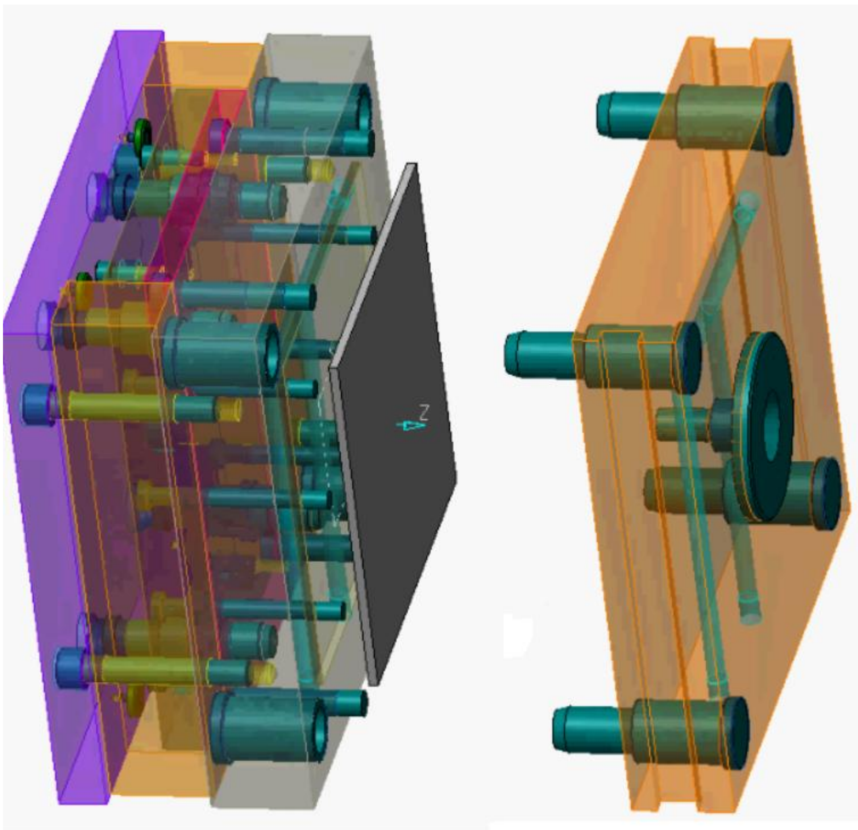
Constanta Maritime University
Naval ElectroMechanics Faculty

RESEARCHES AND CONTRIBUTIONS REGARDING THE OPTIMIZATION OF THE MOLD INJECTION PROCESS TO INCREASE THE QUALITY FOR SOME COMPONENTS AND ACCESSORIES OF POLYMERIC MATERIALS

- ABSTRACT -



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INTRODUCTION

The motivation for choosing the study of polymeric materials and the injection process, as the main subject of this PhD thesis was based on a technical passion of mine. This concern has been initiated by my university and master studies at the Polytechnic University of Bucharest and continued through practical work (Matris Metal Plast Bucharest, as a CAD Engineer) and teaching (Constanta Maritime University) later.

Thesis has proposed to achieve series of contributions regarding the optimization of injection process to increase the quality of polymer parts. The mathematical model, analytical and numerical representation and experiments were set up in a whole, which attempts to provide a valid solution for the major objective of this PhD thesis.

Most of the actual parts are made of molded polymeric materials which have a great advantage in comparison with the classic materials. Large chemical companies produce most of the 200 million tones per year of plastic materials. Evan the molds require high prices for their production, they are necessary because of the several advantages of the resulting parts: shapes with great complexity, automatic control of the molding process, high speed of the technological process, accuracy and quality of the final product, low or null costs for the postprocessing of the parts.

The quality of the final part is a complex concept which may be approached from different points of view. Research offers the instruments employed to define the best strategies for the effective production of molded polymers: materials and parameters of the molding process.

CHAPTER 1. The actuality and the importance areas. General aspects

The first chapter present a brief history of the development and use of polymeric materials, the actuality and the importance fields of injected polymeric materials use and general issues regarding the injection technology, followed by a general classification of the injection molds.

I have been described the construction and working mode of an injection mold design and manufacturing and in the end of this chapter was presented the importance of using the computer in this area.

