity has to remain warm enough allowing the mold filling by the injection unit (Fig. 74).

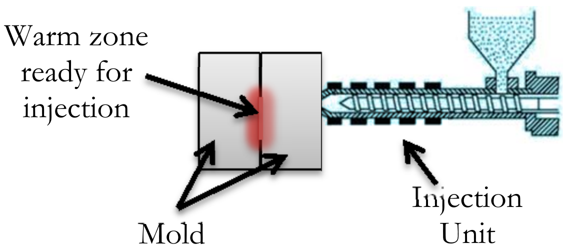


Fig. 74 Mold filling scheme

3. After injection, the cavity containing hot polymer must be cooled. As in the first phase as in this one, the contact between mold and injection unit is irrelevant, however the mold must be kept closed in order to prevent spillage of the molten polymer (Fig. 75). When polymer reaches the ejection temperature the mold can be opened.

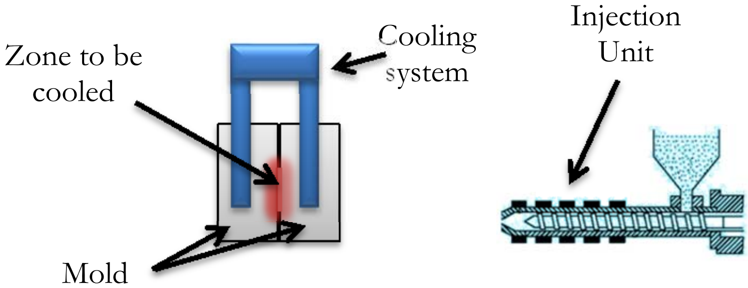


Fig. 75 Mold cooling scheme

Problem reformulation changes the problem contradiction. The new contradiction model now concerns to mould temperature-changing versus the time to get this variation (Fig. 76).

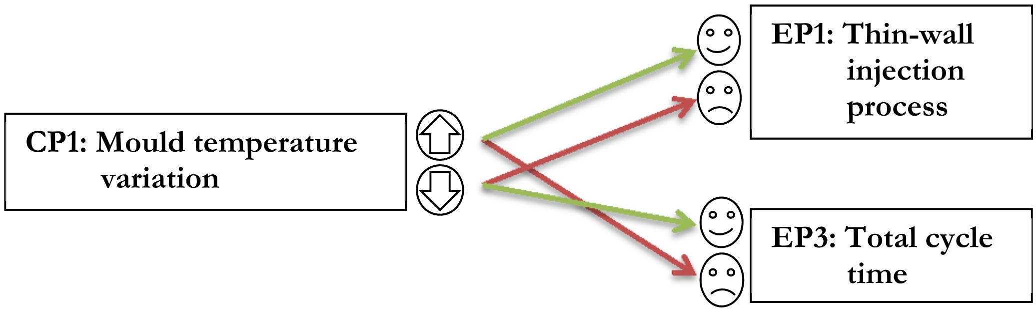


Fig. 76 Reformulation of the contradiction model

Thus a first ideal solution is machinery with movable injection unit combined with fast heating and cooling system.

Inventive principles

The Altshuller's Matrix is a database of knows solutions (principles) able to overcome contradictions.
Identify the parameter it wants to improve with one of the generic technical parameters located along the left vertical column. Respectively, identify the parameter that gets worse with one of the generic parameters located along the horizontal row of parameters.

To improve: **Temperature** Gets worse: **Loss of time**.

Find a cell in the matrix which is the intersection of vertical and horizontal axes respectively the parameters you selected. There are several numbers which indicate which inventive principles to use to solve the problem.
A principle listed first in a selected cell of the matrix was most frequently used to solve this type of contradiction.

{35} Parameter changes

- Change an object's physical state (e.g. to a gas, liquid, or solid.)
  - Freeze the liquid centers of filled candies, and then dip in melted chocolate, instead of handling the messy, gooey, hot liquid.
  - Transport oxygen or nitrogen or petroleum gas as a liquid, instead of a gas, to reduce volume.

- Change the concentration or consistency.
  - Liquid hand soap is concentrated and more viscous than bar soap at the point of use, making it easier to dispense in the correct amount and more sanitary when shared by several people.
- Change the degree of flexibility.
  - Use adjustable dampers to reduce the noise of parts falling into a container by restricting the motion of the walls of the container.
  - Vulcanize rubber to change its flexibility and durability.
- Change the temperature.
  - Raise the temperature above the Curie point to change a ferromagnetic substance to a paramagnetic substance.
  - Raise the temperature of food to cook it. (Changes taste, aroma, texture, chemical properties, etc.)
  - Lower the temperature of medical specimens to preserve them for later analysis.

{28} Mechanics substitution

- Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.
  - Replace a physical fence to confine a dog or cat with an acoustic *fence* (signal audible to the animal).
  - Use a bad smelling compound in natural gas to alert users to leakage, instead of a mechanical or electrical sensor.
- Use electric, magnetic and electromagnetic fields to interact with the object.
  - To mix 2 powders, electrostatically charge one positive and the other negative. Either use fields to direct them, or mix them mechanically and let their acquired fields cause the grains of powder to pair up.
- Change from static to movable fields, from unstructured fields to those having structure.
  - Early communications used omnidirectional broadcasting. We now use antennas with very detailed structure of the pattern of radiation.
- Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.
  - Heat a substance containing ferromagnetic material by using varying magnetic field. When the temperature exceeds the Curie point, the material becomes paramagnetic, and no longer absorbs heat.

{21} Skipping

- Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.
  - Use a high speed dentist s drill to avoid heating tissue.
  - Cut plastic faster than heat can propagate in the material, to avoid deforming the shape.

{18} Mechanical vibration

- Cause an object to oscillate or vibrate.
  - Electric carving knife with vibrating blades
- Increase its frequency (even up to the ultrasonic).
  - Distribute powder with vibration.
- Use an object's resonant frequency.
  - Destroy gall stones or kidney stones using ultrasonic resonance.
- Use piezoelectric vibrators instead of mechanical ones.
  - Quartz crystal oscillations drive high accuracy clocks.
- Use combined ultrasonic and electromagnetic field oscillations.
  - Mixing alloys in an induction furnace Use piezoelectric vibrators instead of mechanical ones.

It needs to interpret proposed inventive principles in terms of specific product. The recommended principles are very general. Regard them as guidelines for further thinking and searching for a solution to the problem.
Some hints were found like:

- Use substances with a different physical state is a direction of solution
- Localize heating and cooling in the interesting area. Use a surface coating, located in the area of interest.
- Make a modular mold according to the phase to which is subjected
- Use a material sensitive to the effects of heating and/or cooling without directed contact, like electromagnetic field, ultrasound or other scientific effect.

Usually if no solution can be proposed in terms of formulated contradiction, try to change the parameter that gets worse. Formulate a new contradiction. Repeat the problem solving process, thus redefine the parameter that it wants to improve and formulate a new contradiction.
If the Altshuller's matrix does not help after several attempts, use Inventive Standards, Pointer to Physical effects or ARIZ.

4.3.2 Substance-Field analysis

Once localize the part of the product where a problem arises this analysis can start. It might as well include components of a surrounding environment which interact with the product.
Substance-Field (Su-field) Analysis is a TRIZ analytical tool for modeling problems related to existing technological systems. Every system is created to perform some functions. The desired function is the output from an object or substance (S1), caused by another object (S2) with the help of some means (types of energy, Field, F). The general term, substance has been used in the classical TRIZ literature to refer to some object. Substances are objects of any level of complexity. They can be single items or complex systems. The action or means of accomplishing the action is called a field. Su-field Analysis provides a fast, simple model to use for considering different ideas drawn from the knowledge base (Fig. 77).

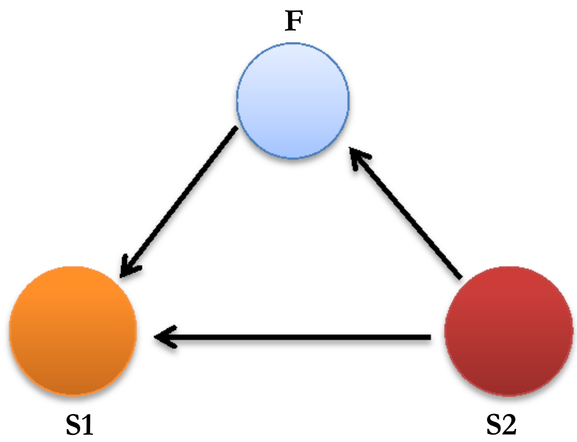


Fig. 77 Substance/Field model

If the problem includes interaction between two components, define what type of physical interaction exists between the two selected components and what physical field provides the interaction.
The identification of substances (**S1** and **S2**) depends upon the application. Either substance could be a material, tool, part, person or environment. **S1** is the recipient of the systems action. **S2** is the means by which some source of energy is applied to **S1**. The source of energy, or field (**F**), which acts upon the substances, is often:

(Me) - Mechanical
(Th) - Thermal
(Ch) - Chemical
(E) - Electrical
(M) - Magnetic
(G) - Gravitational

Select one or two substance objects of the product which cause problem, or have to be changed, or which properties have to be measured or detected.
Indicate what type of unsatisfactory interaction is between the components. Is it missing, excessive, harmful or insufficient? Draw a corresponding line between the components. A type of the line indicates the problem.

Su-field modeling applied to both situations that happen during the thin-wall injection molding process is the following (Fig. 78).

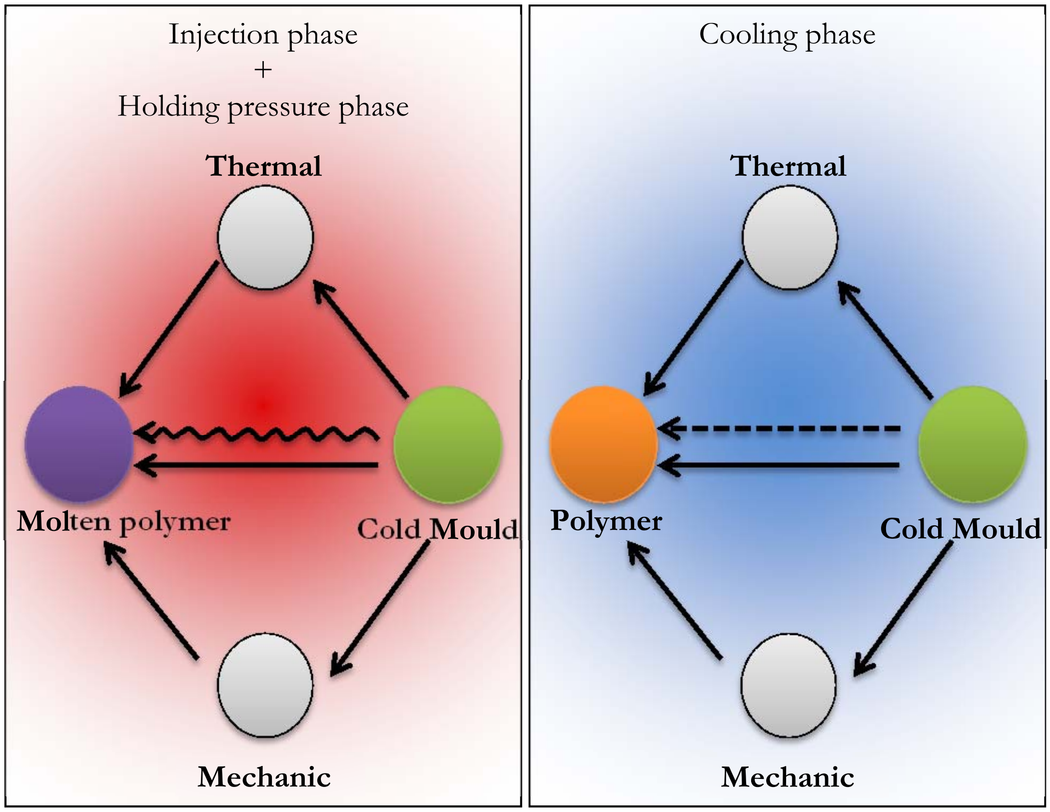


Fig. 78 Substance-Field model applied to thin-wall injection molding process: Model 1, Model 2

The cold mould is harmful during the first phase while the cold mould is not cold enough during the second phase.

In classical TRIZ the 76 Standard Solutions are grouped into five classes like in the scheme.

Classification of Standards

- Class 1: Improving interactions and eliminating harmful effects
  - Class 1.1: Synthesis and improvement of a Su-Field
  - Class 1.2: Destruction of a Su-Field
- Class 2: Evolution of systems
  - Class 2.1: Transition to complex Su-Fields
  - Class 2.2: Use of available level resources
  - Class 2.3: Rhythm Coordination
  - Class 2.4: Complex Forced Su-Fields
- Class 3: Transition to macro and micro levels
  - Class 3.1: Bi-Poly Systems
  - Class 3.2: Transition to micro
- Class 4: Detection and Measurement problems
  - Class 4.1: Roundabout ways
  - Class 4.2: Synthesis and improvement of measuring systems
  - Class 4.3, 4.4, 4.5: Further development of measuring systems
- Class 5: Meta-solutions, helpers
  - Class 5.1: Introduction of Substances
  - Class 5.2: Introduction of Fields
  - Class 5.3: Use of Phase Transitions
  - Class 5.4: Application of Physical Effects
  - Class 5.5: Application of Chemical Effects

It needs to define what type of problem is. Is it a modification problem or a problem which deals with detection or measurement? Or it wants to predict the evolution of the selected component or a product?

- Every situation refers to classes of the standards which have to be used use: Modification problem: Classes 1 and 2
- Measurement/ Detection problem: Class 4
- Prediction problem: Class 2 and 3
- Class 5 specifies how to introduce new components to a system under restrictions on introduction of new components.

Modification Problem

If the problem involves a single component it want to change, use Standard 1-1-1 and go to the phase of verification of a solution.
Select which group of Standards it will use. If the problem involves a harmful interaction, go to the standards of Group 1.2. If the interaction is insufficient or excessive, go to Group 1.1.
Browse each inventive standard until you find a standard with the left part matching your substance-field model.
Complete or change initial substance-field model as recommended by the selected inventive standard.
If it is unclear what new field or substance to choose, use lists of fields (Fig. 79) and substances (Fig. 80) to find out if the fields or substances listed can be introduced and solve the problem.

FIELDS AND FORCES			
Mechanical Fields	**Electromagnetic fields**	**Other fields**	**Field Dynamics**
Gravity forces	Electric discharges	Heating	Single wave
Friction forces	Electrostatic field	Cooling	Oscillation
Elasticity	Electric current	Thermal shock	Pulsation
Internal tension	Skin current	Odor	Resonance
Inertia	Foucault currents	Taste	Standing wave
Centrifugal forces	Magnetic field	Chemical reactions	Traveling wave
Lifting forces (lifting)	Microwaves	Nuclear forces	Field gradient
Mechanical vibrations (oscillations)	Electromagnetic field		Reflection
Acoustic vibrations(oscillations)	Radio waves		Refraction
Buoyancy	Infrared waves		Focusing
Pressure of liquids and gases	Coherent light (laser)		Shielding
Diffusion	Visible light		Amplification
Osmosis	Ultraviolet rays		Scanning
Thermal tension	X-rays		Scattering
Sound	Electron beam		Interfering
Ultrasound			Expansion
Coriolis forces			Structuring
			Filtering

Fig. 79 Table of Field and Forces for a Su-Field model

SUBSTANCES		
States of substance	**Transformable substances**	**Other substances**
Perforated	Evaporated	Adhesive
Porous	Boiled	Easily breakable
Elastic	Sublimated	Easily removable
Granulated	Condensed	Bimetallic
Powdered	Melted	Luminescent
Liquid	Mixed	Changing color
Gel	Gas-generating/absorbing	With low or high friction
Paste	Liquid-generating/absorbing	Conductive
Emulsion	Dissolved/crystallized	Electrorheological fluid
Suspension	Hardened	Semiconductive
Foam	Polymerized/de-polymerized	Ferromagnetic fluid
Aerosol	Heat generating/ absorbing/accumulating	Ferromagnetic solids/powders
Gas	Explosive	Magnetic
Plasma	Flammable	Dielectric
	With shape memory	Transparent
	With Curie Point	Photosensitive
	Piezoelectric	Photochromatic
	Mixed/composed/decomposed	X-ray sensitive
	Products of dissociation/recombination	Changing electrical resistance
		Chemically active

Fig. 80 Table of Substances for a Su-Field model

According to the system of standard solutions, the following transformation may be applied to a Su-Field System:

- Introduction of a New Substance: a new element, an internal additive, an external additive, a resource already available in the environment.
- Introduction of a New Field
- Modification of a Substance, modification of the Tool, modification of the Object, modification of the environment surrounding the substances of the Su-Field System.
- Modification of a Field
- Use of Physical, Chemical, Geometrical Effects;
- A combination of any of the previous transformations.

The previous modifications can be applied to a whole element or to a portion in terms of changes/variations of any resource, such as:

- Space: number of dimensions, topology, shape, size;
- Time: timing of action, duration of action, frequency of action;
- Properties: chemical properties, physical (electrical, magnetic, optical…) properties
- Energy: amount of energy, type of energy (kinetic, thermal, electrical…)

Applying of standard solutions

Referring to Model1 and Model2 of Fig. 78 the suitable standard solutions are:

- STANDARD 1.1.2: Improving interactions by introducing additives into the objects

If there is a Substance-Field System which is not easy to change as required, and the conditions do not contain any limitations on the introduction of additives to given substances, the problem is to be solved by a transition (permanent or temporary) to an internal complex Substance-Field System, introducing additives in the present substances. These additives enhance controllability or impart the required properties to the Substance-Field System (Fig. 81).

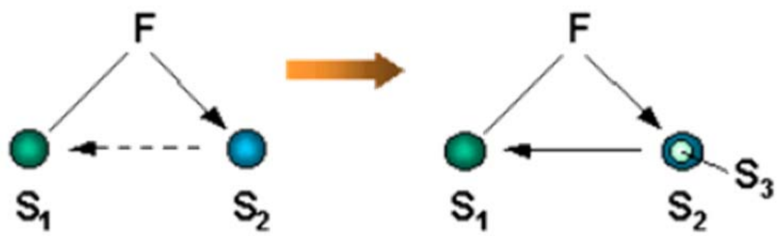


Fig. 81 STANDARD 1.1.2

Introduce a frictionless material inside the polymer (or on the mold surface) in order to facilitate the slip and the desired position (mold filling).

- STANDARD 1.1.3: Improving interactions by introducing additives into a system

If there is a Substance-Field System which is not easy to change as required, and the conditions contain limitations on the introduction of additives into the existing substances, the problem can be solved by a transition (permanent or temporary) to an external complex Substance-Field System, attaching to one of these substances an external substance which improves controllability or brings the required properties to the Substance-Field System (Fig. 82).

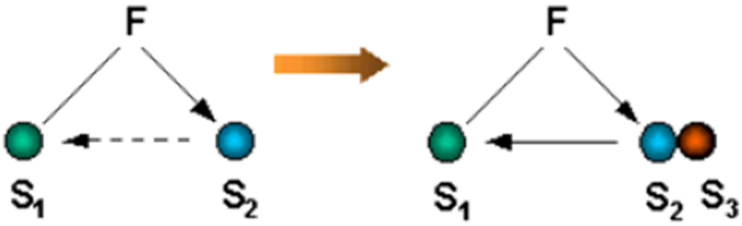


Fig. 82 STANDARD 1.1.3

Introduce a conductive material in order to help heat transfer between the surface of interest and the mold during the cooling phase

- STANDARD 1.1.7: Providing maximum of effect of action

If a maximum effect of action on a substance is required and this is not allowed, the maximum action has to be preserved but directed to another substance attached to the first one (Fig. 83).

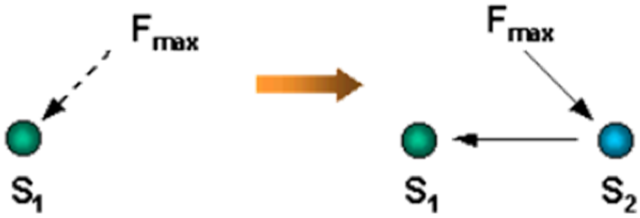


Fig. 83 STANDARD 1.1.7

Cool down the mold in order to increase the velocity of polymer cooling.

- STANDARD 1.1.8.1: Providing selective effect by maximum field and protective substance

If a selective effect of action is required (maximum in certain zones, while the minimum is maintained in other zones), the field has to be maximal; then a protective substance is introduced in places where a minimum effect is required.

Heat up or cool down the mold surface making it isolated from the rest of the mold namely only in the restricted area of interest rather than the full mold.

- STANDARD 1.2.1: Elimination of harmful interaction by a foreign substance

If useful and harmful effects appear between two substances in a Substance-Field System and there is no need to maintain a direct contact between the substances, the problem is solved by introducing a third substance between them (Fig. 84).

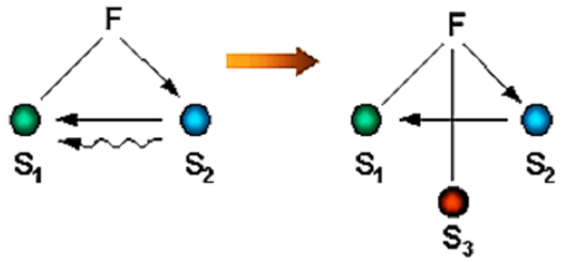


Fig. 84 STANDARD 1.2.1

Place an insulating coating which allows the polymer to flow into the cavity but avoiding the heat transfer during the injection phase and holding pressure phase.

- STANDARD 1.2.2: Elimination of harmful interaction by modification of an existing substance

If there are a useful and a harmful effects between two substances, and there is no need to maintain direct contact between the substances, and it is forbidden or inconvenient to use foreign substances, the problem can be solved by introducing a third substance between the two. In this case, the third substance is to be a modification of the first or the second substances (Fig. 85).

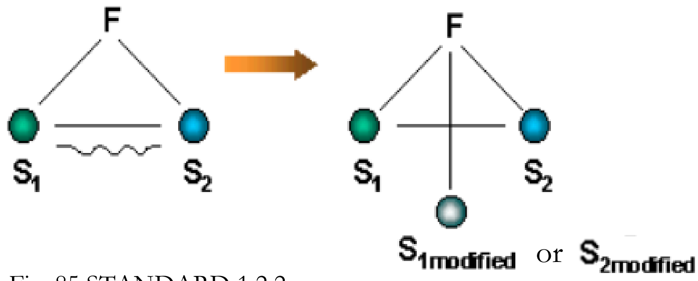


Fig. 85 STANDARD 1.2.2

Make the entire mold of an insulating material but which is wear resistant, high pressures resistant and high temperatures resistant.

- STANDARD 1.2.4: Elimination of a harmful effect by a new field

If useful and harmful effects appear between two substances in a Substance-Field System, and a direct contact between the substances must be maintained, the problem can be solved by transition to a dual Substance-Field System, in which the useful effect is provided by the existing field while a new field neutralizes the harmful effect (or transforms the harmful effect into a useful effect) (Fig. 86).

