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Simulator Development for Active Learning of the Fundamentals of Plastic Injection Moulding*

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This paper describes some aspects of new teaching software and its academic application. This program is an alternative for enhancing and improving the resources available for students to acquire practical knowledge in plastic injection moulding parameterisation. An injection moulding simulator has been developed that allows preliminary machine capacity determination, an analysis of the number of cavities, in order to define the injection cycle parameter, and defects analysis and its representation. The simulator is used by students on the plastics injection course. The environment allows the student to carry out an iterative process in order to optimise the injection moulding process parameters. All decision-making is based on an Expert System whose response is similar to that of a skilled machine operator.

Keywords: injection moulding; simulation; plastics; virtual reality; simulator

INTRODUCTION

SIMULATORS are being used increasingly in many applications. Training centres for aircraft pilots, military devices or special vehicles were initial developments in this field. Simulators have become more popular with the expanding capabilities of personal computers and the consequent low cost and power of graphics hardware and software. Education simulators are not new and a large number of applications have been developed in several areas. Some emphasise their use as an educational tool and others centre on the 'goodness' of the mathematical model being implemented [1]. Many experiments directly related to manufacturing processes have been carried out such as that by Simpson [2], where students controlled all factors of the production process. Other similar approaches were carried out at Washington University [3] where Shah [4] describes a realistic simulation on the collaborative robust design of a product in the course of an academic year. At Syracuse University [5] students can attend a course on mass production to develop a specific product. Simpson [6] proposes comparing manual and mass production of paper aeroplanes. With regard to manufacturing process simulators based on expert systems, the work presented by Liu is noteworthy [7], where a modular system is developed for machine tool simulation. In other works such as that by Lee [8], which is more specifically oriented to ultra-precision machining, two virtual solid machine models are presented. Virtual environments for control education are presented by Fernandez [9] developed in MATLAB GUI to be used in practical sessions and by Peek [10] with a DC-motor simulator developed in NI LabVIEW.

Recently, there has been research into virtual injection moulding [11] that develops a new virtual reality environment aimed at reducing development time in the early design stage of the mould. Another work [12] presents a new method for combining artificial neural networks and genetic algorithms used for process optimisation. Optimal tuning of the injection moulding process has also been dealt with in previous works, such as by Ivester [13] who employs a virtual environment provided by an input–output model to make an iterative search of the optimal input parameters. Another approach is a knowledge-based strategy [14], where an on-line estimation of the process window is provided during tuning. The major influence of specific parameters in microinjection moulding has also recently been modelled [15].

With regard to the training of technical staff in plastic transformation processes, a difficulty is usually encountered in transmitting know-how that is strongly based on the skilled operators' experience, which leads to inefficient and time-consuming training programmes. This work is oriented towards the development of an optimised software application to be used in injection moulding process parameterisation. There are some existing software applications that partially or collaterally approach this background problem. The PICAT Program® [16] allows one to simulate and modify the injection parameters of a part in

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order to study its possible defects. The program deals with four part templates with very simple non-realistic geometry. PICAT is basically a machine operator training software and is therefore oriented towards completing the training of partially trained personnel; for this reason, it is not recommended for new students in this field. On the other hand, PICAT ignores the problems that are of major interest to a plastic transformation company such which machine size to use and the recommended number of cavities in the mould. It also ignores aspects related to the mould design, such as runner type, thermal balance, mould size, etc.

Other types of existing software applications are based on numerical simulation, generally oriented to improving mould design tasks, such as Moldflow® [17]. These programs have in common their mathematical modelling of the plastic flow during the transformation process and, additionally, allow analysis of any warpage and shrinkage defects. Nevertheless, these programs are difficult to learn, and the difficulty involved in the correct interpretation of the results that they provide is quite considerable, since a critical and specialised analysis is required. The conclusion is that only highly trained personnel can obtain trustworthy results from their use, and therefore these programs are unsuitable for new students.

METHODOLOGY

The basic statement in the injection process can be solved as follows:

1. Technical and economic problems derived from the preliminary definition of the mould
2. Problems derived from selection of the machine from the available machines
3. Parameterisation problems in the injection cycle.

The end company (automotive, aeronautical, etc.) defines the geometry, material and batch size of the parts to inject. With these data, the plastic transformation company draws up a production plan to obtain the maximum required geometrical and visual quality at the lowest possible cost, within the available resources (human and machinery with their respective operating costs). Early decisions are technical and economic, such as the number of cavities in the mould, mould type, runner type, etc. (financial feasibility). Machine selection is the next step: injection rate, plasticising rate, clamping force (technical feasibility). Finally the cycle parameterisation is carried out: adjusting temperatures, times, pressures and velocities in the injection moulding machine (part quality).