Injection molding is a process that has been used in a wide variety of industries for many years. This process uses amorphous and crystaline thermoplastic resins that are heated to a stable temperature and compressed into a mold. Molten plastic is injected at high pressure into a mold, which is the inverse of the desired shape.

Process design of injection molding involves the selection of the injection molding material, machine, mould design, production scheduling, cost estimation, and determination of injection molding parameters.

The chapter 1 presents also the optimization of the mold design using the CAD technology. Pro/Engineer Mold Tool Design leads users through a logical step by step approach to create plastic injection molds. Pro/Engineer Mold Design furnishes standard component libraries, an extensive choice of industry standard mold bases, automated generation of all required components and associative electrode design, reduces time to market, improves quality and lower cost.

The author presents a personal contribution of a mold injection designed in 2004 using ProEngineer, at Matris Metal Plast, were she worked as a design engineer. Using the software offered dramatic time saving potential by removing much of the repetition prevalent in mold tooling design and freeing up our time for more important tasks.

CHAPTER 2. The current stage of knowledge regarding the mold filling

In this chapter the author analyze the mold injection process, the polymer flow and the phenomena occurring. She also presents the analysis and optimization of plastic injection, using the "method of filling visualization", through CAE simulation software for the process.

The mold injection process involves the following sequence of steps: (a) heating and melting the polymer, (b) pumping the polymer to the shaping unit, (c) forming the melt into the required shape and dimensions, (d) cooling and solidification

In this chapter, the auhor presents a personal contribution using the "visualization method filling" for polymeric part, from 2004 (figure 1). Using this method, she obtains a better injection molding process and mold design. With this method the auhor obtained information such as polymer melt filling patterns, weld line and air trap locations, required injection pressure and clamp tonnage, fiber orientation, cycle time, final part shape and deformation, and mechanical properties of molded parts.

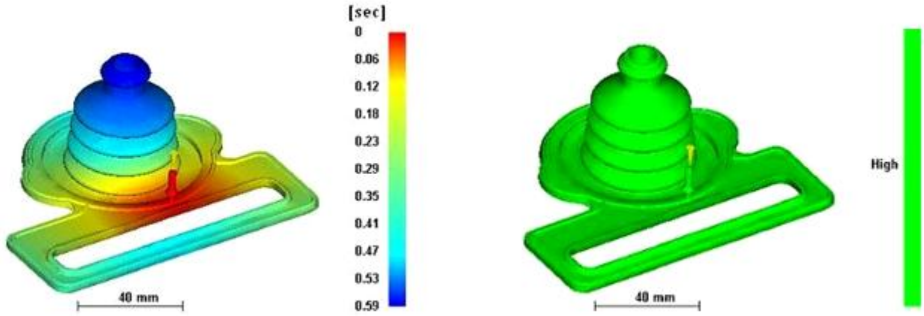


Fig. 1 Time and quality of filling

The "visualization method filling" improves the quality of the injection molding process with polymeric material; describe the phenomenons which appear when the thermoplastic flows into the mold cavity. This method shows us the thermoplastic evolution in time.

CHAPTER 3. Mathematical model for the couple „mold injection – polymeric material"

This chapter presents the mathematical model for the couple „mold injection – polymeric material". In order to be able to predict and model complex polymer flows, one must first determinate the mathematics equations that govern the flow: the conservation of mass, the conservation of momentum, and the conservation of energy.

For a polymeric material with density ρ, specific heat at constant pressure in most general form these equations can be written as follows:

- Conservation of mass:

$$\frac{D\rho}{Dt} + \rho(\nabla \cdot \bar{v}) = 0\,, \qquad (1)$$

where notation (2) means material derivative, which is a particular kind of time derivative, in which the material point is held constant:

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \bar{\nu} \cdot \nabla\,, \qquad (2)$$

- Conservation of momentum:

$$\rho D\bar{v}/Dt = -[\nabla \cdot \bar{\bar{\tau}}] - [\nabla p] + \rho \bar{g}\,. \qquad (3)$$

The equation (3) is one of the most general laws governing fluid flow and is called the Navier-Stokes Equation. In these equations $\bar{\nu}$ is the velocity vector, p is the pressure, $\bar{\bar{\tau}}$ is the stress tensor and $\bar{g}$ is the vector of the body force per unit mass acting on the fluid.