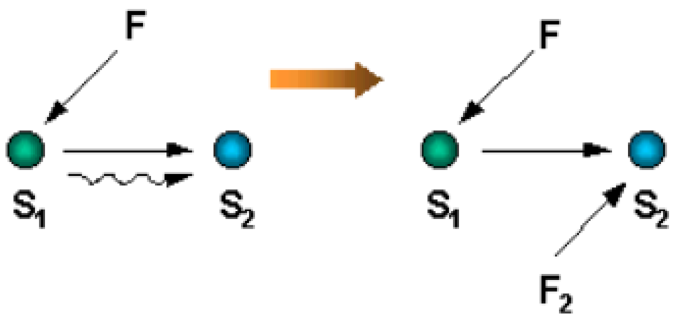


Fig. 86 STANDARD 1.2.4

Heat up the mold in order to prevent polymer cooling.

- STANDARD 2.1.1: Synthesis of a Chain Substance-Field System

Efficiency of Substance-Field System can be improved by transforming one of the parts of the Substance-Field System into an independently controllable Substance-Field System, thus forming a chain Substance-Field System (Fig. 87).

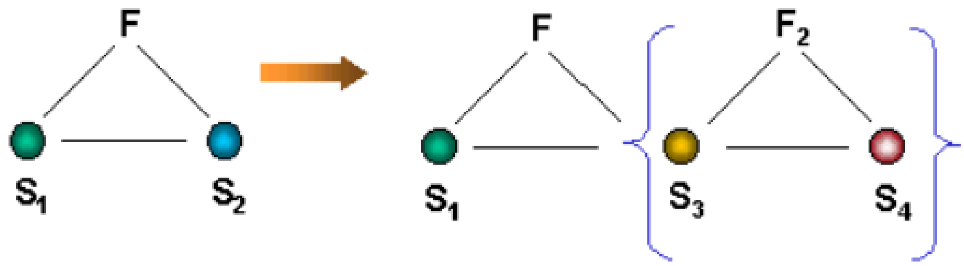


Fig. 87 STANDARD 2.1.1

It's a solution of a mold with integrated heating and/or cooling system.

- STANDARD 2.1.2: Synthesis of a Dual Substance-Field System

If it is necessary to improve the efficiency of Substance-Field System, and replacement of Substance-Field System elements is not allowed, the problem can be solved by the synthesis of a dual Substance-Field System through introducing a second field which is easy to control (Fig. 88).

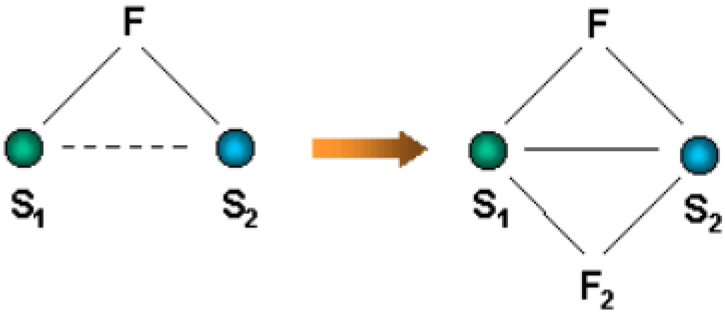


Fig. 88 STANDARD 2.1.2

Use electric field combined with thermal field like in Peltier effect to get mold cooling.

- STANDARD 2.2.2: Increasing a degree of fragmentation of substance components

Efficiency of a Substance-Field System can be improved by increasing the degree of fragmentation of the object which acts as a "tool" in Substance-Field System, which in the end of its evolution will be replaced with a new field that can deliver a function of the tool (Fig. 89).

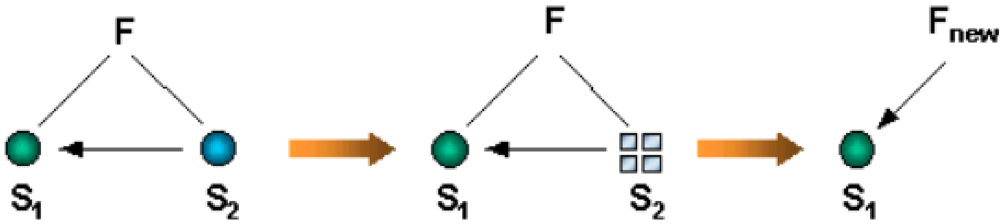


Fig. 89 STANDARD 2.2.2

Make the mold divisible into several parts as many functions as it has.

- STANDARD 2.2.3: Transition to capillary porous objects

Efficiency of a Substance-Field System can be improved by replacing a solid object in the Substance-Field Mode with a capillary porous one (Fig. 90).

The further evolution of the capillary porous objects passes the following phases:

1. Solid object
2. Object with one cavity
3. Object with multiple cavities (perforated)
4. Capillary porous object
5. Capillary porous object with a predefined porous structure.

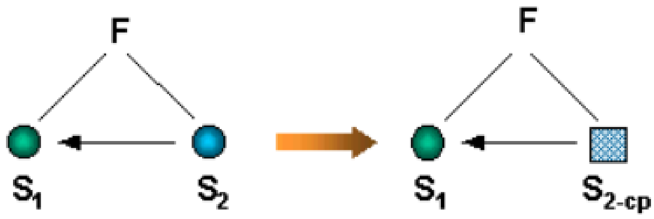


Fig. 90 STANDARD 2.2.3

Make porous part of the mold, the porosity allows hot or cold fluids to pass through, but at the same time maintains the structure resistant to stress.

- STANDARD 2.3.2: Matching/unmatching frequencies

Efficiency of a complex Substance-Field System can be improved by matching (or mismatching) frequencies of the fields being used.

Make the mold heating and the mold cooling compatible with the phases of the injection molding cycle in order to avoid loss of time.

- STANDARD 2.4.1: Synthesis of a Substance-Field System with ferromagnetic substance

Efficiency of a Substance-Field System can be enhanced by introducing a ferromagnetic substance and a magnetic field to the system (Fig. 91).
The standard indicates the use of a ferromagnetic substance that is not in a fragmented state. Ferromagnetic substances can be introduced to all types of Substance-Field Systems (listed in class 1).

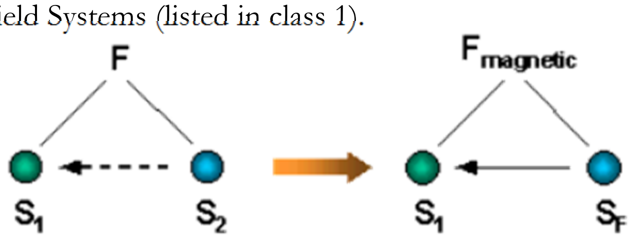


Fig. 91 STANDARD 2.4.1

Use the magnetocaloric effect to get the mold cooling

Scientific effects

Hereinafter is a short list where scientific effects without detail are mentioned

- Magnetocaloric effect

The magnetocaloric effect is a change in the temperature of a magnetic caused by an adiabatic change in the intensity of the magnetic field in which it is placed.
Thus, paramagnetics and ferromagnetics become heated in the process of magnetization. For ferromagnetics, this effect has maximum values around the Curie point; for paramagnetics, the magnetocaloric effect increases as the temperature decreases. When the field changes adiabatically, the alignment of moments is destroyed partially or fully (if the field is switched off) at the expense of the internal energy. This leads to cooling of the magnetic.
Magnetic refrigeration is a cooling technology using the magneto-caloric effect (Fig. 92). While the thermoelectric cooling is operated by applying electrical voltage, the magnetic refrigeration is driven by applying magnetic field. With applying magnetic fields, randomly oriented magnetic spins align along the magnetic field's direction, thereby decreasing the magnetic entropy and heat capacity. From the repeating magnetization and demagnetization processes with heat transfer from the material into outside of the system, the irreversible magnetic entropy change gives rise to the magnetic cooling. The issues of the magneto-caloric materials development for commercial uses are the higher critical temperatures than room temperature and the giant spin entropy change near transition temperature. For the fundamental materials research, we'll study on the crystalline field effect, magnetic phase transition, and structural phase transition for various magnetic materials.

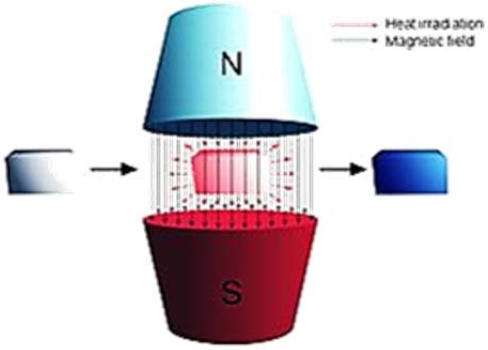


Fig. 92 Magnetic refrigeration

- Peltier Effect

The Peltier effect describes production of absorption of heat when the electric current passes through a contact between two dissimilar conductors. When the current direction is switched, heat production is replaced by absorption. This effect has been already described in the previous chapter.

- Photo-adsorption effect

Adsorption commonly refers to the process of assimilation of a substance on the surface of a body. Light radiation may have an effect on this process.
The photo-adsorption effect refers to the dependence of the adsorption capacity of an adsorbent (semiconductor) on lighting. This capacity may increase (positive photo-adsorption) or decrease (negative photo-adsorption).
This effect is used in regulation of pressure in a closed volume. The photo-adsorption effect is influenced by an electric field. The field is applied perpendicularly to the surface of the semiconductor (adsorbent).

- Ranque-Hilsch Effect

Compressed air is supplied to the vortex tube and passes through nozzles that are tangent to an internal counterbore. These nozzles set the air in a vortex motion.
This spinning stream of air turns and passes down the hot tube in the form of a spinning shell, similar to a tornado. A valve at one end of the tube allows some of the warmed air to escape. What does not escape, heads back down the tube as a second vortex inside the low-pressure area of the larger vortex. This inner vortex loses heat and exhausts thru the other end as cold air.
This effect is used in vortex tube to create cold and hot air streams from the compressed air.

- Ultrasound

Sound frequencies above the audibility threshold are called ultrasonic frequencies. Conventionally, the boundary of ultrasonic waves is around 20 kHz. Due to its high frequency and corresponding small wavelength, ultrasound is characterized by a number of distinctive properties.
Due to their small wavelength, ultrasonic waves they can form precisely focused beams. The laws of reflection apply to ultrasound waves as well. A concave mirror reflector can orient the waves form the source in a precisely chosen direction. Ultrasound does not diffract and propagates in straight lines.
As mentioned in the previous chapter this method is currently being used in particular application of molding process.

- Phase transitions

Phase transition (phase transformation, phase change) is a transition of a body from one phase to another. First-kind and second-kind phase transitions are differentiated. This effect is the main currently used for this kind of problem.

- Absorption (electromagnetic radiation)

The process by which the energy of a photon is taken up by matter, typically the electrons of an atom. The electromagnetic energy is transformed to another form of energy, e.g. to heat.

- Arc discharge

Arc discharge is an electric discharge in gas occurring at a high current density with the voltage between the electrodes running into tens of volts. Arc discharge is a result of intensive emission of thermoelectrons by the hot cathode. Accelerated by the electric field, electrons produce collision ionization of gas molecules. That is why the electric resistance of the gaseous gap between the electrodes is low. Alongside with an increase in the strength of current during the discharge, the conductivity of the gaseous gap increases to such a degree that the voltage between the electrodes of the arc drops (descending volt-ampere characteristic). At the atmospheric pressure the cathode may heat up to 3000°C. The electron bombardment of the anode creates a depression, or the arc crater, in the anode. The temperature in the crater is around 4000°C. The temperature of gas in the electric arc channel amounts to 5000 - 6000 °C. If the temperature of the cathode is relatively low (such as in a mercury-arc lamp), the arc discharge occurs mainly due to the cold emission of electrons from the cathode.

- Diffusion

Diffusion is spontaneous mutual penetration and mixing of particles of two contacting gases, liquids or solids. At constant temperature, in chemically pure gases diffusion is caused by varying density in different parts of the gas volume. In gas mixtures, diffusion is caused by difference in density of gases in different parts of the mixture volume.
In chemically homogeneous gas, diffusion effect occurs as a transfer of gas from areas with higher gas density into areas of lower density.

- Dufour effect

The Dufour effect is the occurrence of temperature difference due to diffusive mixing of two non-interacting gases that stay at equal temperatures. This effect is opposite to thermal diffusion. Stationary diffusive mixing of gases (e.g. of hydrogen and nitrogen) gives rise to a temperature difference amounting to several degrees. Dufour effect has not been detected in liquids, since in liquids its numerical value is by 1000 times lower, observation being obscured by masking action of heat of liquid mixing and by the fact the it takes 100 times longer period for equilibrium state to set in in liquids. Create temperature difference by diffusive mixing of non-interacting gases staying at equal temperatures.

- Induction heating

The process of heating an electrically conducting object (usually a metal) by electromagnetic induction, where eddy currents are generated within the metal and resistance leads to Joule heating of the metal.

- Avalanche breakdown

A phenomenon that can occur in both insulating and semiconducting materials (solids, liquids, or gases), allowing very large currents to flow within materials which are otherwise good insulators. Occurs when the electric field in the material is great enough to accelerate free electrons to the point that, when they strike atoms in the material, they can knock other electrons free: the number of free electrons is thus increased rapidly as newly generated particles become part of the process.

- Thermal conduction

The spontaneous transfer of thermal energy through matter, from a region of higher temperature to a region of lower temperature. Conduction acts to equalize temperature differences. It is also described as heat energy transferred from one material to another by direct contact.

- Forced convection

Heat advection by a fluid which is not due to the natural forces of buoyancy induced by heating. In forced heat convection, transfer of heat is due to movement in the fluid which results from many other forces, such as (for example) a fan or pump.

- Infrared radiation

Infrared (IR) radiation is electromagnetic radiation whose wavelength is longer than that of visible light (400-700 nm), but shorter than that of terahertz radiation (3-300 μm) and microwaves (~30,000 μm). Infrared radiation spans roughly three orders of magnitude (750 nm and 1000 μm).

- Joule-Lenz effect

The process by which the passage of an electric current through a conductor releases heat. Heat generated is a function of current, resistance and time. Also known as Joule heating, Ohmic heating or resitive heating.

- Heat pipes

Among other heat exchange systems, heat pipes are a remarkable innovation, and they are currently used also in the field of injection molding. In the simplest case, the heat pipe is a closed metal cylinder with interior walls covered with a layer of porous capillary material impregnated with easily evaporating liquid. The flow of liquid accounts for the pipe's thermal conductivity: at the hot end the liquid evaporates and removes heat; the vapor moves to the cold end as in natural convection. At the cold end the vapor condenses and releases heat. Generated liquid returns to the hot end of the pipe through the porous material. This closed cycle, the infinite circulation of heat and mass without a moving component makes the heat pipe look like a perpetually working machine.

- Loop heat pipe

A two-phase heat transfer device that uses capillary action to remove heat from a source and passively move it to a condenser or radiator. Similar to heat pipe but has advantage of being able provide reliable operation over long distance and ability to operate against gravity. Designs range from powerful & large to miniature (micro loop heat pipe). Widely used in both ground based as well as space applications.

- Laser light

A device that emits light (electromagnetic radiation) through a process called stimulated emission. Light is electromagnetic radiation of a wavelength that is visible to the human eye (in a range from about 380 or 400 nanometres to about 760 or 780 nm)

- Dielectric Heating

The phenomenon in which radiowave, or microwave electromagnetic radiation, heats a dielectric material, especially as caused by dipole rotation. Microwaves are electromagnetic waves with wavelengths ranging from as long as one meter to as short as one millimeter, or equivalently, with frequencies between 300 MHz (0.3 GHz) and 300 GHz.

- Electrocaloric Effect

A phenomenon in which a material shows a reversible temperature change under an applied electric field. Often considered the physical inverse of the pyroelectric effect. The underlying mechanism of the effect is not fully established, however, as with any isolated (adiabatic) temperature change, the effect comes from the voltage raising or lowering the entropy of the system. Analogous to the magnetocaloric effect.

- Exothermic reaction

An exothermic reaction is a chemical reaction accompanied by the release of heat. In other words, the energy needed for the reaction to occur is less than the total energy released. As a result of this, the extra energy is released, usually in the form of heat.

- Plasma

A partially ionized gas, in which a certain proportion of electrons are free rather than being bound to an atom or molecule. The ability of the positive and negative charges to move somewhat independently makes the plasma electrically conductive so that it responds strongly to electromagnetic fields. Plasma therefore has properties quite unlike those of solids, liquids or gases and is considered to be a distinct state of matter.

- FIN

A flat surface that extends from an object, usually for the purpose of increasing surface area, increasing stiffness or for obtaining a hydrodynamic or aerodynamic interaction with an external relatively moving fluid.

- Thermal hall effect

The thermal analog of the Hall effect, i.e. a thermal gradient is produced across a solid instead of an electric field. When a magnetic field is applied, an orthogonal temperature gradient develops. For conductors, a significant portion of the thermal current is carried by the electrons. In particular, the Righi-Leduc Effect describes the heat flow resulting from a perpendicular temperature gradient and vice versa, and the Maggi-Righi-Leduc effect describes changes in thermal conductivity when placing a conductor in a magnetic field.

- Righi-Leduc effect

A magnetic field applied at right angles to the direction of a temperature gradient in an electrical conductor will produce a temperature difference at right angles to the direction of both the temperature gradient and the magnetic field.

- Second sound

A quantum mechanical phenomenon in which heat transfer occurs by wave-like motion, rather than by the more usual mechanism of diffusion. Heat takes the place of pressure in normal sound waves. This leads to a very high thermal conductivity. It is known as 'second sound' because the wave motion of heat is similar to the propagation of sound in air.

- Thermoacoustic engine

Thermoacoustic devices which use high-amplitude sound waves to pump heat from one place to another, or use a heat difference to induce high-amplitude sound waves. Can be divided into standing wave and travelling wave devices. These two types can again be divided in two thermodynamic classes, a prime mover (or simply heat engine), and a heat pump. The prime mover creates work using heat and a heat pump creates or moves heat using work.

- Thermomagnetic convection

Ferrofluids can be used to transfer heat, since heat and mass transport in such magnetic fluids can be controlled using an external magnetic field. This form of heat transfer can be useful for cases where conventional convection fails to provide adequate heat transfer, e.g., in miniature microscale devices or under reduced gravity conditions.

4.4 How to develop a good system?

The specific problem relating to the improvement of Thin-wall injection molding process has been analyzed and dissected until it was reduced to ideal contradictions. These contradictions were resolved and then were given many directions of solutions. These solutions were found, in the first instance, with the Inventive Principles and subsequently with the Standard Solutions.
The analysis led various alternatives for problem solving. Many of them can be combined with each other. At this point it needs to design different systems depending on the market requirements since the first rule is to get cost-effective system.
Like anything else, there's not the perfect system, but each system can be adapted to particular requirements.

Moreover it's necessary to investigate the scientific effects get and consult the relative specialists.

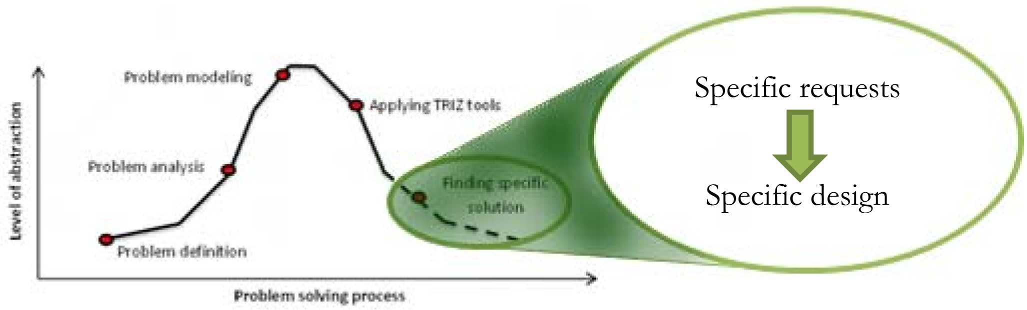


Fig. 93 Problem solving scheme: specific solutions

5 Main parameters evaluation

Some of the next experiments were carried out as part of the international Mi-Nanotech project in which the TECOS Company took part in the role of leader. It's a multiannual long project that starts in 2009.
The aim of the project is to develop an efficient micro-injection mould and also production processes, required for serial production of micro parts. Overall goal of the project is to provide tailored and cost-effective methodologies for development technology required for optimization of production miniaturized components. Attention is made on the following issues:

- Determination of mould characteristic and micro-parts production strategy
- Reach an optimal surface tempering control of the micro-injection moulding process using Peltier-elements
- Innovative cooling system with use of cooling fluids mixed with nano-particles
- Structuring of surfaces with nano-coatings
- Testing and completion of mould
- Provide tailored and cost-effective methodologies for production medium-size series

The proposed product development strategy offers high flexibility and cost effectiveness. Additionally, it provides more freedom and testing opportunities during the development of new micro devices.
The micro-injection mould will be test in production line for production miniaturized and micro parts owned by one of the consortium partners.
Certain experiments pursued in the Mi-Nanotech project have the common goal of the project of this thesis. Therefore, from a certain moment on, the two projects were integrated side by side in parallel approach.
Previous experiments that TECOS made in this field (Fig. 95) had already given good results and were consistent with those predicted by the simulations (Fig. 94), but nowadays the concept of thin-wall injection molding optimization requires more thrust accordingly an evolution of the methodology.

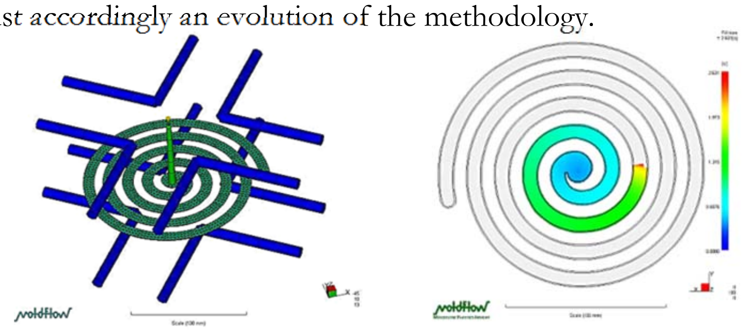


Fig. 94 Simulation with a 1[mm] thin-wall spiral mold

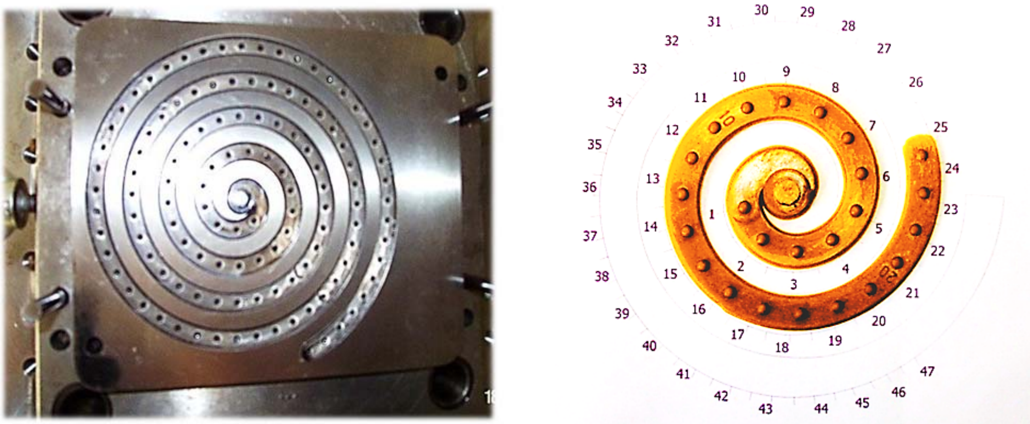


Fig. 95 Mould and relative molded part made in TVK AKU 5 with 50% wood content

As previously said the thin-wall molding process is characterized by 150:1 of flow-length to wall-thickness ratios. Tecos tests would like to push these numbers till 600:1 ratios.
The analysis performed up to now has cleared that main two parameters of influence of a good thin-wall molding process are the **heating/cooling mold time** and the **filling mold success**.
The goal of the next analysis is to make preliminary qualitative tests and to show how these experiments are predictable by simulations. Will be conducted heating-cooling and filling numeric simulations and the relative tests on machinery.
At the moment it's still not possible to make all simulations with single software due to software limitation, thus simulations must be split.
Nevertheless all simulations and experiments are finalized with everything that has been made available by the company.