This decision-making procedure is difficult to transmit to students considering that, within this sector, the individual tasks are not carried out by a single company. The improved methodology and the program developed presented in this work, aim to support new students who are studying the thermoplastics injection process and help them to solve these problems in a reasoned, effective and ordered way.

The methodology defined for decision- making can be established as follows:

1. An initial estimation of the number of cavities in the mould
2. Technical limits on number of cavities depending on: machine plasticising rate, machine injection rate, and machine clamping force
3. Machine selection from among those available
4. Definition of cycle parameters
5. Quality estimation of injected parts
6. Cycle time optimisation
7. Optimisation of the number of cavities.

These tasks must be carried out by an expert system that will provide, through an iterative procedure, the optimisation of cycle time and the number of cavities.

The first estimation of the number of cavities can be found by applying the following expression:

$$C = (C_{hm} + C_{ho}) \cdot t_{cycle} \cdot \frac{Lot}{n^o\ cav} + C_{mould}. \quad (1)$$

Equation (1) represents the total cost of a part batch, without taking into consideration the material cost, and allows one to obtain an initial recommendation for the most economic number of cavities, employing estimations for hourly cost of machine and operator, cycle time, batch size, and mould cost. Usually the standard behaviour in cost of typical consumer plastic parts is as represented in Fig. 1, where a minimum cost can be observed at a determined number of mould cavities.

This figure allows one to establish a comparison criterion, with injection machinery specifications using the following equations:

$$N^o cav = \frac{C_p \cdot T_p - W_{sprue/runners}}{W_{part}} \quad (2)$$

$$N^o cav = \frac{C_i - V_{sprue/runners}}{V_{part}} \quad (3)$$

$$N^o cav = \frac{\frac{F_{clamp}}{P_{clamp}} - S_{proy/sprue/runners}}{S_{proy/part}}. \quad (4)$$

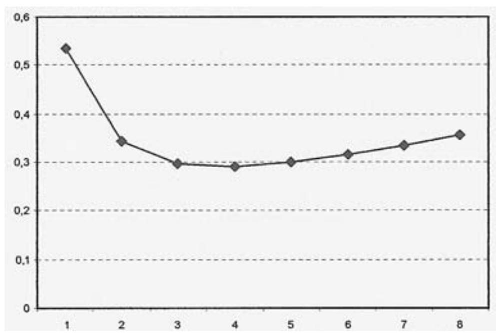

Fig. 1. Cost per unit versus number of cavities in the mould.

Table 1. Injection cycle parameters

T1	Barrel Plasticising temperature 1
T2	Barrel Plasticising temperature 2
T3	Barrel Plasticising temperature 3
T4	Injection chamber temperature
T5	Nozzle temperature
t1	Injection time
t2	Hold pressure time
t3	Opening time
t4	Ejection time
t5	Closing time
Pi	Injection pressure
Vi	Injection velocity
Pp	Part program

Table 2. Defect hierarchy

1	Temperature out of range
2	Incomplete filling
3	Exfoliation
4	Warpage
5	Ejector marks
6	Burn marks
7	Discolouration

Table 3. Defects inferred for certain parameters or combinations

	Inferred defects					
Controlled parameter	**2**	**3**	**4**	**5**	**6**	**7**
T1 to T5 ↑	0	2	0	0	1	2
T5 ↓	1	0	0	0	0	0
t1 ↓	2	2	1	0	0	0
t1 ↓↓	4	4	4	0	0	0
t2 ↓	0	1	1	1	0	0
t2 ↓↓	0	4	4	4	0	0
t2 ↑↑	0	0	0	0	0	1
pi ↓	0	1	1	0	0	0
pi ↓↓	3	4	4	0	0	0
pi ↑↑	0	0	0	0	0	0
Vi ↓	2	0	0	0	0	0
Vi ↑	0	1	1	0	0	0
T5 ↓ t1 ↓	4	4	4	0	0	0
t1 ↓ t2 ↓ pi ↓	4	4	4	1	0	0
T2 ↑ pi ↓	0	0	0	0	1	0
t1 ↑ t2 ↓ pi ↓ vi ↑	2	4	4	1	0	0
T1 to T5 ↑ t2↑	0	2	0	0	1	4

These equations give the maximum theoretical numbers relative to injection machine specifications with respect to: plasticising rate (Equation (2)), injection rate (Equation (3)), and clamping force (Equation (4)). The most suitable machine will be selected to achieve the economic number but within the technical limits.

The next step is to define the most suitable cycle parameters to obtain the objective quality for injected parts. The parameters in Table 1 were selected in order to define the injection cycle.