For practical needs these equations are simplified. Usually, isotropic material and symmetric stress tensor are assumed. If material density is assumed to be constant, for the incompressible fluid the equation (3) reduces to:

$$\left(\nabla \cdot \bar{v}\right) = 0. \tag{4}$$

Assumption of constant material density during the injection molding filling stage does not introduce big error because most of fluids are practically incompressible at the pressures encountered at the filling stage.

- Conservation of energy:

$$\rho C_p \left(\frac{DT}{Dt}\right) = \lambda \nabla T - \left(\left\{\nabla \bar{v}\right\} : \bar{\bar{\tau}}\right). \tag{5}$$

If the material has constant density and constant thermal conductivity λ, equation (5) describe the conservation of energy, where C_p is the specific heat at constant pressure.

The general form for the constituent equations for incompressible non-Newtonian fluid is:

$$\bar{\bar{\tau}} = \eta \bar{\bar{\Delta}}, \tag{6}$$

where $\bar{\bar{\tau}}$ is the viscous stress tensor, $\bar{\bar{\Delta}}$ is the velocity of deformation tensor and η is the fluid viscosity.

The Ostwald de Waele, model approximates polymer melt flows, describe in cylindrical coordinates:

$$\tau_{rz} = m\left(-dv_z/dr\right)^n. \tag{7}$$

where m $[N/m^2 \cdot s^n]$ is the consistency index and n is the (flow) power-law index.

CHAPTER 4. Analytical and numerical solutions for the „mold injection – polymeric material" model

The Chapter 4 describes the analytical and numerical implementation of the proposed model „mold injection – polymeric material". Next, the author analyzes the flow of the plastic melt phenomena occurring in the mold, through simulations with dedicated software.

Commercial software, such as MoldFlow, offer powerful tools to simulate the molding process in the free surface approximation. The program allows us to decide which the best parameters of the molding process are and predict the flow behavior of thermoplastic melts, so the high quality final products may be efficiently manufactured. The numerical simulation employed to validate the mold designs which are very expensive, also eliminates the risks and avoids the losses.

In the numerical analysis the author puts emphasis on determining the distribution of residual stresses in injected parts. We intend to reduce the residual stresses from the polymeric parts, to obtain high quality. Studies were performed on three different types of plastics: acrylonitrile-butadiene-styrene (ABS), polypropylene (PP) and polystyrene (PS).

Several studies were performed, for different values of melt temperatures (for ABS between 200^{o}C - 260^{o}C, for PP between 210^{o}C - 270^{o}C and for PS between 185^{o}C - 245^{o}C) and different sizes of the mesh (8 mm, 7 mm, 6 mm, 5 mm, 4 mm, 3 mm, 2 mm) to determinate the optimum injection process.

As it can be noticed, the results of the numerical simulation are in common sense ranges of values. One can also notice that the results are stable, no unusual variation being recorded, so the author tooks the base mesh of 5 mm. The author determinates the residual stresses in two critical points. The first one is near the point of injection and the second one is near the plate edge, in the part depth of 3,3 mm, as you can see in table 1.

Tabel 1 Values of residual stresses from numerical analysis

Polymeric material	Mesh sizes [mm]	Residual stress near the injection point “a” [MPa]	Residual stress near the plate edge “b” [MPa]
ABS	5	1,840	1,430
PP	5	2,453	1,571
PS	5	1,981	1,458

CHAPTER 5. Determination of elastic constants and residual stresses in polymeric materials

In this chapter the author describes the experiments, the equipment used, the methodology, working data and numerical and experimental validation. The polymers of interest are acrylonitrile butadiene styrene (ABS) polypropylene (PP) and polystyrene (PS). First, the author designed and manufactured the mold for this parts using Visi 15 software, at Complet Project S.R.L Bucharest.

Then, the author determinated the elastic constants. Stretching tests were performed on these three samples, as you can in the figure 2.