Will be explained in detail the mold design, explaining why certain system choices. This design was carried out in an earlier period as project aimed at Mi-Nanotech.

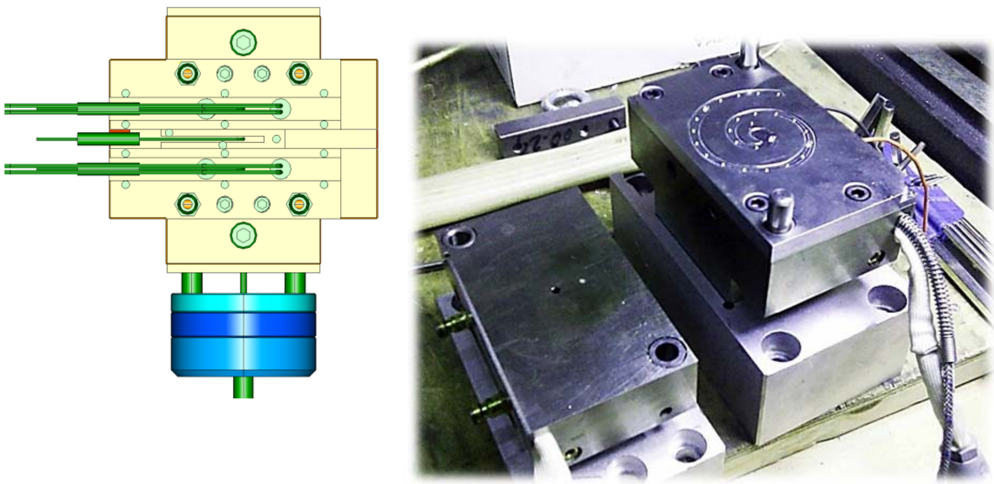


Fig. 96 Cad model of the spiral mold and open state of the existent spiral mould

Subsequently using the ANSYS software will be performed thermal simulations of the mold in order to characterize the timing. Parallel to this are executed thermal experiments in order to compare these results with the previous ones.

Fig. 97 Mould with cable connection for thermal experiment

Generally these types of tests are implemented by TECOS neither on computer nor even in practice. The thermal simulations that TECOS are usually employs only relating to the heating of the mold, which generally takes place again via cartridge heaters which therefore does not involve the use of ANSYS CFD (required for fluid domains). These simulations are thought to evaluate the temperature profile and not the timing to get there.

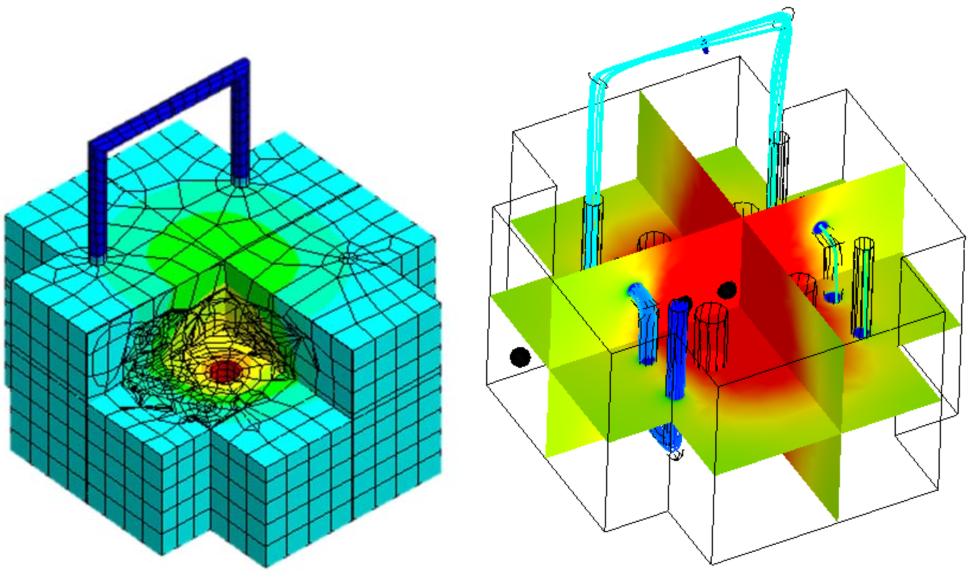


Fig. 98 ANSYS Transient Thermal™ versus ANSYS Fluid Flow (CFX)™

Regarding the filling tests as first thing should be selected the suitable polymers for the purpose. Which are easy to manage and that do not have any particular problems of degradation. Datasheet and features of these materials must be well known.

Fig. 99 Polymer pellets

Will be performed simulations of mold filling, neglecting the cooling phase of the same. However, for a limitation of Autodesk Moldflow™ software it's not available the results importing for the temperature profiles obtained with ANSYS™. It can only be set the average temperature of the mold. Consequently from this point of view, it guesses variations between simulations and reality.

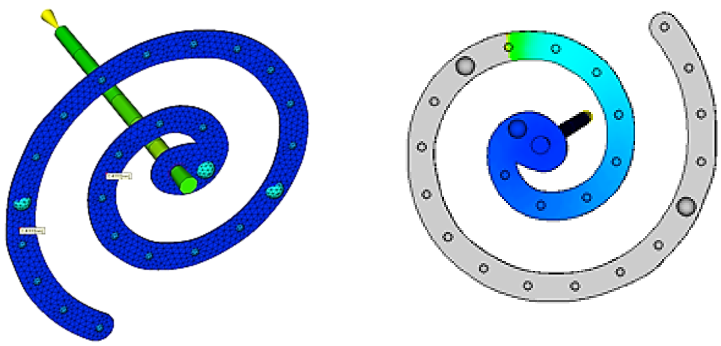


Fig. 100 Autodesk Moldflow Insight simulation applied to the spiral shape

Then will be performed the dimensional inspection of the mould via three-dimensional optical measurement system as to be able to offset any kind of error about geometric factors and dimensional tolerance.

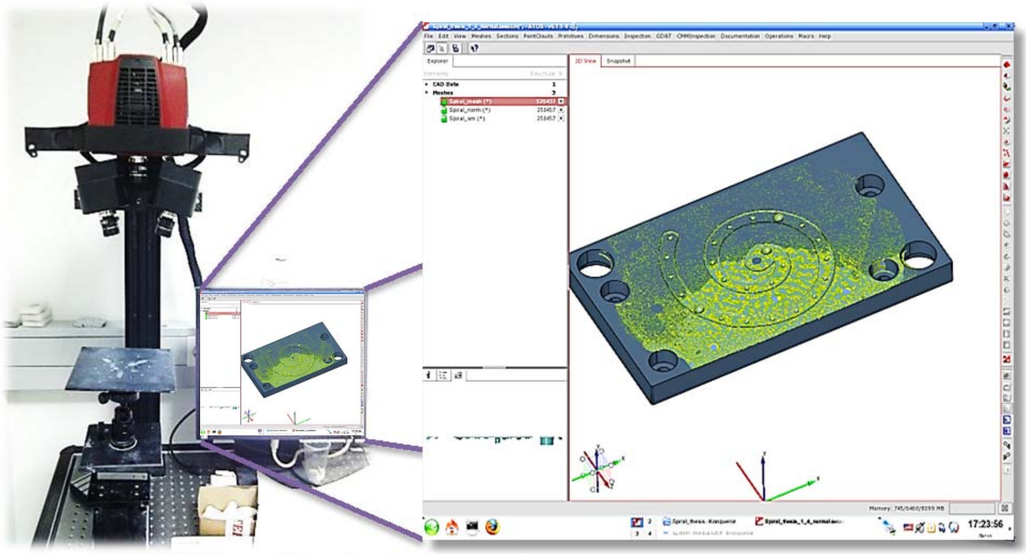


Fig. 101 Three-dimensional scanner and spiral plate dimensional inspection

Lastly will be conducted filling experiments on the machine spending the same parameters used in the. At this time there are big variation between experiments and simulation then comparison is still under investigation.

Fig. 102 Mould mounted on the machine and cataloged results for the spiral component

Mould design

The mold (Fig. 103) has been designed by TECOS engineers considering lots of different aspects. First of all, mold had to be as cheaper as possible since this was just a preliminary experiment. It had to be also suitable for other experiments. For these reasons it has been decided to edit an existing mold and to adapt it for such aim. Main parts of the mold will be described below.

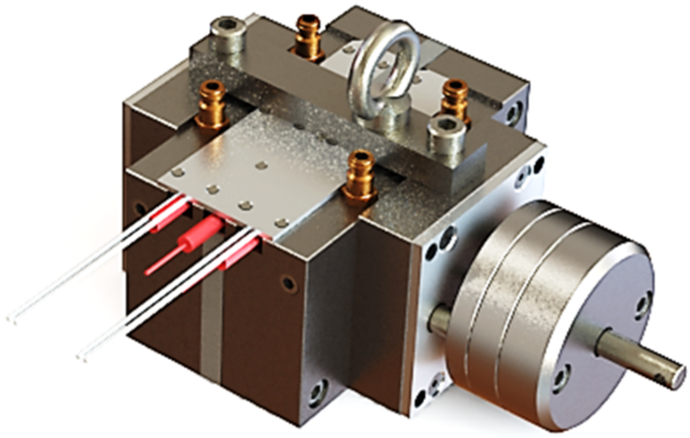


Fig. 103 Mould rendering

- **Spiral plate**

Heart of the mold is the removable plate with the spiral shape. Goal of this experiment is to show the benefits of increasing the mold temperature on the flow length. The spiral has 24 spots arranged at a relative distance of 10[mm]. The thickness is constant and equal to 0.4[mm]. Thus the maximum reachable ratio is 600[mm]. It's made in typical injection molding tool material, the 1.2343 steel with 48 HRC (UNI: X 37 CrMoV 51 KU). The center of the spiral is the starting injection point. Just above it, there's a cavity planned for the thermocouple sensor. On the yellow point of the picture (Fig. 104), there's a location for a pressure sensor. The Kistler 6182BC sensor has the ability to reach up to 200 [°C] of stress temperature.

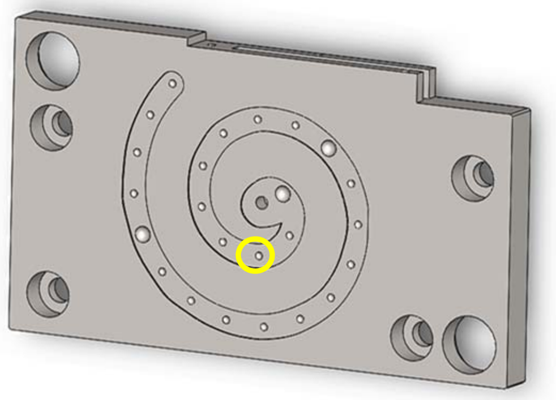


Fig. 104 Spiral plate

- **Mold (injection side)**

This module and the one on the other side too are the most complex. They must take in account of several integrated systems: Injection system, heating system, cooling system and measurement tools.
Each hole and feature is designed for one purpose without going into conflict with another one.
On the picture below (Fig. 105) are shown with different colors all systems. The green one is the injection channel. The red holes are places for the heaters. The blue scheme is the water path, and the yellow point is the thermocouple sensor location. The mold material is the same of the spiral plate: 1.2343 steel with 48 HRC. The water channels are developed to be as effective as possible and they are not made only for water but for other liquids or steam too. Inside and beside the mold are placed special connectors, caps and flow diverters to force the flux direction.

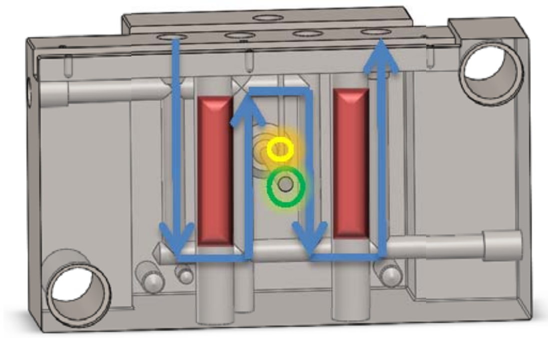


Fig. 105 Internal view of the mold from the injection side with systems scheme

- **Mold (ejection side)**

Like the previous part, this one has the same level of complexity. Main differences are: the ejection system and the connection holes for the spiral plate. In fact, in the center of the mold there's a channel studied for the sliding of the plunger. This is made for pushing up the piece after the cooling phase. This component (Fig. 106) too has the same material of the spiral plate: 1.2343 steel with 48 HRC.

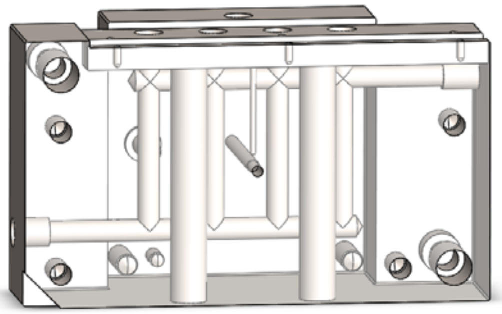


Fig. 106 Internal view of the mold from the ejection side

❑ Heating and measurement tool

The exposed plane (Fig. 107) is the spiral shape plane. In order to avoid other complications the mold structure is symmetric. Four heaters (the green part of the picture) are displaced at the two sides of the spiral plate in a way to have a uniform mold heating. Ceramic heater is one of the most common ways to heat up the mold quickly. There were used four cartridge heaters for a total power of 1.6 [kW]: the HLP™ 10X50/400. The cooling channels are positioned just behind the heaters. To control this process were placed five thermocouples. The cheapest way to monitor the temperature with a good precision is the Hasco™ z1295/5/1.5x71 type J (Fe-CuNi,) thermocouple, with a maximum tolerable temperature of 400 [°C].

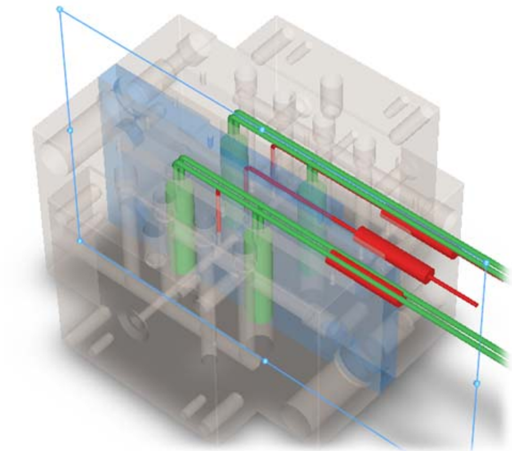
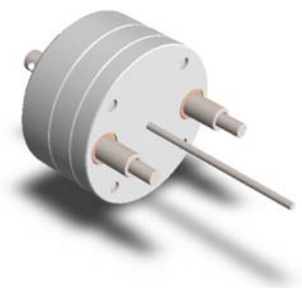


Fig. 107 Heaters and thermocouples position

❑ Ejection system and transport system

The ejection system is connected by screws to the mold and it's also connected to the ejection system placed on the machine (Fig. 108 left side). This part allows pieces to fall down from the mold at the end of the process cycle.
The transport system is mainly consisting of a removable hook that is also made to keep the mold close and to prevent damage during the setup on the machine (Fig. 108 right side). The full mold has a weig



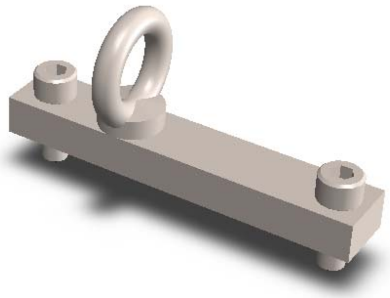


Fig. 108 Ejection system and transport system

5.1 Heating/Cooling test

Goal of this test is to make comparison between numeric simulation and reality estimating the heating time and the cooling time needed during the injection molding cycle.

5.1.1 Ansys™ simulation

The heating simulation is quite easy to model using the Ansys Transient Thermal™ module, but this situation is different. It needs to simulate the mold cooling, and the starting point of this simulation has to be the end point of the mold heating simulation. It requests to use the Ansys Fluid Flow (CFX) ™ module due to the liquid state simulation.
The procedure for these simulations is standard and consists of following steps:

- Defining geometry
- Meshing
- Simulation setup
- Solution
- Results

First of all it's necessary to simplify the cad model of the mold. All useless features and stuff have to be removed. The shape has to be edited too. The number of the bodies must be minimized at the minimum required. In this case the minimum number is four. One of these is the mold, with the appropriate steel properties applied.
The mold contains water channel inside and the four cylinder holes for the heaters.
Water path in this case has to be modeled such as a solid domain. Due to boundary conditions, water domain must be divided in three under parts. The blue one represents a real cable connection that is deformable to allow the mold opening during the injection cycle. On the green water path there's the inlet, on the red water path there the outlet (Fig. 109).

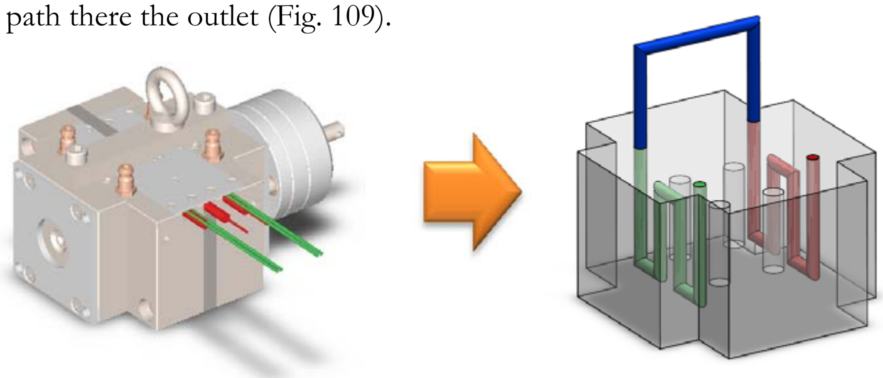


Fig. 109 Mold cad model editing for the FEM simulation

Once the STEP file is ready it has to be meshed. It's well to have a good mesh control to avoid irregularities in the results. ANSYS™ helps this phase using virtual topology control and other mesh control like mapping surfaces, sizing and defining the method for the generated elements. It's better to rename surfaces in this phase than later (Fig. 110). All the simulations were prepared with the suitable accuracy in terms of number of number of finite elements (Fig. 110 right side).

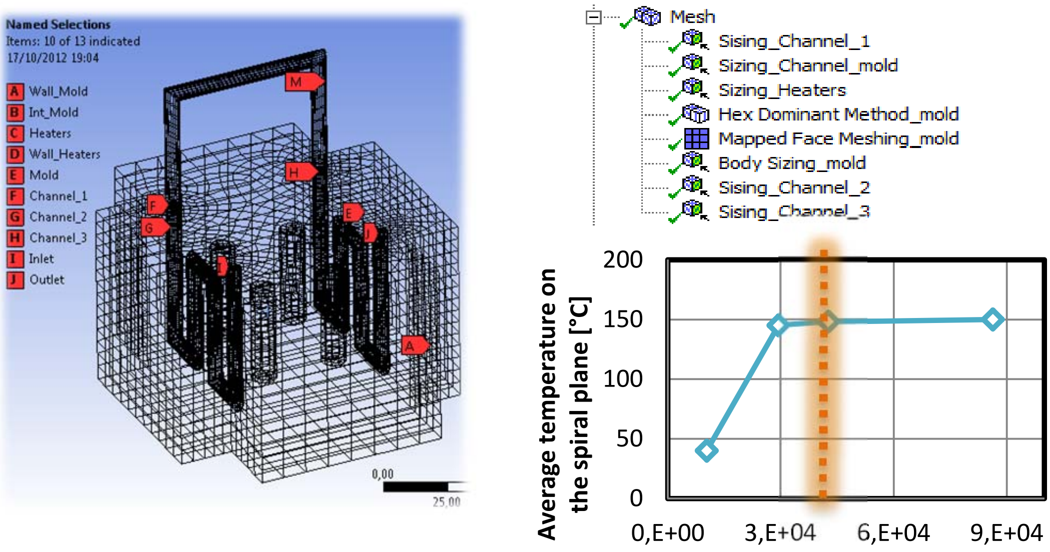


Fig. 110 Mold mesh, relative controls

The next step is the simulation setup. Material properties must be very precise to avoid undesired mistakes. For this reason a temperature design point must be set. Our estimated temperature range is 20-200 [°C] thus the average value 115[°C] has been chosen (Fig. 111).

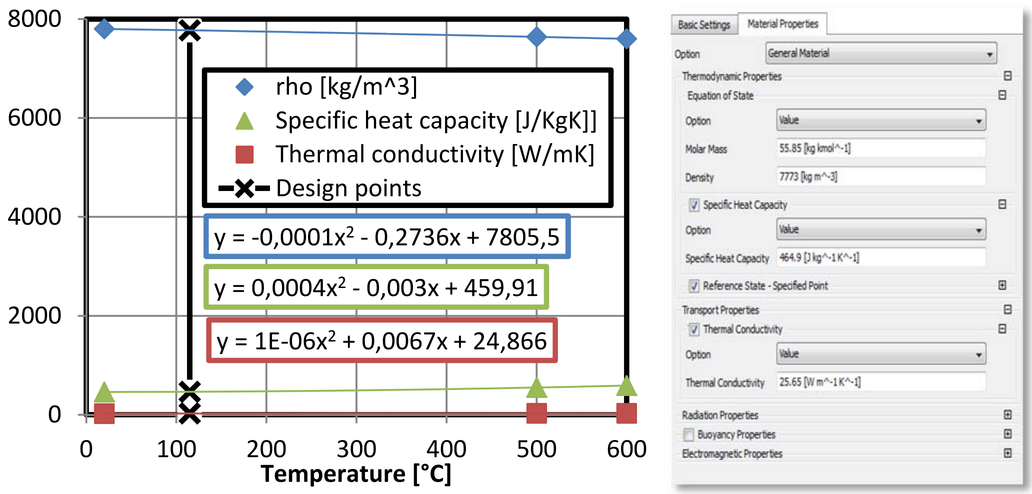


Fig. 111 Data interpolation for 1.2343 steel properties

Three different simulations and relative configurations must be created (Fig. 112 left side). The first one is a steady state simulation. The reason of this simulation is to recreate the initial condition along the whole domain. At the end of this configuration, mold and water path will be at 20 [°C]. Mold and cable connection have adiabatic surfaces with the environment otherwise the simulation should be too complex. The convergence control for the analysis is set on 100 iterations (Fig. 112 right side) In order to estimate the correct values it's always necessary to reach the convergence.