These parameters have been selected as those frequently used in most commercially available Injection Moulding Machine configuration menus. To achieve an estimation of the quality of the injected parts, an expert system has been developed. This system is empirically based on actual injection processes and Moldflow® simulations, and allows one to predict the occurrence of defects.

A representative set of defects has been selected from among all possible defects described in the related bibliography [18–20], and only those directly dependant on cycle parameters adjusted on the moulding machine have been considered, discarding those derived from different causes, such as those derived from incorrect part design (sink marks, welding lines, . . .) or those derived from incorrect mould design (air occlusions, injection marks, . . .). In Table 2 the defects considered as representative and directly related to injection moulding cycle adjustable parameters are shown. They are listed in importance of occurrence.

On the other hand, expert system decision criteria have been established to correlate cycle parameters versus defect appearance, in order to predict defect intensity from 1 (negligible) to 4 (severe). Table 3 shows defects and intensity inferred by the expert system as a response to determined cycle parameters or combinations, Temperature out of range (defect #1) implies no possibility to inject, and '0' means that no defect is predicted. The ↑ symbol means the parameter is growing. A ↑↑ symbol means that the parameter growth is much faster. The ↓ symbol means the parameter is decreasing and if it is doing so much faster the table shows the ↓↓ symbol. For example, when t1 (injection time) decreases, the most important and predictable defect is warpage and, depending on the other parameters, exfoliation and/or incomplete filling would appear.

The described methodology allows one to estimate, in an iterative and realistic manner, cycle parameters for the injection moulding process to ensure that injected parts are free of defects, as well as cycle time estimation, which allows economic optimisation. To apply the developed methodology to be employed by students, a new software application has been developed.

DEVELOPED APPLICATION

Program management is guided from a main window, which can be seen in Fig. 2.

From this window the student has access to the different functionalities of the program:

1. A simulator for injection moulding process data input.
2. Expert system to estimate injected parts quality.
3. Defects display.
4. Technical–economic analysis of the number of cavities.

One of the virtual simulator windows can be seen in Fig. 3. A certain number of parts were selected to be representative of the sizes and materials used in consumer products. The student make selections, starting from the part geometry, material,

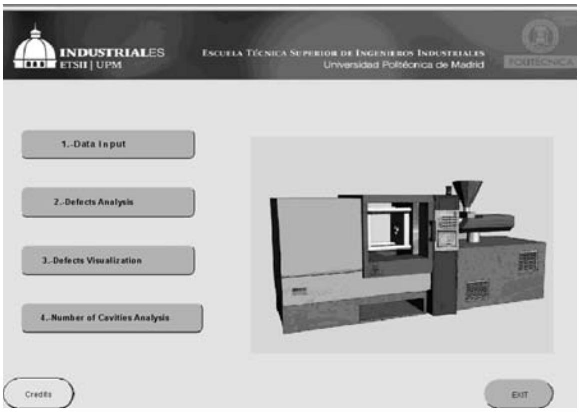

Fig. 2. Main application window.

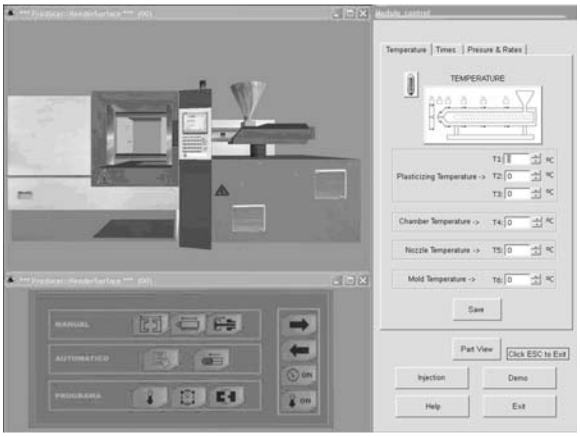

Fig. 4. The simulator environment.

machine size, and cycle parameters in order to simulate the injection moulding of this part.

The program has been developed in a visual programming environment that allows the incorporation of three-dimensional interactive representations, so a virtual machine that is quite similar to those commercially available can be shown to the student. This virtual model has been developed employing an OSG (OpenSceneGraph) based graphical motor, which allows the student to select view the scene from diffent viewpoints, while maintaining the operability of the panel push-buttons.

Once the part, material, and machine size have been selected, the student is led into a virtual injection machine simulator (Fig. 4) that shows a three-dimensional display, where the student can interact by reproducing the typical machine movements and introducing injection cycle parameters for further analysis. Data interchangeability with the virtual environment is based on the CORBA (Common Object Request Broker Architecture) communications standard.