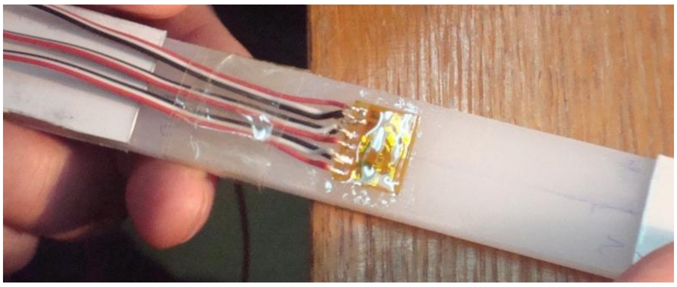


Fig. 2 The polymeric test specimen

The equipment employed for the experiment consists of a microcomputer-control electronic universal testing machine WDW 50-E, having the maximum testing capacity of 50kN, and a P3 strain indicator from Vishay. The stretching tests were performed on samples applying the four different forces 200N, 400N, 600N and 800N. The time between applying the forces was 100 seconds, because we wanted to be in the stationary regime. In these tests, the temperature was measured at 23 ± 2 °C.

With the value of the longitudinal and transversal strain and using the stress-strain relationships is termed Hooke’s Law, we could calculate the elastic constants: the Young’s Modulus, the Poisson’s ratio and the shear Modulus, modulus of rigidity, presented in table 2.

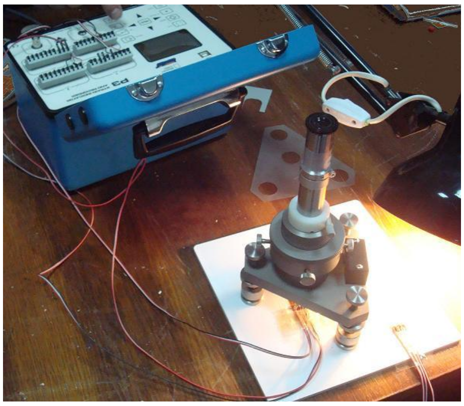
Tabel 2 The elastic constants

	ABS	PP	PS
E [MPa]	2926	2124	3347
v	0,41	0,486	0,358
G [MPa]	1038	714	1232

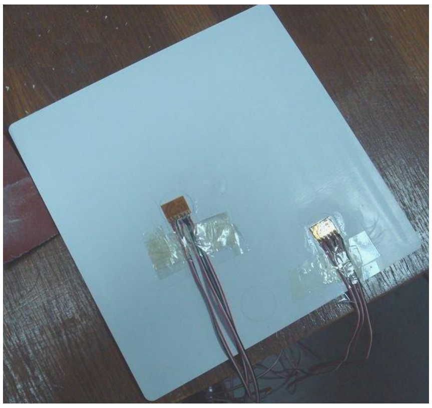
Next, the author presents the measurements of the residual stresses using the strain gage rosette on three different used plastics: ABS, PP and PS. I done it with the most widely used practical technique for measuring residual stresses, the hole-drilling strain gage method described in ASTM Standard E837. With this method, a specially configured electrical resistance strain gage rosette is bonded to the surface of the test object, and a small shallow hole is drilled through the center of the rosette. The local changes in strain due to introduction of the hole are measured, and the relaxed residual stresses are computed from these measurements.

For the experiments we use the same special three-element strain gages rosette, CEA-06-062UL-120, a Vishay Micro-Measurements Model P3, and a precision milling guide model RS-200 (figure 3 - a). The plate polymer test specimens have 200x200x5mm dimensions and they were prepared directly from the injection molding (Complet Project S.R.L Bucharest).

The measurement points, where strain gages rosettes are installed are located in two critical points. The first one is near the point of injection and the second one is near the plate edge, as you can see in figure 3 – b (Technical University "Gh. Asachi").



a. The milling guide model RS-200



b. The polymeric plate

Fig. 3 The hole-drilling strain gage method, ASTM Standard E837

Using the values of the strains measured on the bridge and the physical characteristics of the polymeric material which were computed using experimental values there can be calculated the residual stresses. The results obtained by three methods are presented in table 3.