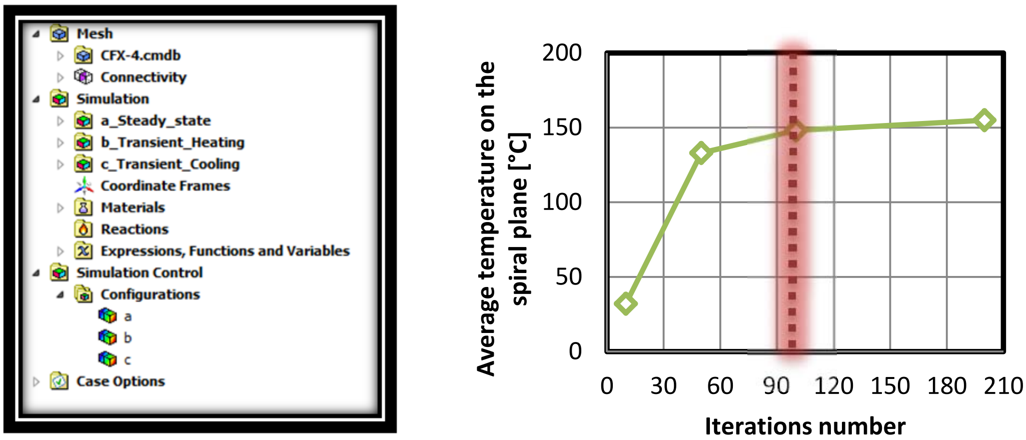


Fig. 112 Simulations setup and convergence control

The second one is a transient heating simulation. The starting point of this one is the end point of the previous analysis. It's made by seven timestep each one with a relative distance of 30 [s]. A heat flux of 1600 [W] is applied on the heaters surfaces of 0.005[mm^2].

The last one is the transient cooling simulation. As in the previous analysis, the end point of the heating simulation is the starting point for this one. Timestep number is still seven but the relative distance is set on 60 [s]. There's no heat flux applied but rather a constant water flow rate with an exact value of 0.0053 [kg/s]. This value has been estimated by other experiments on a coffee machine pump due to the use on the real experiment.

Regarding mold and water domain, the heat transfer equation must be set. Thermal Energy is correct form for this simulation because it is suitable for low speed liquid flow with constant specific heats. An Energy Transport Equation is solved which neglects variable density effects.

Water domain must consider turbulence options. The Shear Stress Transport model is based on the k–model and has the same automatic wall treatment. One of the advantages of the k–formulation is the near wall treatment for low–Reynolds number computations. But the SST model accounts for the transport of the turbulent shear stress and gives highly accurate predictions of the onset and the amount of flow separation so this is a good default choice (Fig. 113).

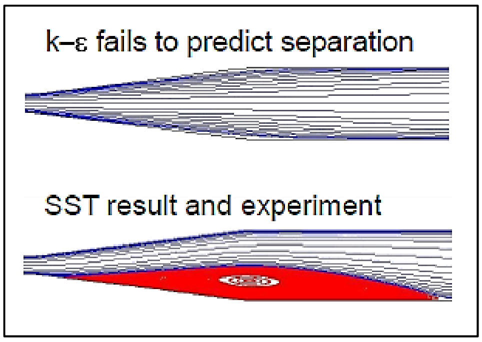


Fig. 113 Shear stress transport model

An important parameter is the convergence criteria and was set to the recommended value by software developers to handle this kind of simulations (Fig. 114).

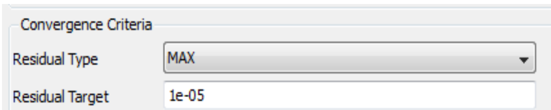


Fig. 114 Convergence criteria

Opening simulation results it's possible to get all needed data.
Black points on the picture below (Fig. 115) represent the thermocouple sensors. It's possible to select the spatial location to probe value from these points. As in the real experiment as here there are five temperature sensors, three of them are inside the mold, one is on the surface and another one is on the water path outlet.
The end of the steady state simulation is shown. Three planes cut the model to demonstrate that the whole body starts at temperature of 20 [°C].

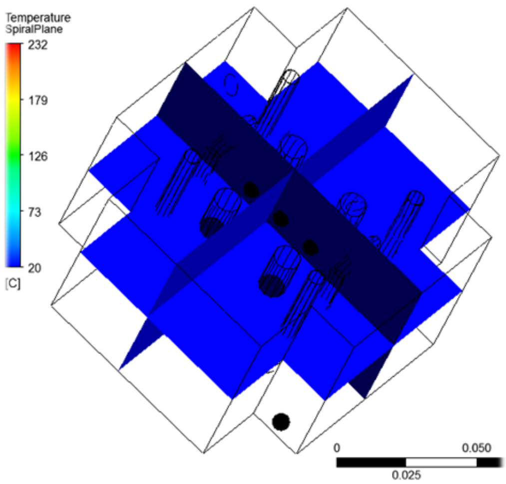


Fig. 115 End of the steady state simulation

The spiral plane is the plane of interest. In the next sequence the heating phase is visible step by step (Fig. 116). Temperature gradient on the spiral plane has two a circular areas, thus the spiral will not see uniform heating. Unluckily this temperature profile cannot be imported to the filling software for a good simulation and this could affect the filling results.

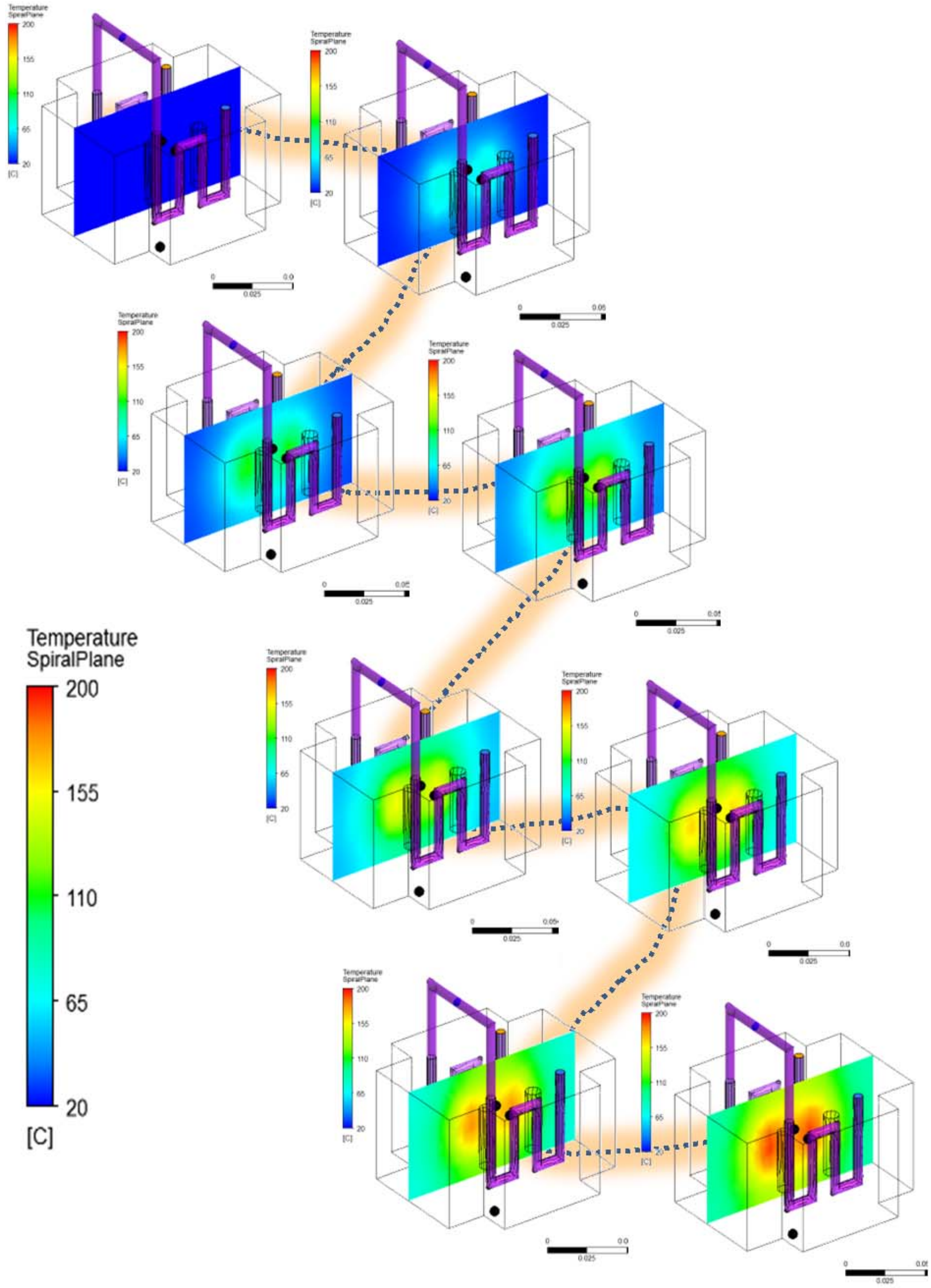


Fig. 116 Simulation of the heating phase

The cooling phase with this low water flow rate it's quite slow, but in this phase this is not important due to data comparison. On the spiral plane the temperature decreases in a uniform way and that means good mold design (Fig. 117).

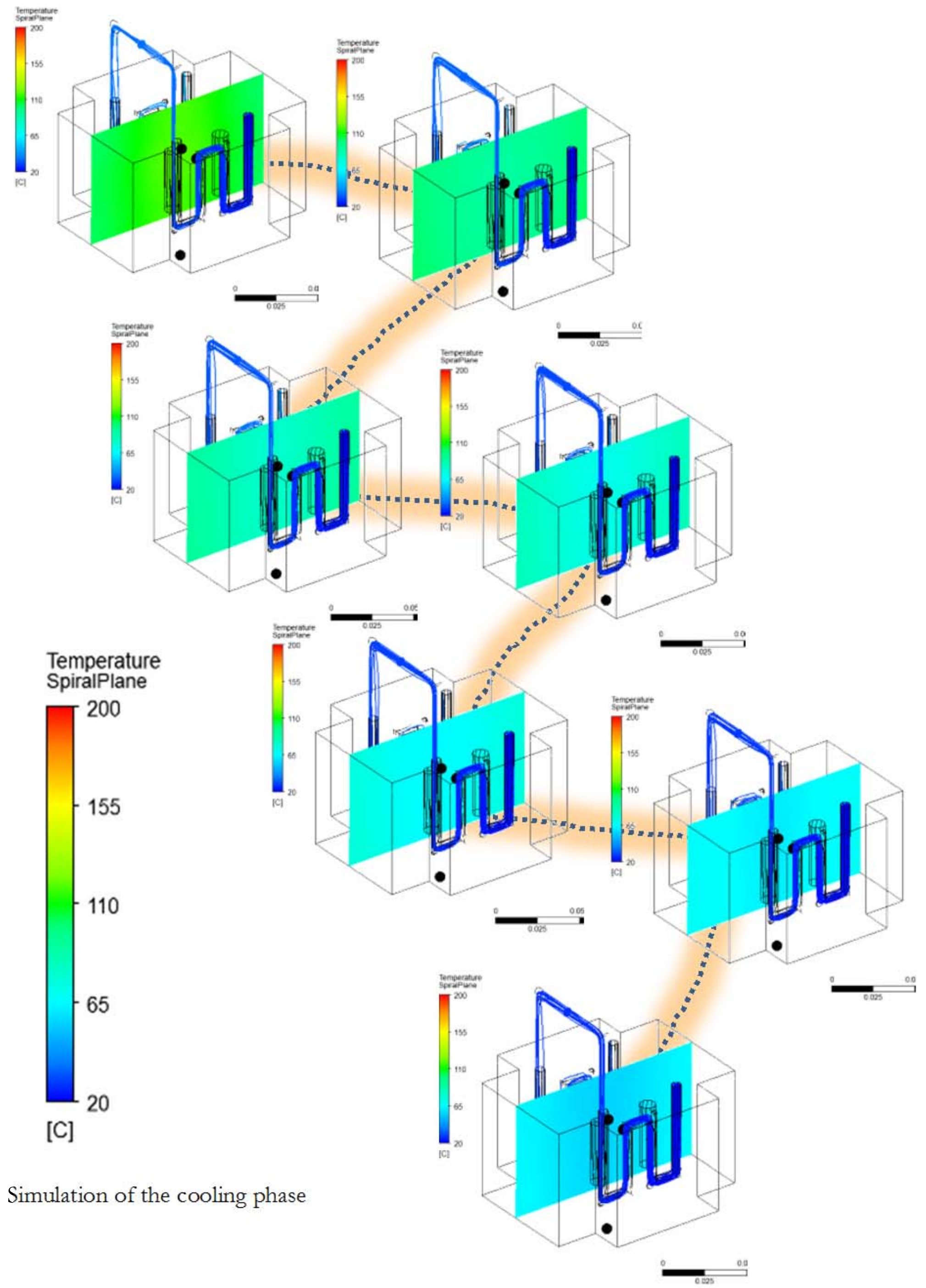


Fig. 117 Simulation of the cooling phase

All results are in the next graph (Fig. 118). During the heating phase sensors inside the mold have the same range of temperature. The sensor of water temperature placed on the outlet has shown the same values of the sensor placed of the surface, consequently the simulation is correct. During the cooling phase, as good as it was expected, the core and the external surface becomes of the same value.

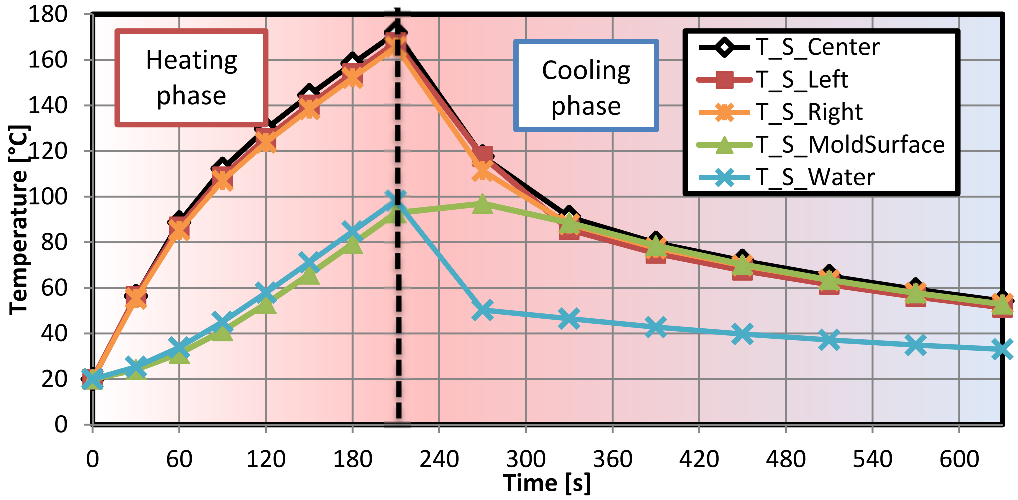


Fig. 118 Graph temperature vs time got from the numeric simulation

5.1.2 Out of the machinery experiment

This experiment can be done out of the injection apparatus. We only need systems to heat up, to cool down and to control the mold temperature (Fig. 119).
Both heaters and thermocouples are connected to the controller with separate switches.
Thermocouples are class-two tolerance. That's mean ±2.5 [°C] in the range -40:333 [°C].

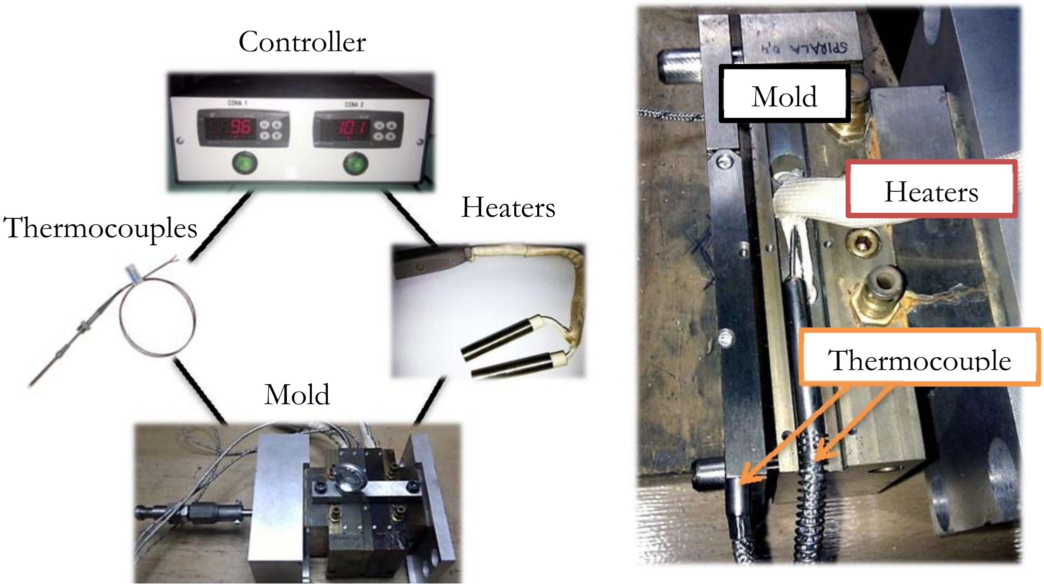


Fig. 119 Connections for heaters and sensors

To make constant water flow a water pump is needed. It has been used a coffee machine pump (ULKA model EP4GW) just because of the availability in TECOS Company (Fig. 120). The water flow rate has been estimated by other preceding experiments and as previously said it is equal to 0.0053 [kg/s].

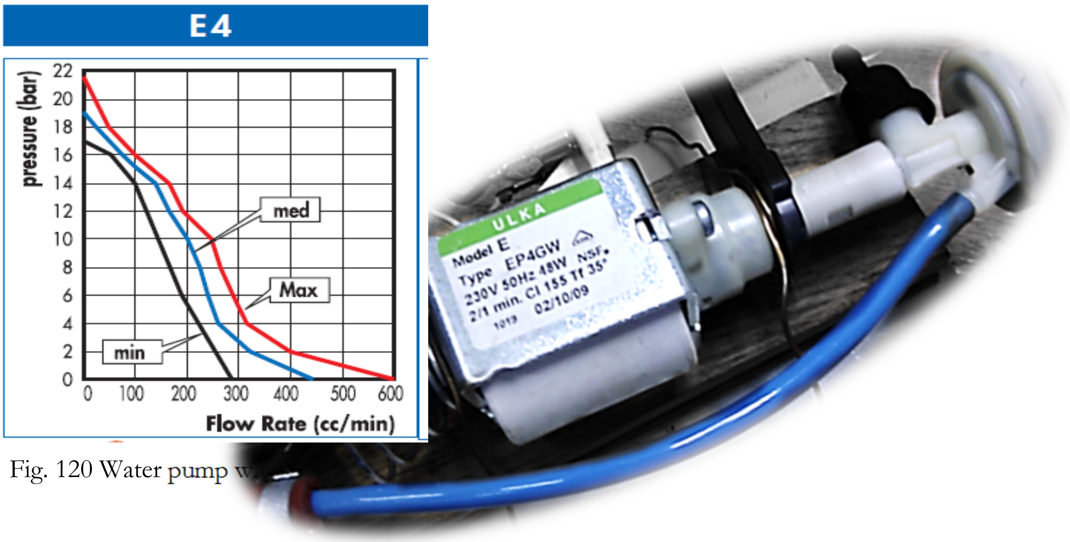


Fig. 120 Water pump w

The scheme and the real configuration of the experiment are shown below (Fig. 121). Black points represent thermocouple sensors, red rectangle with a glow are heaters and the blue path is the water path.

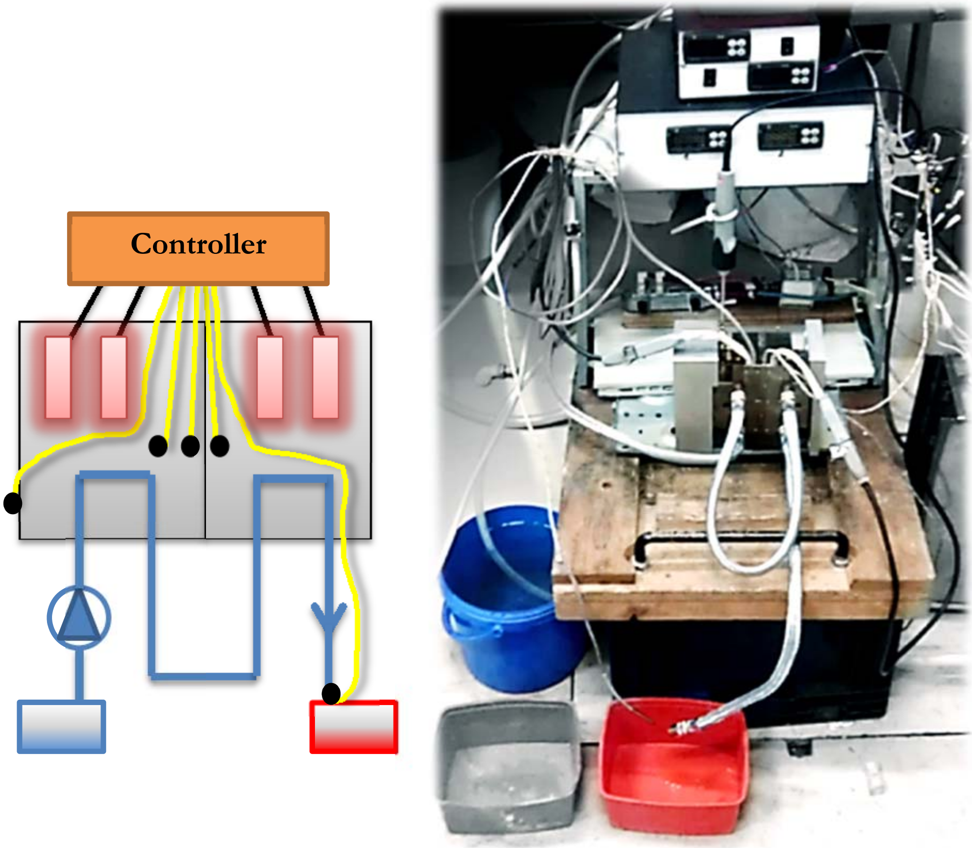


Fig. 121 Scheme and real configuration of the heating-cooling experiment

The results of the experiment measured by sensors are structured in the next graph (Fig. 122). A video was recorded to register the data shown by all controllers. A five-second timestep has been chosen to represents temperatures on a table.
Experiment was made twice in order to check the repeatability; in any case the next graph shows only one series of data because it is not requested big accuracy in this step.