Tabel 3 Experimental residual stress

Point	**Near the injection point "a"**			**Near the plate edge "b"**		
Method	**ASTM 837-92**	**Calibration rosettes**	**H-Drill program**	**ASTM 837-92**	**Calibration rosettes**	**H-Drill program**
Polymeric material ABS						
σ_{min} [MPa]	-1,984	-1,890	-2	-1,723	-1,646	-2
σ_{max} [MPa]	-0,144	-0,150	0	-0,861	-0,833	-1
Polymeric material PP						
σ_{min} [MPa]	-3,001	-2,898	-3	-1,545	-1,518	-2
σ_{max} [MPa]	-1,952	-2,013	-2	-1,349	-1,352	-1
Polymeric material PS						
σ_{min} [MPa]	-2,122	-2,060	-2	-1,580	-1,536	-2
σ_{max} [MPa]	-0,739	-0,758	-1	-0,633	-0,644	-1

At the end of the chapter we compared the results obtained experimentally and numerically, in order to achieve model validation. The results confirmed the validity of the theoretical and numerical models. Using the Huber-Hencky-Mises failure criteria,

$$\sigma_{ech} = \sqrt{\frac{1}{2}\cdot\left[\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2\right]} \quad (8)$$

the author could calculate the values of the yield stress in uniaxial tension (equivalent stress), as you can see in table 4:

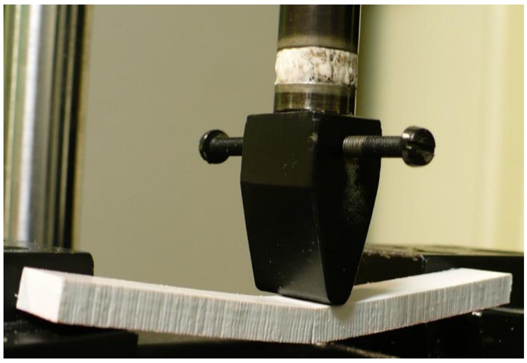
Tabel 4 Experimental and numerical residual stresses value

Polymeric material	Point	σ_{ech} - ASTM 837-92 [MPa]	σ_{ech} - MoldFlow [MPa]	Error δ [%]
ABS	Near the injection point “a”	1,916	1,840	3,97
	Near the plate edge “b”	1,492	1,430	4,16
PP	Near the injection point “a”	2,639	2,453	7,05
	Near the plate edge “b”	1,457	1,571	7,82
PS	Near the injection point “a”	1,865	1,981	6,22
	Near the plate edge “b”	1,377	1,458	5,88

CHAPTER 6. Determination of Charpy impact of polymeric materials. Injection of complex parts on numerical and experimental studies conducted

This chapter presents the evaluation of impact behavior on 3 different used polymeric materials (ABS, PP, PS). The polymeric materials are the same injected parts analized in the previous chapter. The Charpy impact test is a standardized strain rate test which determines the amount of energy absorbed by a material during fracture. For the plastics we used the typical method described in ASTM Standard D 6110. The testing machine that we used is an Instron Dynatup Impact System with Data Acquisition and Control, model 8200 (figure 4 - a, at Polytechnic University of Bucharest). The specimens measure 80±0,2, 10±0,2, 4,9±0,1 (mm), with respect to ASTM D 6110 or SR EN ISO 179 Charpy plastics testing (figure 4 - b).

a. Instron Dynatup Impact, model 8200



b. Polymeric specimen tested

Fig. 4 The Charpy impact test, ASTM Standard D 6110

Experiments are accredited by RENAR organisation. The ABS, PP and PS materials behave very differently at high rates of loading and for that we cannot use static strength tests to predict impact behavior. For the ABS specimen, break type of evidence is amended according to the drop height as to H = 35 mm no breakage, and for H = 40 mm up to H = 80 mm hinge breaking. For the PP specimen, we observed that for the same drop height from the H = 35 mm up to H = 80 mm, we don't have breakage. PP material has a better elasticity, in comparison with ABS material. And for the PS material we have total breaking.

In the same chapter 6, the author made an application of the results for the finite element model of a mechanical part. The knowledge acquired from the previous studies is used for the simulation of the molding of a real part, figure 5. The mold and the polymeric part model were designed by the author and manufactured at Matris Metal Plast, Bucharest.

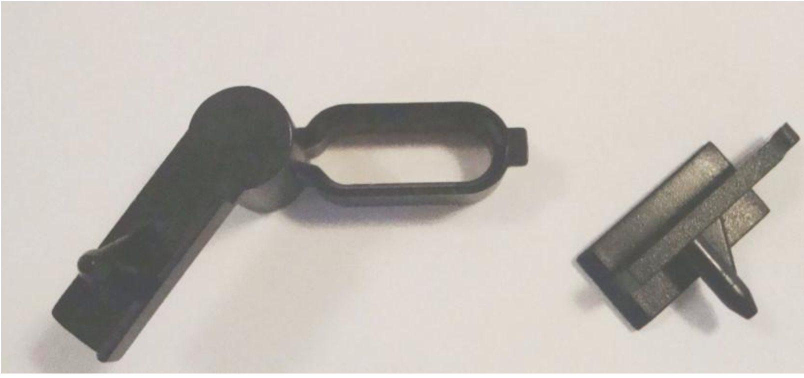


Fig. 5 ABS molded parts

The simulation was done using MoldFlow Plastics Insight, also employed in the previous simulation. The material (ABS) is the same from the previous studies, the characteristics being confirmed by the use of the experimental data. A comparative study was done by simulating the molding for several melt temperatures (between 200^{o}C - 260^{o}C) and different size of mesh (1mm, 2mm, 3mm) the values of the stresses were obtain.

A decision based on the values of the residual stresses may be taken with respect to one or several criteria, such as:

- minimization of the residual stresses in the most stressed areas;
- minimization of the residual stresses in the regions with large loads in running conditions.

Some other measures may be also taken, like:

- a new location of the runner system;
- decision regarding the necessity of annealing or quenching operations for the part.

CHAPTER 7. Polymeric Material Adviser (PMA)

This chapter presents an expert system called "Polymeric Material Adviser" (PMA) developed by the author, for the design process of injection molding. PMA has many and different polymeric materials on hand from several different suppliers, so using this new technology we can choose easily which plastic is best suited for each application. This computer program has been developed to search for the properly polymeric material, a database with many and more used polymeric materials, total flexibility of date's visualization, information about material properties and producer.

Structural the expert system is composed of a MySQL database, a PHP scripting engine and an Apache web server. Functioning architecture is client-server for the software below and the interconnection making through an operating system, in our case UNIX, type FreeBSD. The main application architecture relies on the Open Source Framework built on PHP-MySQL tandem.

The Polymeric Material Adviser describe the molding conditions for the thermoplastic and for the thermoset, the processing conditions, the typical values for temperatures, the typical values of specific pressures on material, and the material change-over and cleaning of plasticizing cylinder. PMA improve the process solution including the selection of the injection molding material, the mechanical and the technological properties of the polymeric material. PMA has many and different polymeric materials on hand from several different suppliers, so we can choose easily which plastic is best suited for each application, as you can see in the figure 6.

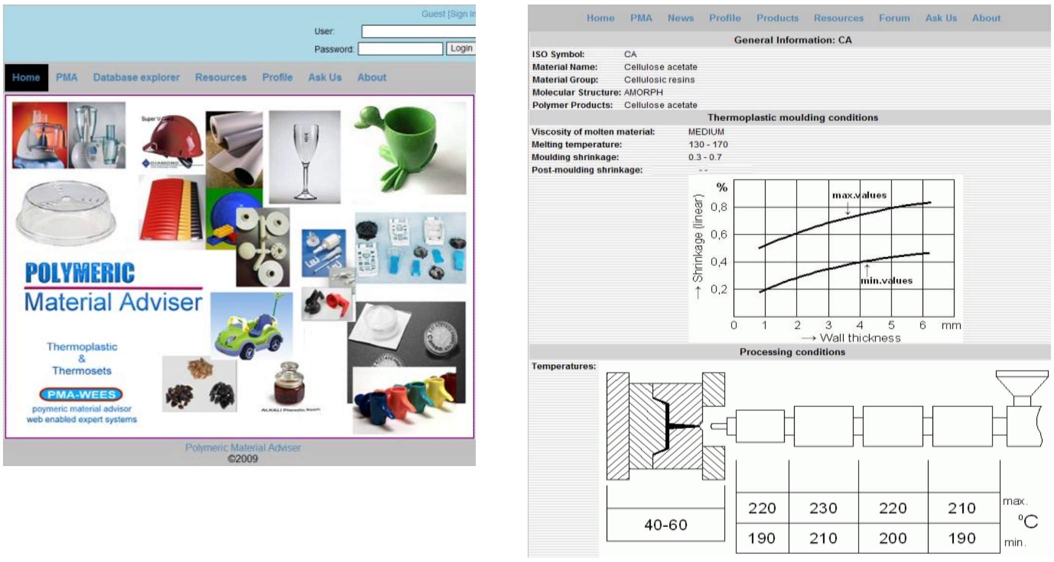


Fig. 6 PMA software interface

The database permits selective queries to generate a complete report for the right material. The database is Word Wide accessible to fulfill the purpose of the Academic demand in the field of Polymeric Materials (http://cmu-edu.eu/pma/).