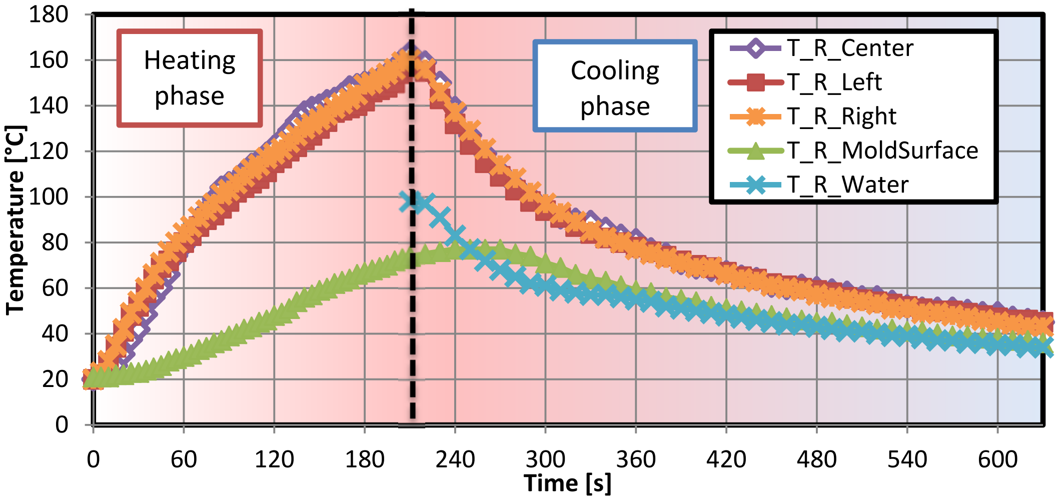


Fig. 122 Graph temperature vs time got from the real experiment

5.1.3 Data comparison

To show the differences between numeric simulation and real experiment every sensor is shown in a separately way.
Checking the next graph (Fig. 123) it's quite visible a constant error of 10 degrees between the real and the predicted value. Anyway considering the thermocouples precision, the difference between the real and the schematic mold shape and the simplified boundary condition on the mold surfaces, the preliminary model gets good results.

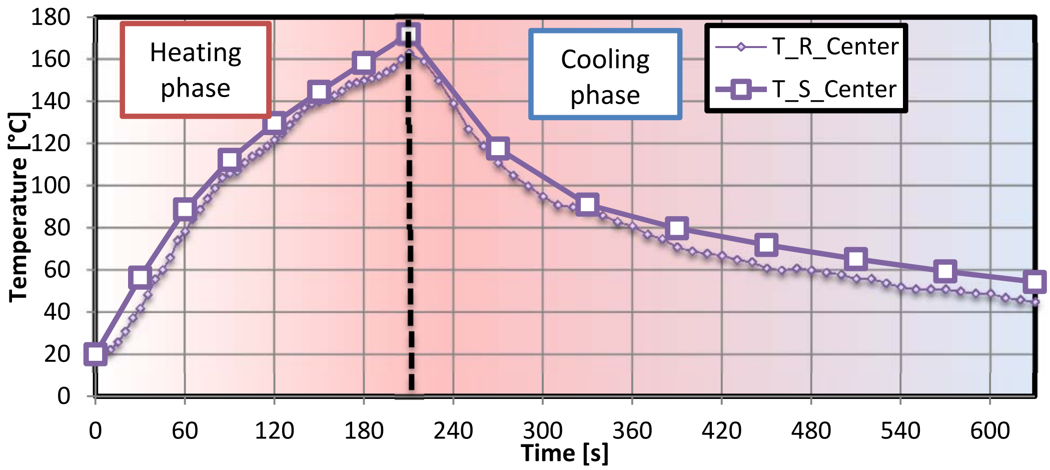


Fig. 123 Temperature in the center of the mold

The same situation expressed before is visible here (Fig. 124). All sensors placed inside the mold show good matching between numeric simulation and real situation.

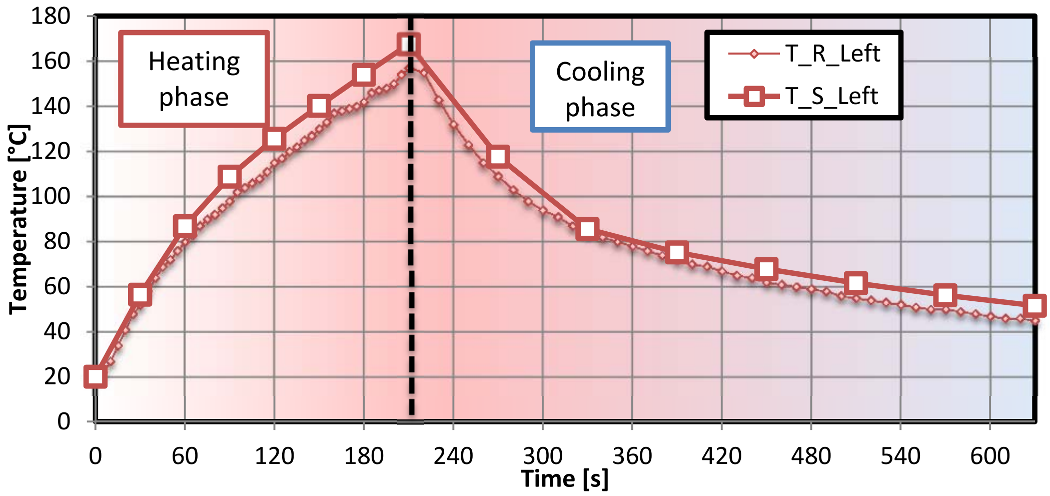


Fig. 124 Temperature in the left side of the mold

Variations in the data can be caused by particular geometry factors that were abolished during the numeric simulation (Fig. 125).

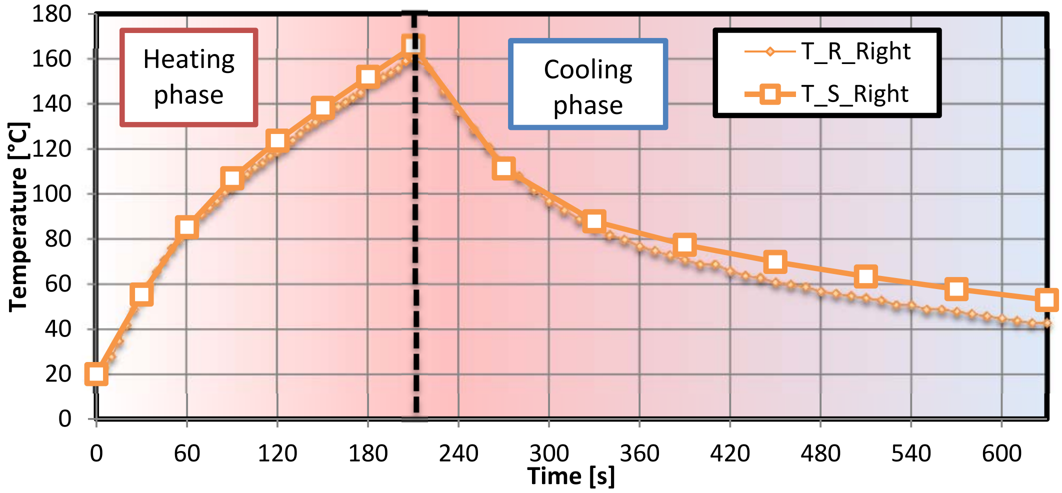


Fig. 125 Temperature in the right side of the mold

Mold surface graph (Fig. 126) shows big variance from the other and this is due to the adiabatic model made on the simulation. This deviation was expected during the modeling phase. In the realty there's a heat exchange with the environment that decrease the temperature that's why real temperature is lower than the simulated one. Anyway inside the injection molding machine such a discrepancy may not exist due to the hot environment.

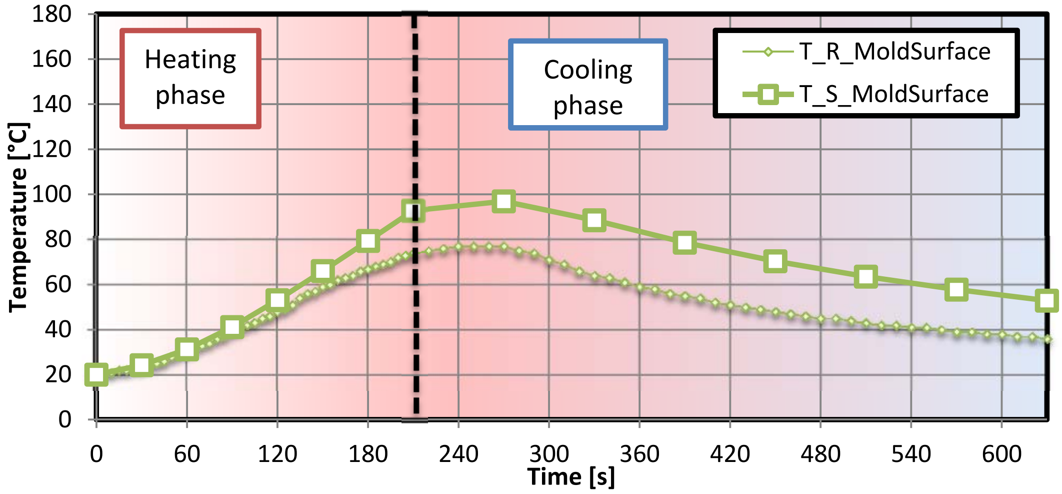


Fig. 126 Temperature on the mold surface

The real temperature of the water at the outlet is higher than the predicted one (Fig. 127). Thus all data are quite correct because they are offset by the adiabatic model. That's mean the phenomenon of thermal dissipation between the mold and the surrounding air is not preponderant.
During the heating phase water circuit was stopped, at the outlet there was no water. That's why there are no available data for the whole heating phase.

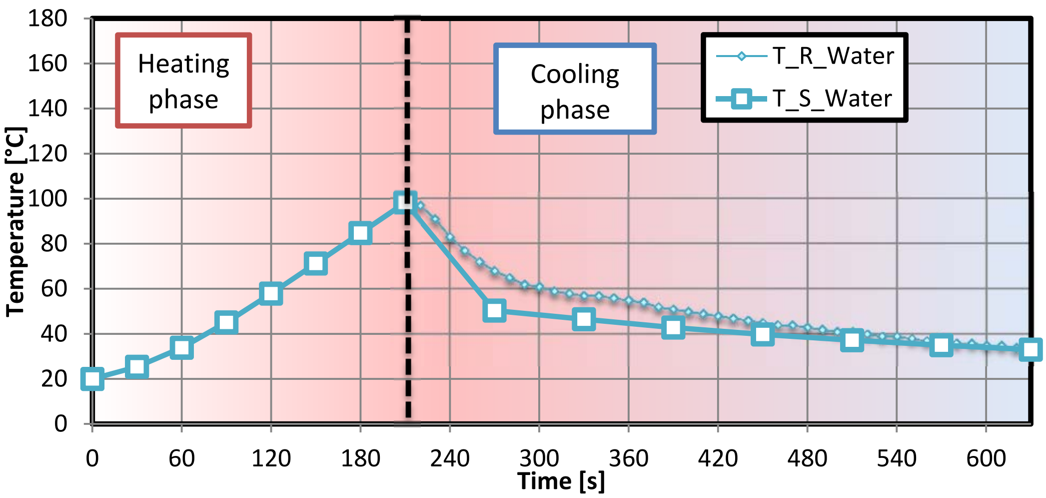


Fig. 127 Temperature at the outlet of the water path

A "simple" simulation like this has not been so easy to lay out. Results are fairly good compared to the simulation setup time and effort. This kind of simulations can be applied just in case of "conventional heating" and "conventional cooling". Inductive and laser heating should be investigated by other methods.
Next step sees filling simulation. Unluckily at this time there's no way to use single software connected to the previous simulation then the modeling phase must start from the beginning. Furthermore as mentioned earlier the plane containing the spiral has not a uniform heating temperature (Fig. 128), however this data profile cannot be imported in the filling simulation software as a result deviations between reality and simulation are already expected.

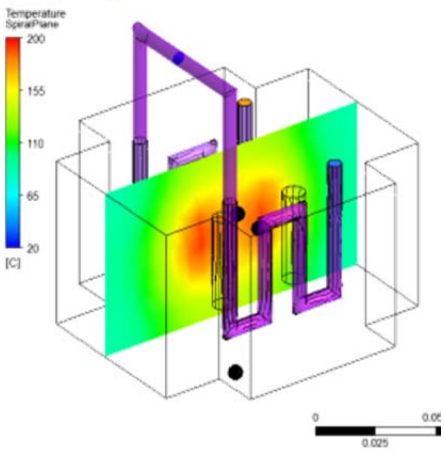


Fig. 128 Mould state at the top of the heating phase

5.2 Filling test

Primarily what is expected form the next experiment series is the correctness of the statements in chapter one. Namely, there are considerably advantages in increasing the mold temperature in terms of obtainable flow length.

Secondly it wants to determinate if numeric simulation can make predictable results.
Previous TECOS experiments, in the field of thin-wall molding process, showed perfect matching with relative numerical simulations. In addition, these simulations are widely used by the company for many processes related to the standard injection molding process. There are many experts in the company who directly collaborate from many years with the companies that develop the FEM software.

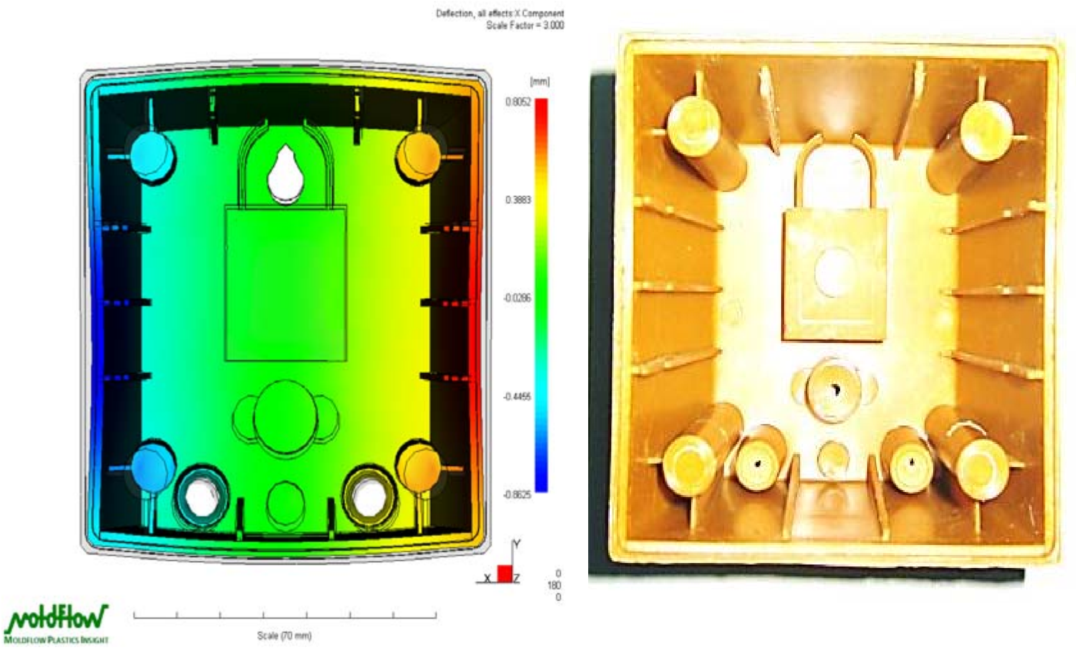


Fig. 129 TECOS simulation and experiment for a cap

However, for these tests there is a marked difference between the results of the simulations and their experimental and at the time there's not a determined reason yet.
For this reason the comparison of results loses value in this context.
Nevertheless, the method to carry out the analysis will be shown.

5.2.1 Polymer choice

The polymer choice is the first step of this analysis. It should be better to find more than one polymer in a way to have more available data for comparison.
The polymer must have a lot of feature to be suitable.

- Available or easily accessible in the TECOS Company
- Supported by a vast amount of certified data by the polymer manufactory
- Supported by a vast amount of certified data by the side of numerical software
- Resistant to degradation due to high temperatures: it is seen that if it plans to reach high mold temperatures, these require longer heating and cooling times. In these time periods the material may remain for a long time in the barrel undergoing high temperatures. Hence if it is not strong enough it may deteriorate.
- Widely used in plastic injection molding process: these tests should always look at the commercial end point.
- Low transition and melt temperature: in order to avoid long time experiments
- Recyclable for other experiments

The choice fell on three materials with very distinct characteristics.

LG ABS HF380 (ABS)

ABS means Acrylonitrile butadiene styrene and it's a thermoplastic amorphous resin.
Produced by LG Chem Ltd.
Molten polymer molecules in an unstressed state are randomly oriented and entangled with other molecules. Amorphous materials retain this type of entangled and disoriented molecular configuration regardless of their states (Fig. 130).

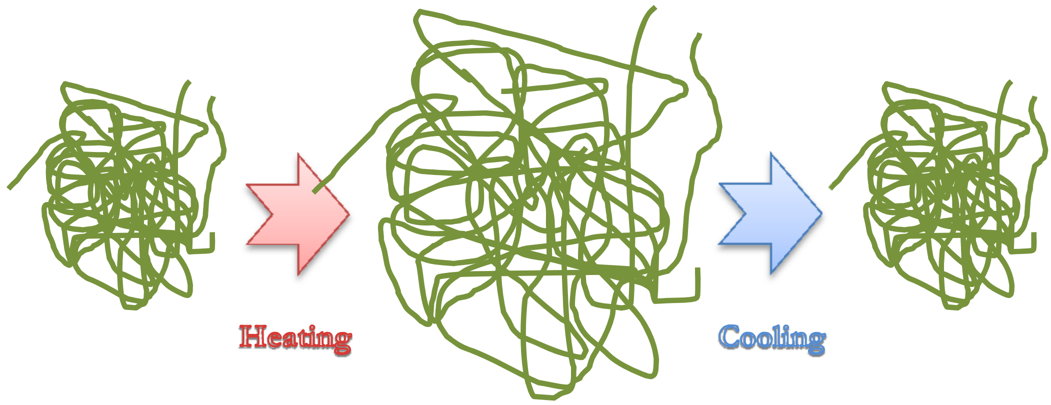


Fig. 130 Amorphous polymer structure

ABS is a combination three monomers, each of the monomers impart different properties: hardness, chemical and heat resistance from acrylonitrile; precessability, gloss and strenghth from styrene, and toughness and impact resistance from butadiene. The polymerization of monomers produces two phases, a continuous phase styrene-acrylonitrile and a dispersed phase of polybutadiene rubber. The ratio of these two phases influences properties.
The LG HF-380 has good flowbility and excellent processability. It is suitable for lots of different stuff like telephones, electric fan, mixer, water purifier, toy, and kitchen. The melt temperature of LG HF-380 is around 235 [°C]. The ejection temperature is around 89 [°C].

Ultradur B 4300 G6 (PBT)

This polymer is an easy flowing injection molding PBT with 30% glass fiber reinforcement fo rigid, tough, and dimensionally stable parts.
Produced by BASF SE.
PBT means PolyBurylene Terephthalates and is one of the toughest engineering thermoplastic semicrystalline resins. Semicrystalline materials are polymer chains that do not have bulky pendat groups, chain braches, or cross-links. They may accommodate themselves in a well-ordered regular polymer crystallite when the molten polymers are cooled below the melting temperature (Fig. 131).

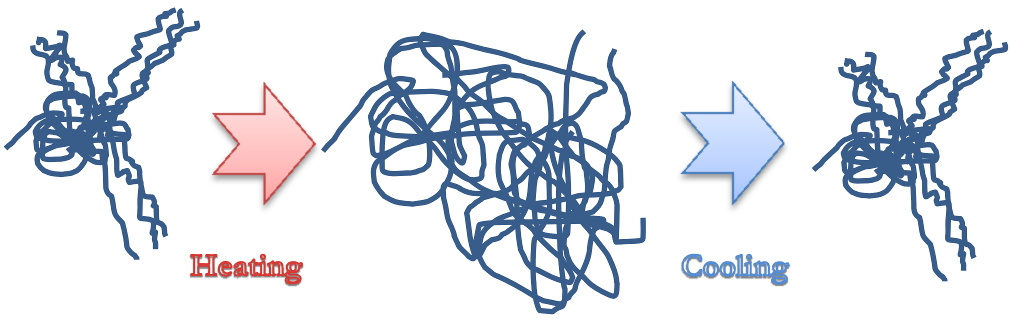


Fig. 131 Semicrystalline polymer structure

It's a and it has excellent chemical resistance, mechanical strength, electrical properties and heat resistance, all of which are stable over a broad range of environmental conditions. PBT, which is a polyester, is produced by the polycondensation reacton of dimethylterephthalate an butanediol. The glass fiber reduces shrinkage in the flow direction, but not in the cross flow.
Typical applications include windshield wiper arms, printed circuit boards, housings, consoles, contact carriers, and covers. The melt temperature of Ultradur B 4300 G6 is around 255 [°C]. The ejection temperature is around 116 [°C].

Polifor 12 CA/40 HD (PP)

The last one is a PolyPropylene homopolymer filled with 40% calcium carbonate. Produced by SO.F.TER. SPA.
PP is produced by the polymerization of propylene using stereospecific catalysts. Mainly, isotactic PP is produced. This linear plastic is semi-crystalline because of ordered molecular structure, like the previous material.
Polypropylene is the third most-widely used thermoplastic polymer at a global level. The main features which have determined its past and present success are: high stiffness and abrasion resistance, low specific gravity, high impact and fatigue resistance, excellent resistance to chemical agents, low hygroscopic sensitivity, easy processability, the possibility to modify its features through a wide range of fillers, reinforcing agents and additives.
The natural disadvantages of polypropylene, such as post-moulding shrinkage and low resistance to weathering or flames, can be easily overcome by using mineral fillers, glass fibers, thermostabilizing additives which can significantly improve its resistance to the UV-rays, fire and the most aggressive lyes. In this case the calcium carbonate confers good aesthetic properties and good toughness. The melt temperature of Polifor 12 CA/40 HD is around 210 [°C]. The glass transition temperature is around 120 [°C]. The ejection temperature is around 112 [°C].

5.2.2 Autodesk Moldflow Insight™ simulation

Goal of simulations is making respectable prediction on the filled flow length applied to the spiral shape previously descripted. Simulations will be pursued changing mould temperature, and material.
These simulations are integral part of Mi-Nanotech project and were pursued by a team of TECOS industry experts in order to test results prediction compared to the real ones.
TECOS engineer strictly collaborate with lots of software houses with the purpose of improve them and consequently take considerable field advantages.
Thin-wall injection molding currently requires a lot of effort since the numerical simulations give results very far from the evidence.
Following is the adopted procedure to simulate this case of application using the most used software by the company for molding simulations, namely Autodesk Moldflow Insight™.

- Defining geometry and meshing
- Selecting simulation and material type
- Process setting
- Results

Geometry and meshing

Analyzing a model is a complex operation and modeling the way in which a non-Newtonian fluid like molten plastic flows through complex model geometry is difficult.
There are three different types of mesh used in Autodesk Moldflow Insight™: Midplane, Dual Domain, and 3D.
For Midplane and Dual Domain analysis technologies, structural analyses offer both shell and beam elements. Tetrahedral elements are used to model the 3D mesh type.