CHAPTER 8. Final conclusions, personal contributions and future prospects

Final conclusions

Using CAD technology we can define even the most complex geometry for creating single and multiple cavity molds. We can evaluate easily mold draft, undercut and thickness problems and examine forming and secondary forming dies. With help of CAD we reduce need for redesigns through automatic updating of tooling models, drawings and electrodes and we eliminate costly rework via interference checking and mold opening simulation.

The research method presented in the paper uses the best features of the experimental and numerical studies in order to solve a practical problem concerning a polymer part.

Regarding the experiment, both the viscoelastic behavior of the material and the experimental conditions, have a great influence on the results of the measurements. Special care was dedicated to avoid the apparition of the parasitic effects.

For the plate-wise specimen the results of the experimental and of the numerical studies are close one to the other.

The part was studied using different mesh sizes and several technological conditions and significant conclusions were drawn.

Even the study of the real part may look theoretical; the results have a high degree of confidence only if experimental values are employed to define and to calibrate the numerical model.

The study offers information and a methodology which may be applied in practical conditions for a large number of parts manufactured from the same material and for several technological constraints, the conclusions being an effective support in the decision making process.

Standard test method such as Charpy is an important tool for raw material research and quality control. The total energy, W [J] accumulates over time and increased to achieve a level of constancy, then it is absorbed in the polymeric material.

The strain measurement on a plastic or composite test object will frequently call for much greater skill, expertise, and knowledge of mechanics than that typically required with the structural metals.

Personal contributions

I described the mathematical model for the couple "mold injection – polymeric material" and the flow through a channel with a melt free section, considered the model rheology of the melt polymeric described by Ostwald de Waele model.

I made a spreadsheet using Excel environment through which I validated the mathematical model proposed (http://cmu-edu.eu/pma/validare.xls.)

I examined the flow phenomena occurring in the mold and I have optimized the injection process, using the dedicated software, MoldFlow. I made the numerical analysis for three different polymer types of acrylonitrile-butadiene-styrene (ABS), polypropylene (PP) and polystyrene (PS), reducing the residual stresses and optimized the mold injection process and mold design.

Using analytical and numerical solutions obtained I injected 8 types of polymer (ABS, PP, PA6, LURAN, HDPE, LDPE, POM and PS) into a mold, which I designed it using CAD/CAM/CAE tools.

I examined three types of polymer injected: acrylonitrile-butadiene-styrene (ABS), polypropylene (PP) and polystyrene (PS). I measured the residual stresses using the hole-drilling strain gage method described in ASTM Standard E837.

I developed a spreadsheet for calculating residual stresses in different parts of any material for which elastic constants are known and is World Wide accessible (http://cmu-edu.eu/pma/TR.xls)

I determined the Charpy impact resistance on three types of polymer specimens without notch (ABS, PP and PS), method described in ASTM Standard D 6110.

I used the knowledge acquired from the previous studies for the simulation of the molding of a real part.

At the end of the PhD thesis, I developed an expert system called "Polymeric Material Adviser" (PMA) to improve the polymeric mold injection (http://cmu-edu.eu/pma).

Future prospects

For the other five types of polymer injected into the mold designed, I intend to determine the elastic constants and to measure the residual stresses using hole-drilling strain gage method. Also I want to measure the residual stresses using other method, called "the layer removal".

Starting with the concept of the Polymeric Material Adviser, I propose a sharing knowledge space and storage resources in educational web environment, called Mold Injection Encyclopedia (MIE), which run as a wiki software. This type of wiki system allows to create and to edit web pages using a common web browser. It will be implemented as a software engine, which is an open source that runs on one or more web servers, with the content generally stored in a relational database management system.