- Beam elements are 2-noded elements, used for tasks like modeling cold runners and cooling channels. The longitudinal axis of the elements is straight, so that when modeling curved beams, they provide a "faceted" approximation to the true geometry.

- Triangle elements are 3-noded elements used to model Midplane or Dual Domain mesh types. The thickness of each element is assumed to be constant. The element formulations account for membrane, flexural and transverse shear deformations. This allows both "thin" and "moderately thick" plates and shells to be modeled.

- Tetrahedral elements are 4-noded elements used to model the 3D mesh type. The tetrahedral element, which is used to provide an accurate 3D representation of a thick or solid part, has four nodes, four faces and six edges.

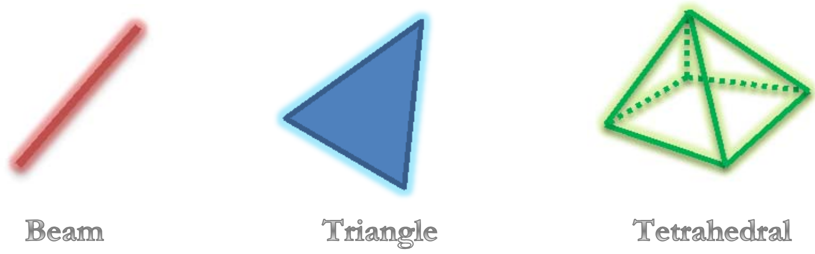


Fig. 132 Types of available finite elements in Autodesk Moldflow Insight™

A Midplane mesh consists of a web of 3-noded triangular elements and forms a 2D representation of a solid model. The Midplane mesh provides the basis for the Fill+Pack analysis. The aspect ratio of mesh elements can affect analysis performance. High aspect ratios can cause a slower analysis, and affect results. Increase the mesh density until there is no significant change in result detail. The best solution for controlling mesh density, is to apply a uniform mesh density across the part, and then refine the mesh in areas of interest. In general, we recommend that the mesh be refined in areas where rapid changes in conditions occur (for example, at the gate).
In the case of spiral shape the Midplane geometry is the following (Fig. 133), the finite element number applied to this plane 3038. Just a plane is needed, thus an IGES planar model it's enough

Fig. 133 Spiral plane in IGES format

Dual Domain analysis technology allows you to perform detailed analyses directly on thin-wall .The Dual Domain analysis technology removes the need to midplane the geometry for an analyses, significantly reducing model preparation time. The surface mesh analysis works by simulating the flow of the melt on both the top and bottom parts of the mold cavity.

The injection channel can be easily modeled with beam elements. Picture below (Fig. 134) shows a color distinction on that channel: the green region is the molded part, while the red region means nozzle, that's why the position of a yellow arrow which indicates the inlet. The total amount of finite elements is 6432, more than twice of Midplane mesh. A STEP or IGES model is required.

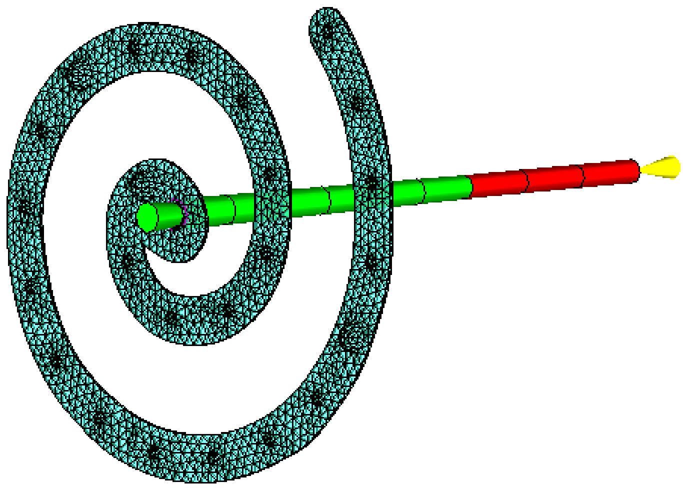


Fig. 134 Dual Domain mesh and beam elements applied to the spiral model

A 3D mesh represents the CAD model by filling the volume of the model with four-node, tetrahedral elements (tetra).
3D meshes work well for parts that are thick or solid because tetra give a true 3D representation of the model. A 3D analysis does not make the assumptions that are made for Midplane or Dual Domain analyses. Therefore, 3D analyses often require additional computational time to complete. This makes a 3D mesh more appropriate for thick models with complicated shapes, while Midplane and Dual Domain meshes are more applicable for thin-walled, shell-like parts. Lots of simulations concerning the spiral shape were developed by TECOS with the 3D elements due to software house recommendation. The superficial mesh correspond with the same of the Dual Domain mesh but 6 and 12 layers are superimposed into two different model of the spiral thickness for a total respective amount of 63658 and 150642 finite elements. 3D spiral simulation requires long time to be solved due to the huge finite elements number compared to the Dual Domain. Only STEP model can satisfy requested mesh type.

Simulation type and material definition

Simulation category influences nature of mesh.
The flow length on a thin part is mainly guided by the filling and packing phase (Fig. 135 left side). That's why all different kinds of simulation are superfluous. In the case of cooling simulation the mould and cooling channels must take place in the modeling.
It is expected the increasing of the mould temperature allows a mould filling also during the packing phase.

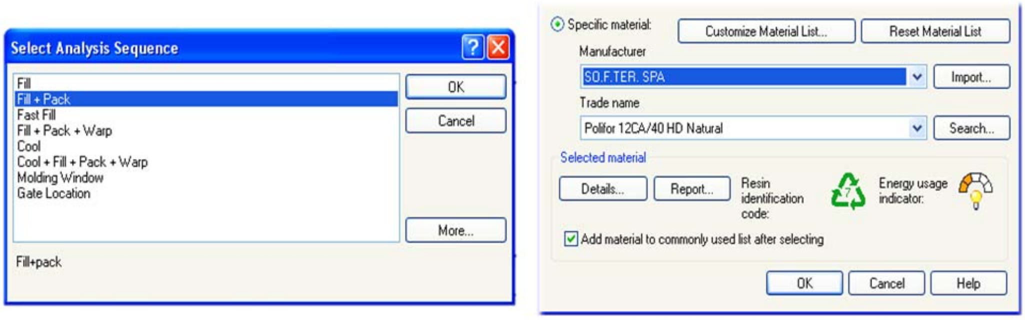


Fig. 135 Simulation type and material detail windows

Material must set up in this step but duplicating simulation material can be simply replaced with another one (Fig. 135 right side).

Process setting

This is the most important stage of the simulation. In the window below (Fig. 136) are shown all main process setting that can put in the program.

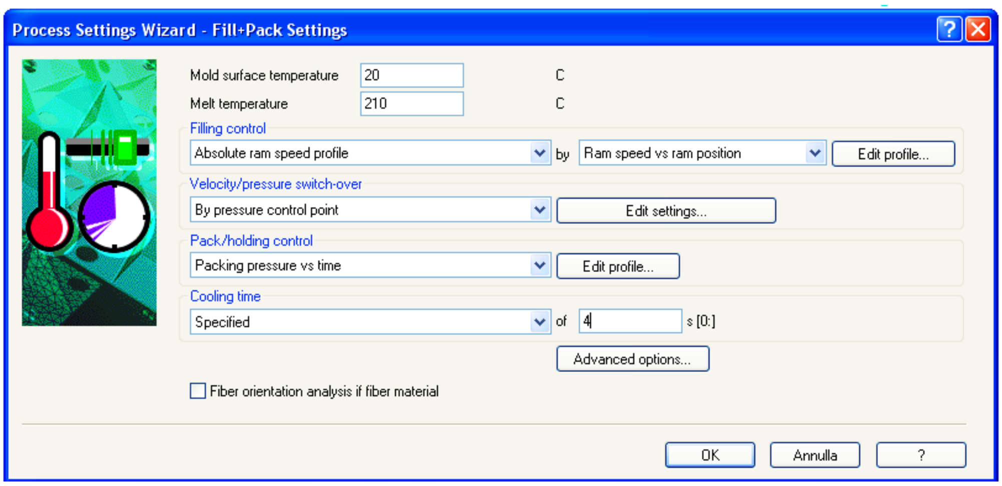


Fig. 136 Process setting window

The mold surface temperature is uniform and equal to a desirable value. However previous ANSYS™ simulation has not shown a uniform profile of the mould surface. This substantial difference can generate variations in real data.
The melt temperature is the temperature at the outlet of the nozzle and must be identical to the real one that is programmed on the machine (Fig. 137). This sameness should be applied to all the entered parameters.

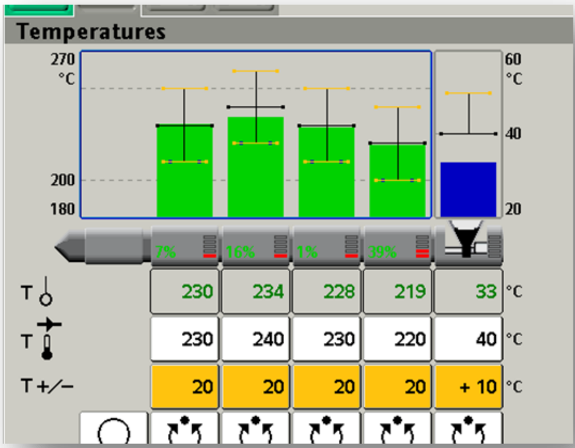


Fig. 137 Barrel profile temperature on the machine during a normal injection cycle

The filling control is set on the ram speed profile as a function of the ram position. The speed is constant for the whole path with a value of 150 [mm/s] that is the maximum reachable by the injection molding machine (Fig. 138).

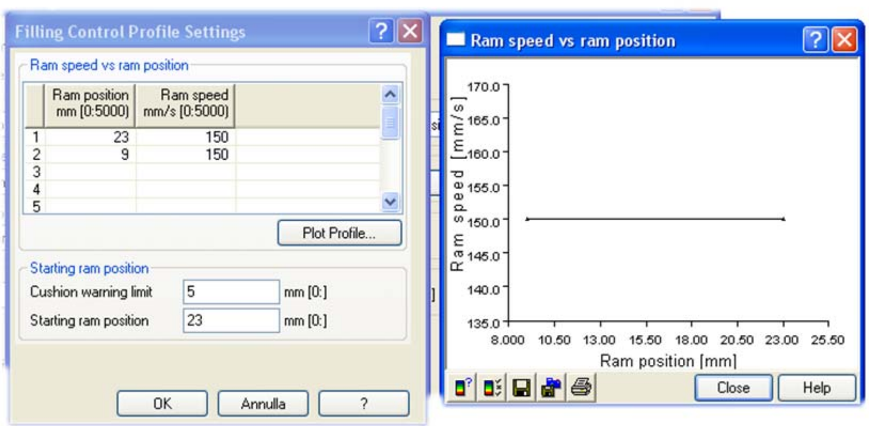


Fig. 138 Filling control profile settings

The switch-over point is controlled by a pressure sensor placed on the third bubble point (Fig. 139 left side). When the sensor feels 30 [Bar] the filling phase stops and the holding pressure phase begins.
The holding pressure has a duration of 4 [s] with a constant level of 1000 [bar] (Fig. 139 right side). Then cooling time is set on 4 [s] without pressure applied in the simulation, but this value can be quite random in this phase because not a really cooling simulation is performed.

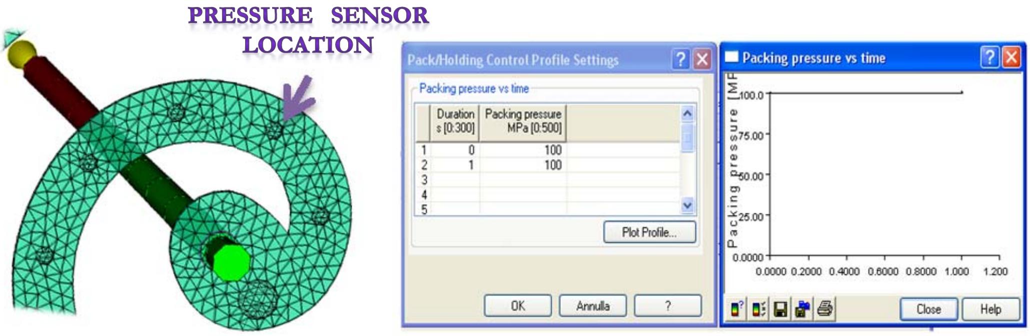


Fig. 139 Pressure sensor location on the spiral component and Packing control profile settings

Some advanced options (Fig. 140) must be checked that are mold material and response time of the injection molding machine. Mold material has to be the correct one because it influences specific heat and thermal conductivity of the mold. Moreover the correct machinery has to be found on database and Machine hydraulic response time should be set on 0.02 [s], due to optimization made on the real machinery.

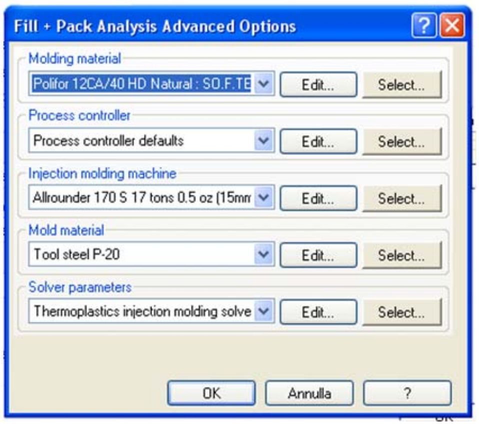


Fig. 140 Fill+Pack Advanced options

Thus now all is ready for simulations. Once a simulation is ready, all other can be created as copy of the original but changing only some parameters.
Lots of simulations were done. Mold temperature is the most important parameter to check. Material is another parameter, because some material properties may be better described inside the software database. Then the type of mesh, because different models of same the problem can give different results.

Simulation results

The first picture (Fig. 141) show the mesh influences on the results. The Midplane mesh type displays longer flow length the others kinds. It's important to show that there's not such a big variation between Dual domain and 3D in general however the time requested to solve Dual Domain simulation is almost 5 times lower that the 3D with 6 layers and even 21 times lower than the 3D with 12 layers. Thus all analysis will be performed with the Dual Domain mesh.

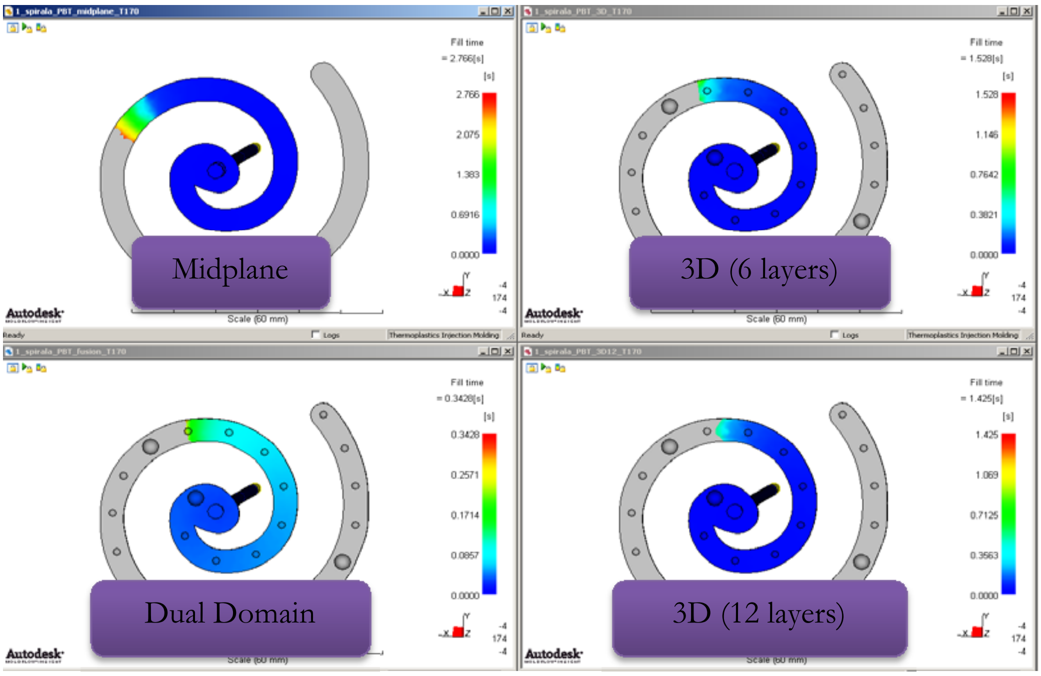


Fig. 141 Mesh influence on the result flow length

Main parameter it wants to show is the influence of the mold temperature to the flow length. As it was expected the flow length increase with the mold temperature (Fig. 142) but how much it depends from the polymer.

Temperature points are not randomly chosen but studied for the real experiment, but this will be explained later. Graph shows different patterns of polymers (Fig. 143).

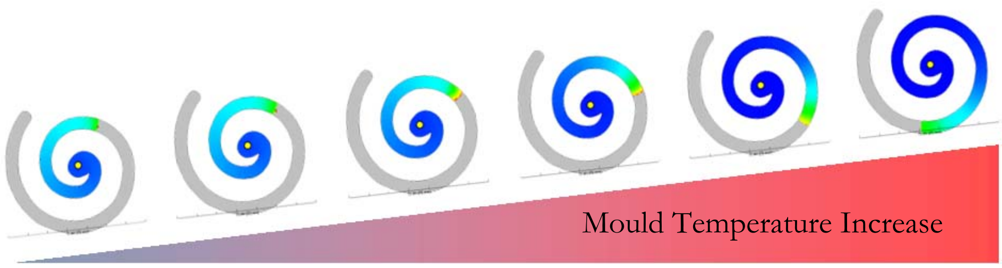


Fig. 142 Scheme of relation between mould temperature and flow length

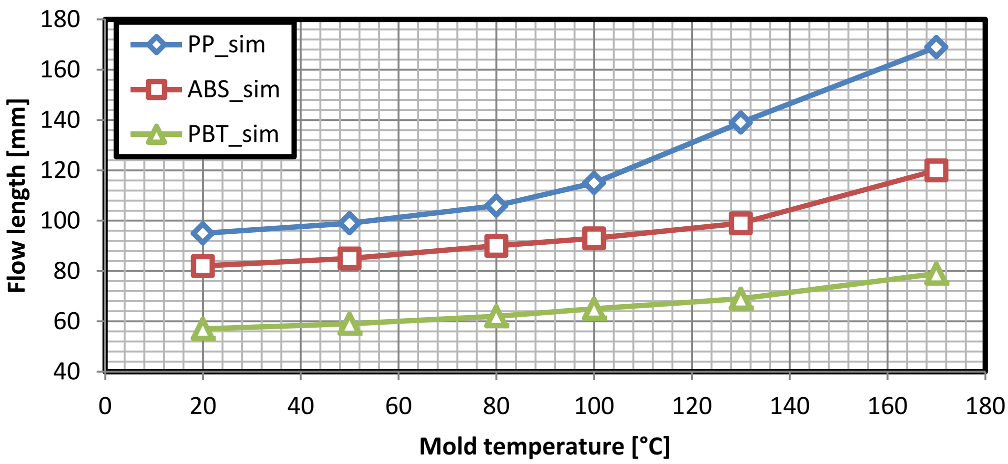


Fig. 143 Graph of Mold temperature vs Flow length for PP, ABS and PBT in the spiral simulation

5.2.3 Dimensional inspection

In order to validate the mold shape before the injection molding a 3D scanning can be applied to the spiral mould. Tecos Company works with the ATOS II system for a lot of problem cases and this one is one of typical case of reverse engineering but for these experiments was not explicitly requested neither planned.
The spiral experiment is based on a very thin layer plastic part; 0.4 [mm] of thickness. Thus the depth of the mould (Fig. 144) can be easily checked using 3D optical measurement system.

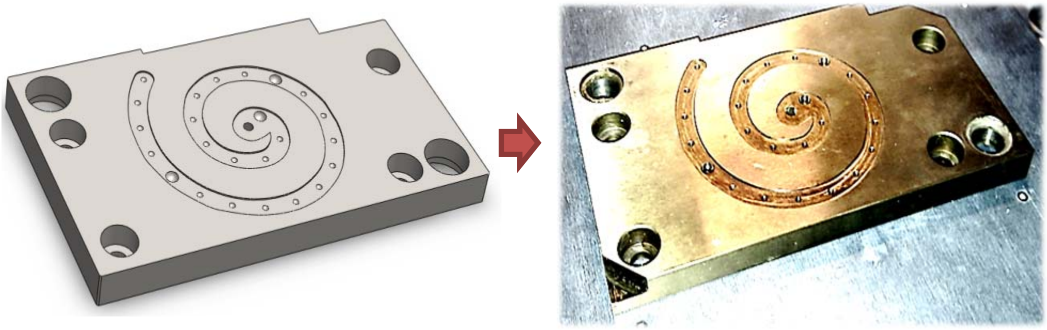


Fig. 144 Visual comparison between the spiral plate cad version and the realized spiral plate

The ATOS II system (Fig. 145 left side) allows with up to two million measuring points per admission and different measuring volumes always an optimum, efficient and high-resolution measurement of the most different objects. The precision of this device is 40 μm. It consists of a pattern projection range sensor based on the triangulation principle. It is equipped with one pattern projector and two cameras with fixed focal lens (Fig. 145 right side) observing the object to be measured from different points of view in order to reduce the effects of occlusions.

Fig. 145 ATOS II System with lens beside

First step is the correct choice of the lens. This verdict depends from two factors: the volume to consider and the precision to gain in that volume.
The scanner is movable therefore it must be placed on a special platform. This application requests a setting with a caliblation-plate that strictly depends from the choosen lens (Fig. 146). Since the spiral plate is too close to the projector light, dark filters are applied and adjusted directly to the lens (Fig. 145 right side).

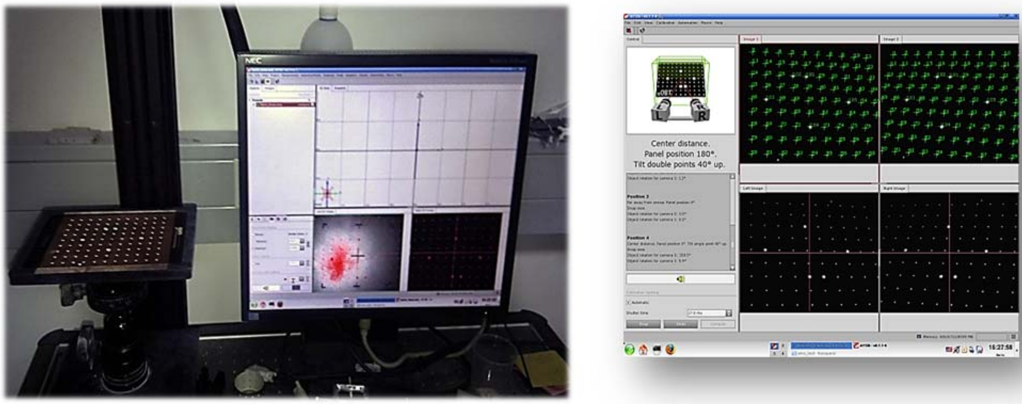


Fig. 146 Calibration procedure for the ATOS II System

Next step is the piece preparation. The spiral plate must be perfectly cleaned in order to avoid mistakes during the measurments. After clening, if the object is too reflective it has to be tarnished with a mixture of magnesium and alcool (Fig. 147 left side). This procedure must be carried out accurately otherwise the dust layer will affect the measurment. Moreover reference points must be positioned paying attentioncto paste them fine (Fig. 147 right side). Reference points are necessary to mix more scansions and to make them all in one model.

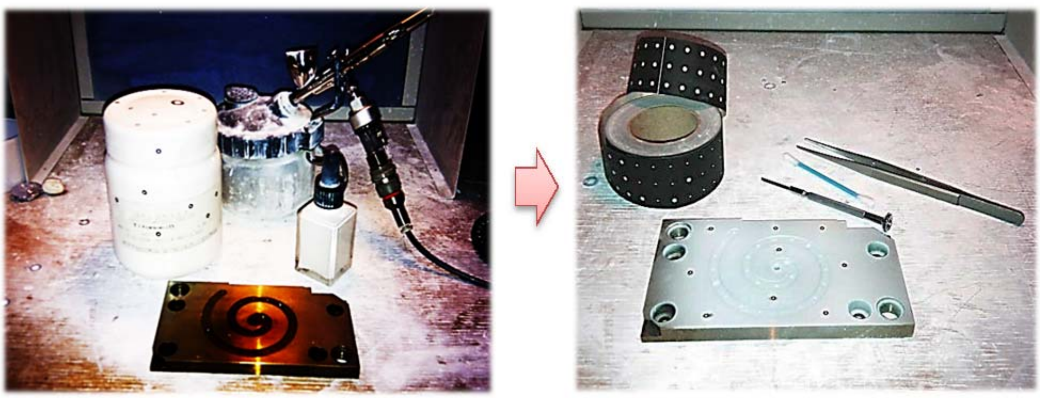


Fig. 147 Spiral plate preparation for 3D scanning procedure

The scanning process can start. Each scansions needs few seconds (Fig. 148). The spiral plate is quite an easy object to scan due to its shape that is mainly developed in the plane with small geometric variations. Four scansions are enough however eight scansions were done in order to get all details.

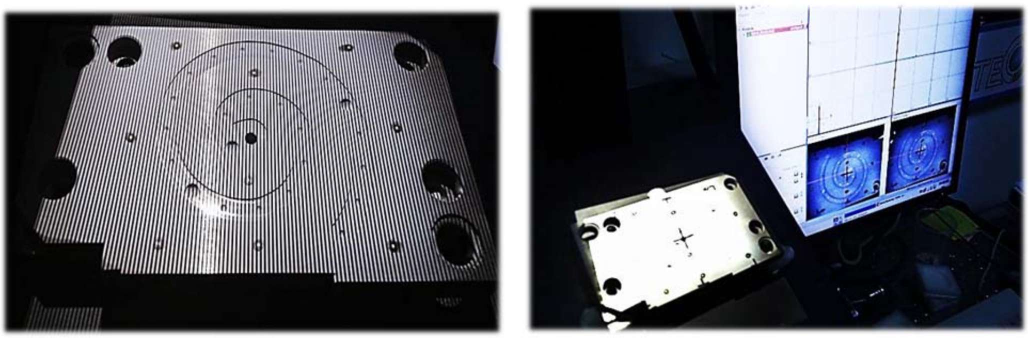


Fig. 148 Spiral plate under ATOS II system scanning

After the first scansion, the ATOS system recognizes the reference point positions and adapts the follower scansion with the common reference points. Afterwards a cloud of points takes the shape of the object captured by the cameras (Fig. 149).

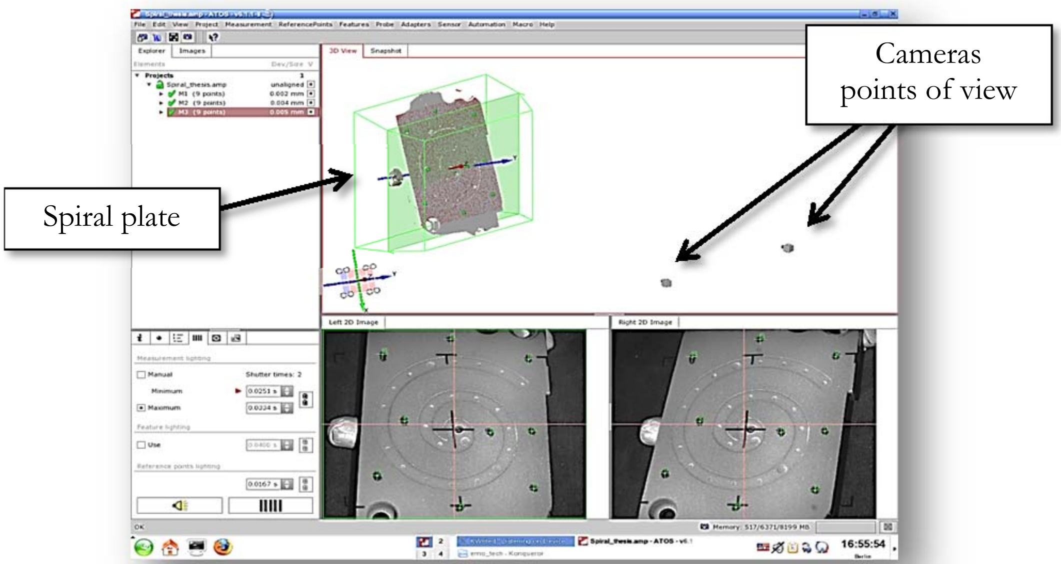


Fig. 149 Cameras point of view during the scan

The scan result is a STL model (Fig. 150) that can be recomputed by different software for the comparison with the original cad model.

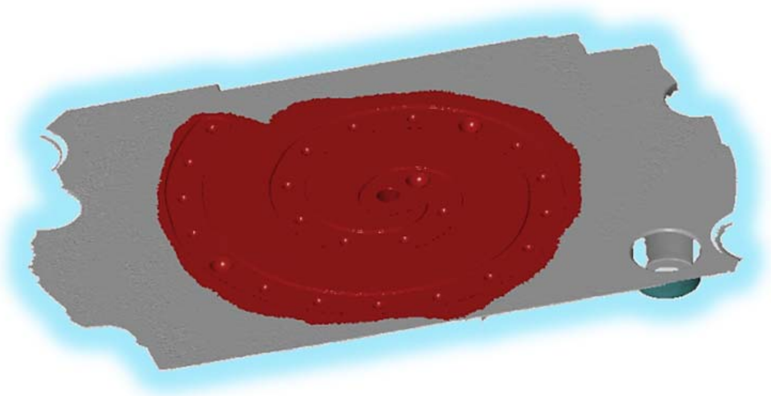


Fig. 150 STL spiral model

The red area of the previous picture (Fig. 150) is the selected that is used for best-fit interpolation with the STEP model (Fig. 144 left side). This area has been chosen arbitrarily and evidently it's the main region of interest. Good comparisons can be obtained by ATOS professional software, but detailed analysis derived by the use of GOM Inspect.
Making the STEP to the STL model overlapping a colored surface appears. Different colors show absolute distances between the two models (Fig. 151). As the high dimensional precision request has been done, as these results fulfill the expectation.

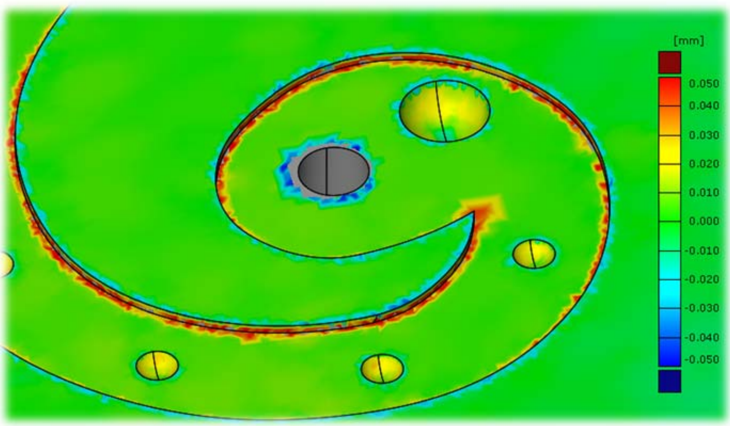


Fig. 151 Particular of the dimensional test on the spiral plate

Lots of probes or section plane can be positioned on the surface to get all requested data.

The green area show a dimensional tolerance of 10 [µm] and that's mean a very good quality for the realized spiral plate (Fig. 152). Thus potential variations between filling simulation and filling experiment don't concern dimensional aspects.

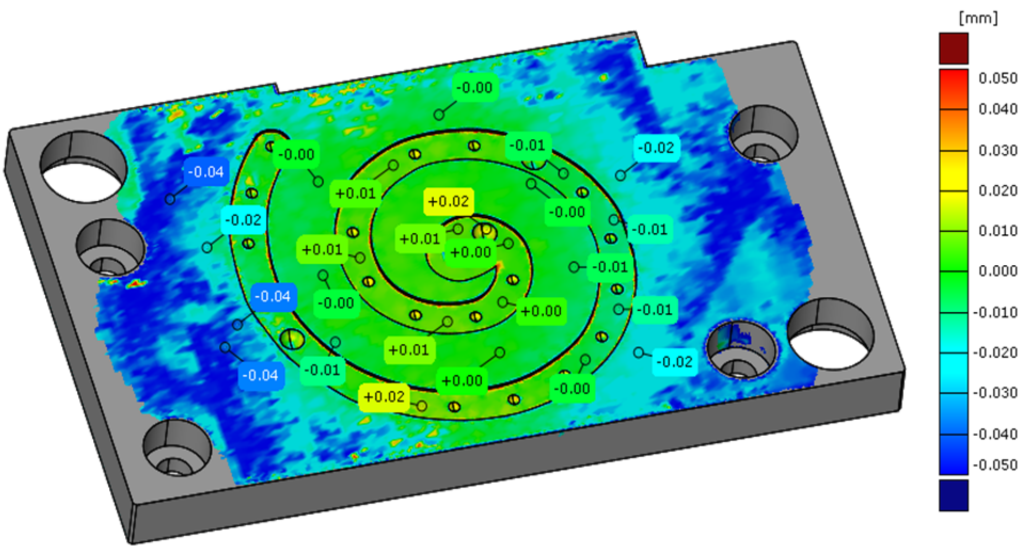


Fig. 152 Dimensional test of the spiral plate with distance probes

5.2.4 Filling experiment

These experiments are the practical transposition of the Autodesk Moldflow Insight™ simulations. However the reality has a bigger degree of complexity.
TECOS Company has many injection molding machines which mostly differ in the size (Fig. 153). The Arburg Allrounder 170s is a small to medium size machine that is regularly busy for the plastic parts production. In those rare moments of inactivity it is used for experiments, like Mi-Nanotech experiments.

Fig. 153 Partial view of TECOS Lab

In the next paragraph will be described the thin-wall injection molding procedure applied to the spiral mold shape.

- Tests planning
- Machine preparation
  - Drying polymer
  - Heating polymer
  - Nozzle cleaning
  - Mold mounting
  - Cycle parameters setup
- Tests execution
- Results

Tests planning

Mold heating is reached by four cartridge heaters the HLP™ 10X50/400, for a total power of 1600 [W]. These heaters are controlled by a temperature device made in TECOS. The temperature is measured inside the mold by three thermocouple sensors, is the Hasco™ z1295/5/1.5x71 type J.
Mold cooling is performed by the Regloplast 90S temperature control unit with a 20 [°] water flow rate.
The mould is obviously the previous described with the addition of two aluminum supports that allow mold to be mounted on this injection molding machine. In order to avoid thermal dispersion both sides of the mold have an insulation plate that is located between support and mold (Fig. 154).

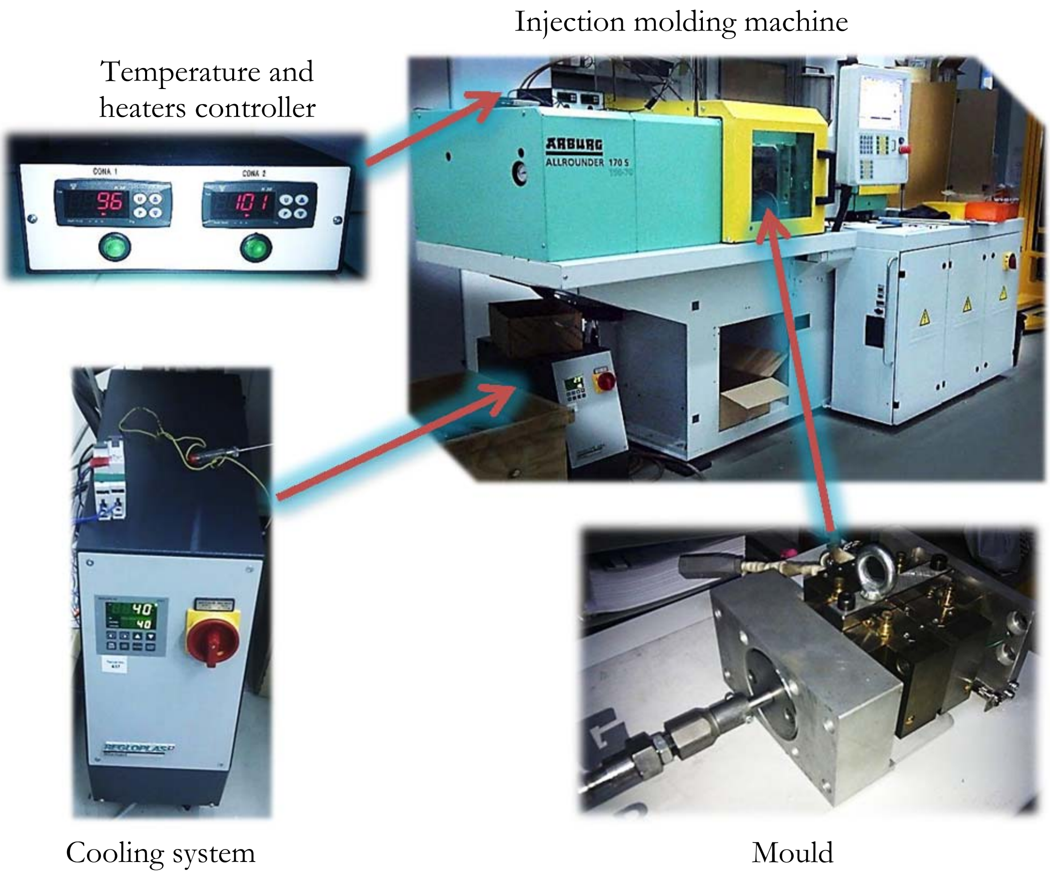


Fig. 154 Injection molding machine configuration

Temperature points are not randomly chosen, they are funcion of material properties.
Following the next scheme (

Fig. 155) , at 20 [°C] none of the system is applied because it’s the environment temperature. From the second to the fourth tenmperature point, only costant heating is required because till 100 [°C] all selected materials can be ejected without problems. Last two temperature points required the cooling phase with the water because otherwise time to ejection becomes huge. During variothermal operations the injection cicle is manual assisted since heating time and cooling time are not precisely extimated.

<table>
<tr><th>Temperature [°C]</th><th>20</th><th>50</th><th>80</th><th>100</th><th>130</th><th>170</th></tr>
<tr><td>Temperature system</td><td>Not applied</td><td colspan="3">Constant heating:
via cartridge heaters</td><td colspan="2">Variothermal:
heating via cartrigde heaters
+
cooling via water</td></tr>
</table>

Fig. 155 Temperature points and relative mold heating/cooling systems applied

Machine preparation

Machine preparation consists of many phases and it's required before starting filling tests.
All experiments were made in different days due to availability of the machine.
The pellets of polymer are contained into bags, and can remain there also for many months. As a result the selected polymer must be dried through external oven in order to avoid moisture residual because Arburg Allrounder 170s machine that TECOS holds, does not have integrated drying system.
Then pellets of polymer must be heated into the barrel according to the specifications provided by the supplier (Fig. 156).

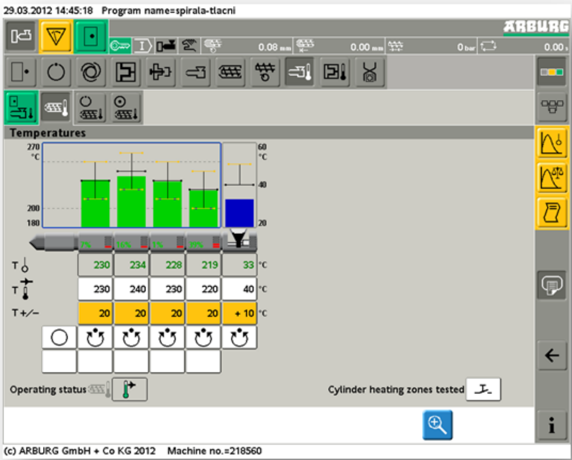


Fig. 156 Barrel temperature profile

Moreover the barrel has to be cleaned until polymer will be perfectly released by the nozzle (Fig. 157).

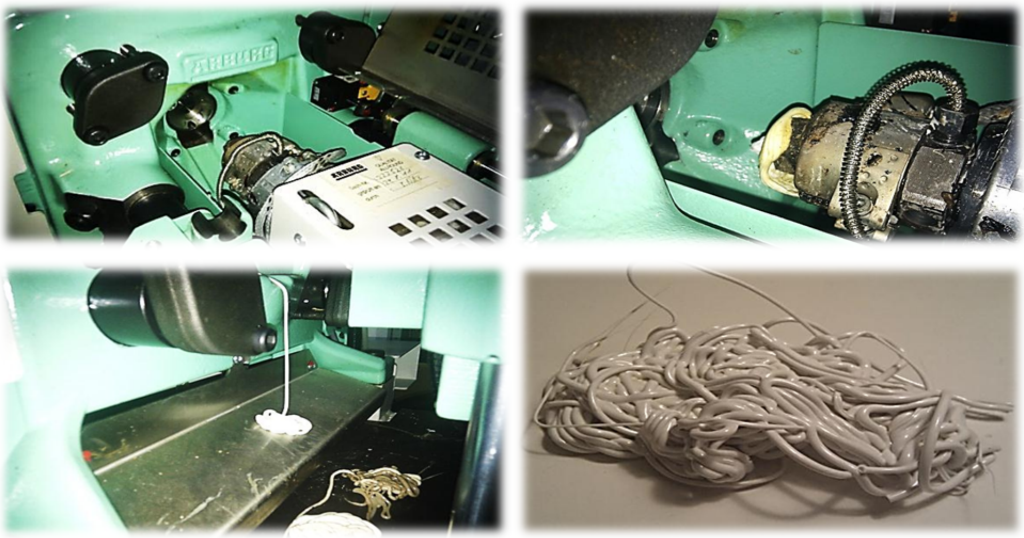


Fig. 157 Nozzle cleaning by using polypropylene

Drying phase and heating phase required long time; consequently meantime mould can be mounted on the machine. If the mold is small one person is enough to manage it, otherwise due to the weight more persons or hoist are needed.
The adopted mould mounting procedure is quite standard:

- Clamp opening
- Fixing closed mold to the machine injection side
- Clamp losing
- Fixing closed mold to the machine ejection side
- Fixing closed mold to the machine ejection system
- Making the electrical and plumbing connections
- Removing mold transport system
- Machine-Mold calibration

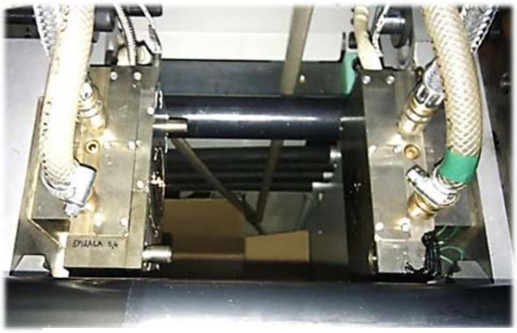


Fig. 158 Mold ready for injection molding

Cycle parameter setup can be saved as an informatics program, thus so unless variables changes it must set only once.
The all cycle phases are represented on the top the machine screen controller (Fig. 159). In the case of variothermal process (Fig. 155) mold heating time and mold cooling time are not well known thus all that cycle starting are got manually.
First step is the mold closing. It's possible to set the speed profile and relative clamp force in order to avoid abrupt closing and a consequent shot. Then a constant clamp force is applied to the mold till the next opening.

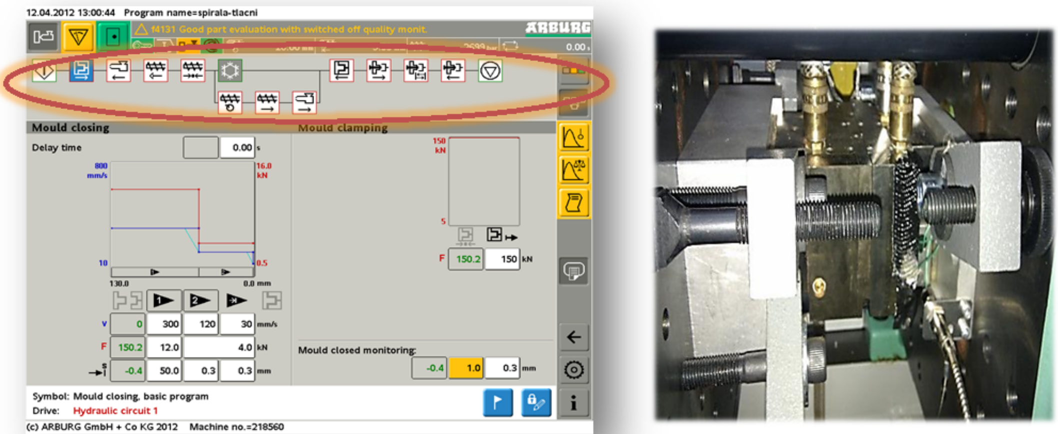


Fig. 159 Mold closing, mold clamping screenshot and closed mold picture

If the nozzle is not on contact with the mold then it's moved to reach that position. The movement of the nozzle is the movement of the whole injection unit. Nozzle advancement is set by force and speed profiles (Fig. 160).

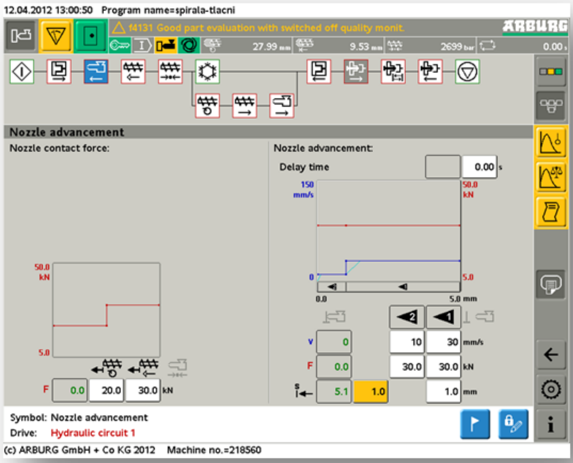


Fig. 160 Nozzle advancement setting screenshot

Next phase is the injection phase, during this phase the screw proceds forward without rotation. This is the most important setting window for the experiment. The dosage stroke influences the quantity of injected material.
The same is for the velocity and the maximum pressure. It's possible to set the velocity, in this case pointed to the maximum with the relative maximum reachable pressure meaused on the injection unit.
Another important paramenter is the switch-over point. Picture below (Fig. 161) shows the screw stroke methods, but in the most of Minanotech experiments were used a pressure point. This pressure point has been measured by a pressure sensor placed on the mold with a switch-over value of 30 [bar].

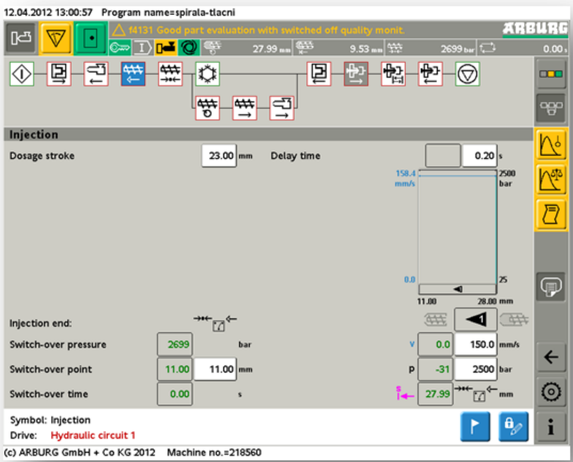


Fig. 161 Injection setting screenshot

Wrong values of switch-over point combined with the incorrect value of clamping force may arise undesired effects (Fig. 162).

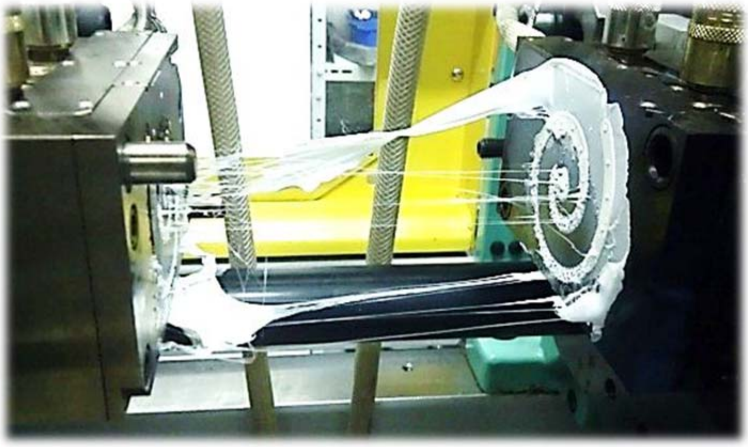


Fig. 162 Flash effect sample

This is the packing phase, it consists of a pressure-time profile (Fig. 163) apllied to fullfill the mold cavity. The profile starts with the reached pressure value during the injection, then a constant holding pressure is applied, after that, pressure must be decreased due to the cooling phase.

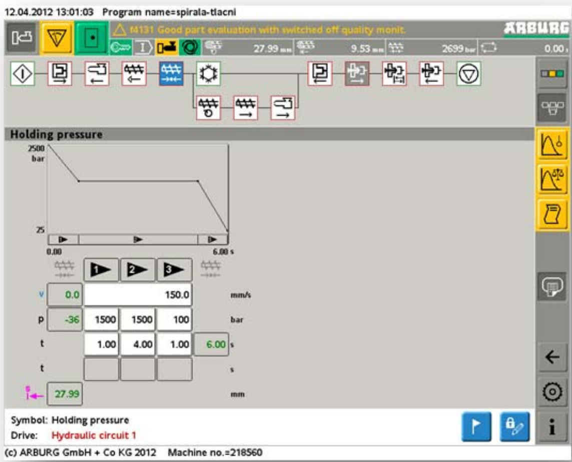


Fig. 163 Holding pressure setting screenshot

Cooling phase is is structured by three practical step but only two separate setting windows (Fig. 164). During this phase the screw proceds backward with a rotation in order to avoid material absence inside the nozzle. Then the entire injection unit has a backward movement but only if this required from the cycle.
In the case of mold heating over the transition temperature, the mold cooling time as the mold heating time are not well known. Therefore here a manual interruption of the automatic process cycle is required in order to reach the requested value of temperature displayed on the external controller.

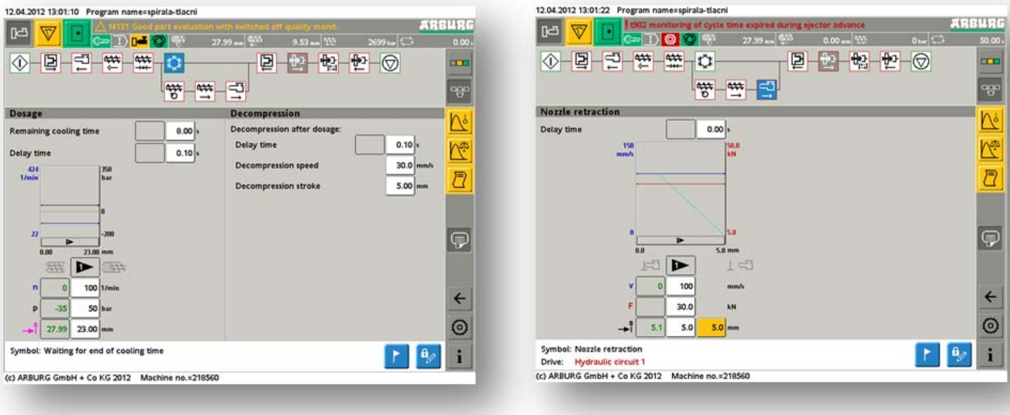


Fig. 164 Cooling phase setting screenshots

When ejection temperature in reached the mold can be opened (Fig. 165 left side). This stage is ruled by speed and force profile like the opposite one. If the ejectin temperature is not reached, the mold is too warm and the piece maybe is still liquid. As a result it remain stuck on the warm mold (Fig. 165 right side).

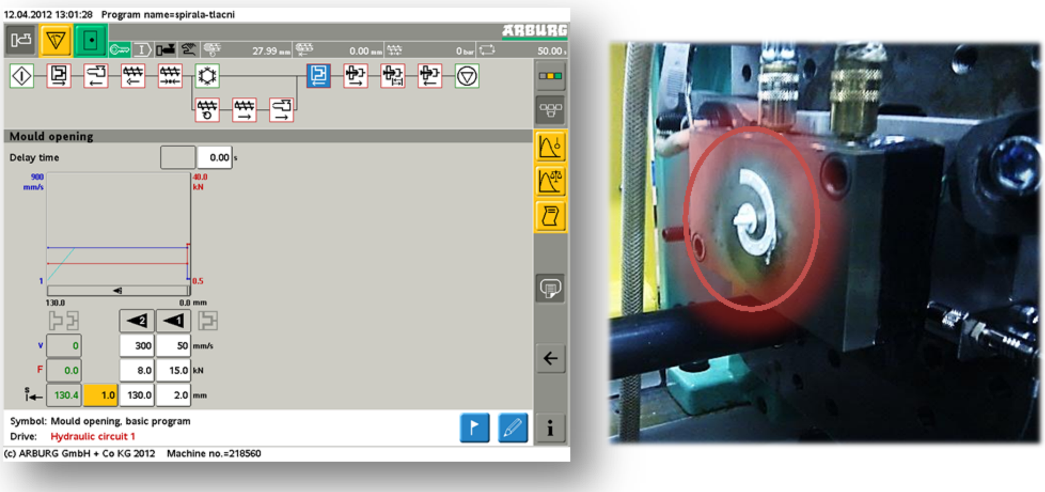


Fig. 165 Mold closing setting screenshot and blocked piece on the mold

Once the mold is opened, the piece must be removed so that a new one can be injected. The ejector proceds forward and backward few times (Fig. 166) allowing the piece to jump out from the mold an dto fall down into a box.
Then the cycle is stopped to check parameters and injected piece, after that it manually restarts, but the mold closing it's manual in the case of variothermal heating as well.

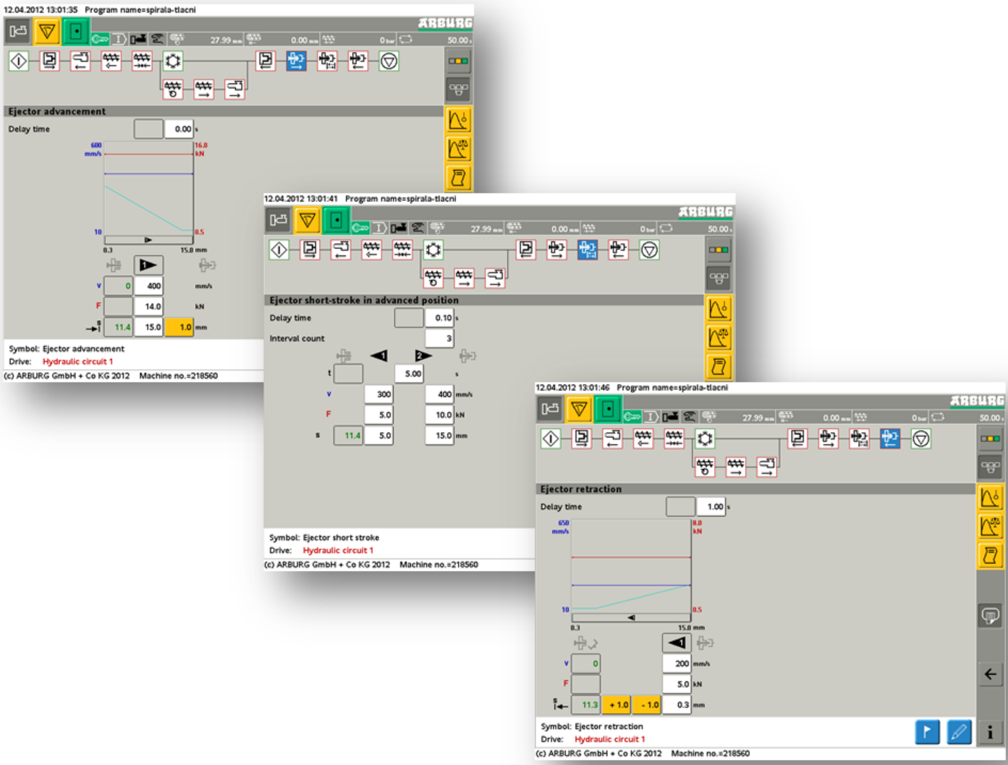


Fig. 166 Ejection phase setting screenshots

Sometimes happens piece remains stuck on the ejection side. This situation is due to mold temperature, but the opposite effect of the previous. Here in fact is the mold is too cold the ejector pin reduces the himself dimension, as a conseguence the injected polymer fill that cavity and quicky freezes. Then ejector works not in properly way (Fig. 167).

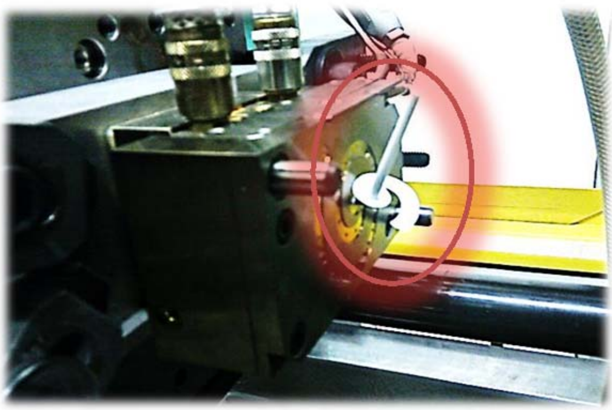


Fig. 167 Ejection problem with the spiral piece

Experiment results

All temperature points were test five times, this number has been considered adequate because the deviation of those replication was practically zero compared with way to measure it.

Fig. 168 Spiral pieces

Therefore the reported data are calculated as the average point of five replication.
All experiments were performed during a long period but with the same environment conditions. As expected by the simulation in addition to theory it's visible flow length escalation with the mold temperature raise. Also the predicted polymer order is correct, but to check the accuracy of these data is better to make close comparison with simulation data.

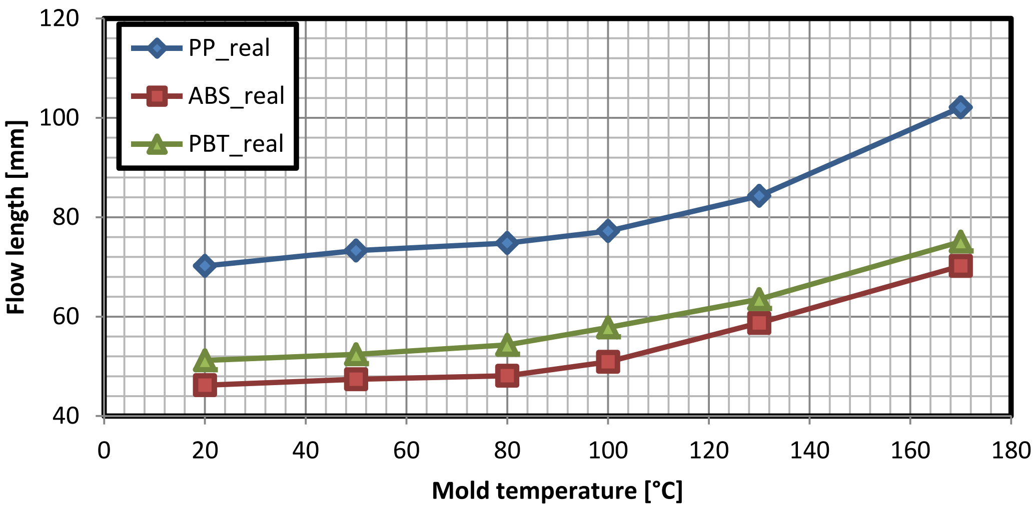


Fig. 169 Graph of Mold temperature vs Flow length for PP, ABS and PBT in the spiral experiments

5.2.5 Data comparison

In the case of **Polifor 12 CA/40 HD** (PP material) the Autodesk Moldflow Insight simulations make totally incorrect prediction. The relative gap varies from 26% to 40% (Fig. 169) and the simulation shows longer flow length respect to is the reality, thus they are not conservative.

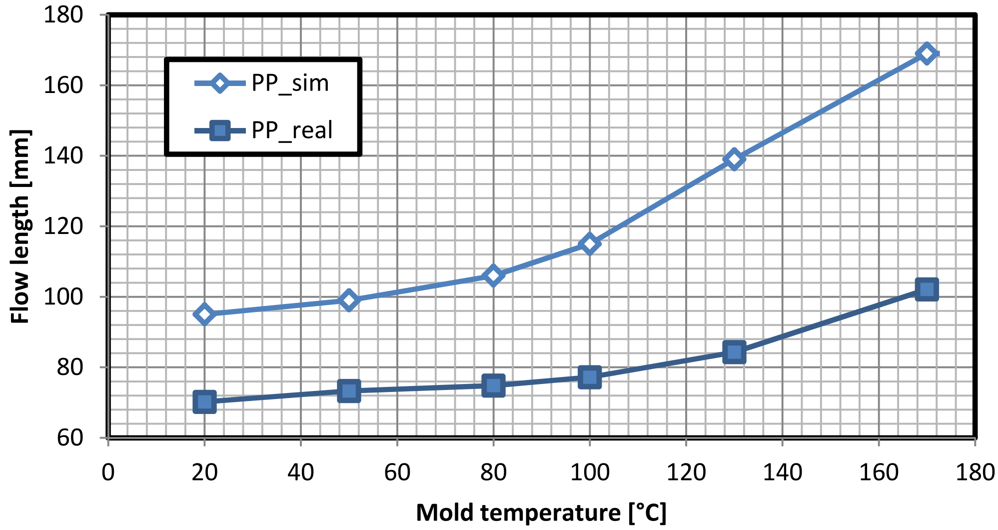


Fig. 170 Comparison between mold filling simulations and mold filling experiments for PP polymer

Regarding the **LG ABS HF380** (ABS material) filling simulations shows always big variation, but at least this error is quite constant. It varies from 41% to 47% (Fig. 171). Here also simulations data are higher of experiments data.

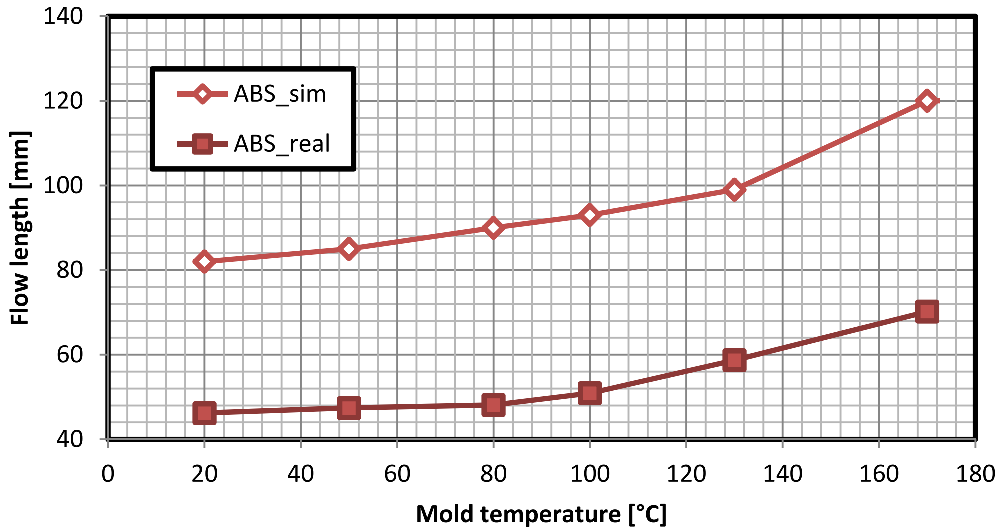


Fig. 171 Comparison between mold filling simulations and mold filling experiments for ABS polymer

The last case with **Ultradur B 4300 G6** (PBT material) shows quite good results because predicted data varies from reality data from 5% to 12% (Fig. 172).
However bearing in mind all three different situations the last one could be considered as a lucky case. And the final report is bad flow length prediction.

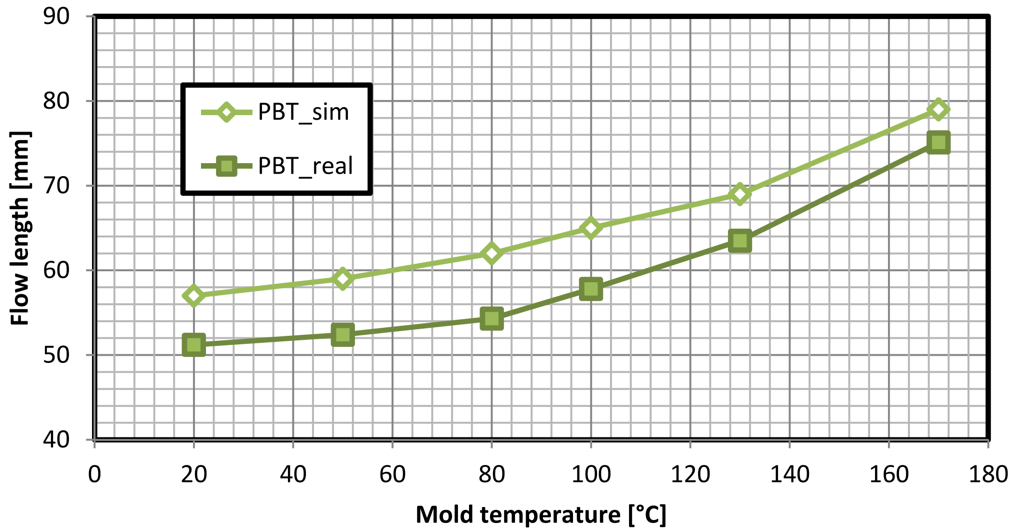


Fig. 172 Comparison between mold filling simulations and mold filling experiments for PBT polymer

At this time not a good response has been found yet, especially because other simulations, with different mold shape, perfectly match with the corresponding real experiments. TECOS Company is strictly working with the Autodesk Software house in order to solve this problem.

- Thanks to this study it's possible to exclude dimensional problems.
- The temperature profile predicted by Ansys simulation shows variation of up to 20 [°C] in the small spiral area. This could suggest a strong influence of temperature on the non-uniform filling of the mold. However at the first temperature point, placed at 20 [°C], the mold temperature is totally uniform thus if this would be the cause of the problem this point should be much closer to the same predicted by simulation.
- Having made other simulations with totally different mold and material it's possible to exclude a machine problem.

Thus at this time other experiments with same materials but different mold will be performed in order to check the goodness of material data.
Otherwise it means that other phenomena play important role in the field of thin-wall injection molding system, but at the moment only hypotheses can be thought.
The TRIZ analysis can be applied also for problem detection and it can use the standard solutions belonging Class 4.
Parallel experiments were started in other Companies to investigate the influence of mold roughness on the flow length with a thin-wall mold, nevertheless preliminary results shows small influences of this parameter on the flow length.

6 Conclusions and future developments

The plastics industry is booming. In particular, the electronics industries such as that of small appliances require a constant search in order to meet the increasingly complex demands of the market (Fig. 173). It's in this area that the research on thin-wall injection molding gains in importance.

Fig. 173 One of the thinnest smartphone in the world

In order to improve these technologies, as it is also ascertained by the previous TRIZ analysis, research is moving in the right direction, and strides can still be made.
It has been seen that a systematic problem solving approach based on the TRIZ method has brought results that are much targeted also in a particular field such as Thin-wall injection molding.
The TRIZ analysis carried out shows ideas for solution not only for rapid mold heating and rapid mold cooling, but also lots of scientific effects that must be investigated more in detail. These ideas must first be designed as a whole and then validated. So the path is still long.

Even the support from the software side is still quite deficient as regards this narrow field, but there are large margins for improvement, already in the communication between different software. In fact as seen, two of the main software used in this field cannot exchange data.

TECOS the company is at the forefront in the resolution of these issues and has already planned a series of experiments to solve them. In the first instance, TECOS together Autodesk will perform calibrations between simulations and experiments to achieve more accurate predictions. TECOS then will create an automatic heating-cooling system, taking advantage of the solutions found by the TRIZ method. In addition other benefits of the heating of the mold will be deepened, such as the elimination of weld lines (Fig. 174).

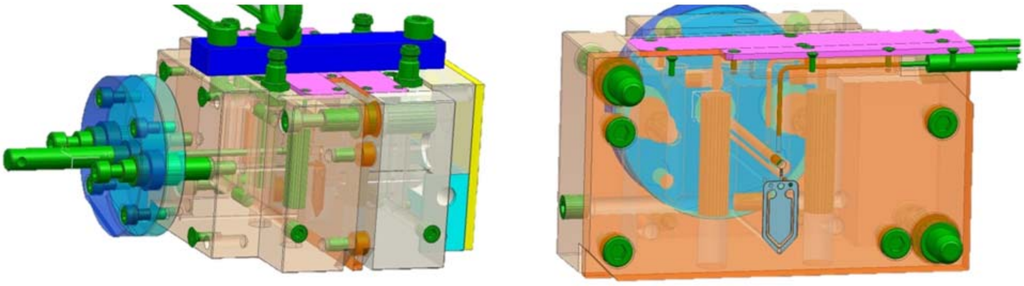


Fig. 174 TECOS tests of new mould for paper clip – weld lines

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