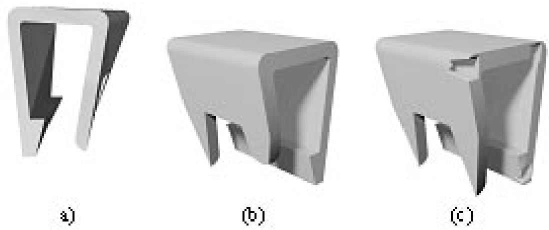

Fig. 5. Three examples of defects display: (a) correct part, (b) incomplete filling, (c) ejector marks.

After the cycle parameters have been chosen, a defect analysis can be carried out; this generates a visual output to observe the defect's occurrence (Fig. 5).

Finally, Fig. 6 shows the panel used to carry out the technical–economic analysis recommended for the mould. This panel is very useful for estimating the actual mould dimensions that are most suitable from an economic point of view, as well as the optimal machine size to carry out the transformation process.

Fig. 3. Part selecting window and an example part.

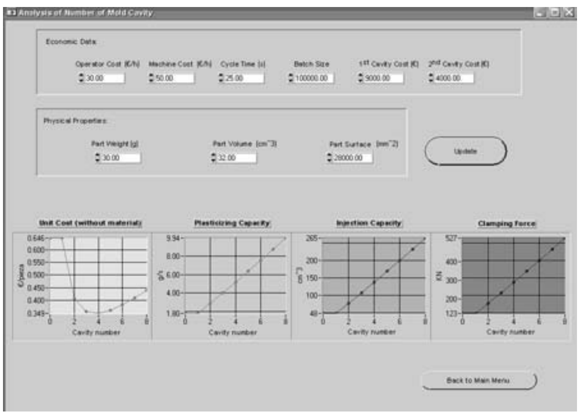

Fig. 6. Technical–economic analysis panel.

Table 4. Compact course topics

Part 1: Polymeric materials and manufacturing processes
Introduction to polymeric materials
Polymer manufacturing processes
Manufacturability analysis on polymeric parts
Defects in injected polymeric parts
Injection moulding process parameterisation
Injection mould design
Part 2: Design of parts in polymeric materials
Design process and material selection
Flexural, screwed, snap fitting & press fitting joints
Design & calculus considerations in plastic gears
Tensional analysis in polymeric parts
Real cases analysis
CAD modelling
Rapid prototyping

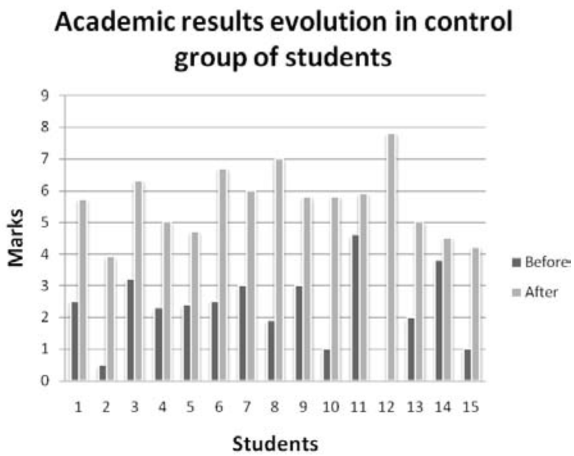

Fig. 7. Evolution of academic results

ACADEMIC RESULTS

The Design and Manufacturing with Plastics course is taught in the 10th semester of the Mechanical & Manufacturing Engineer degrees, at the Universidad Politécnica of Madrid. The basic time allocation is:

- 96 h divided into theoretical and practical lectures;
- 84 h of personal student work.

This is a total of 180 h, equivalent to 6 ECTS.

A test release of the program developed was used with students during the second semester of the 2006–2007 academic year on the course with practical lectures related to the topics 'Defects in injected polymeric parts' and 'Injection moulding process parameterisation'. The results obtained were very promising, taking into account that a control group of only fifteen students were used to test the academic impact of the program's usefulness. The course topics are shown in Table 4.

Figure 7 shows the comparative results attained by the fifteen students of the control group in exams carried out before and after using the new program. A mean improvement of 33% was observed.

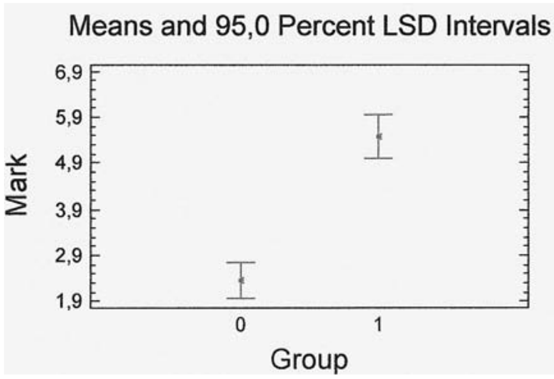

Fig. 8. ANOVA analysis.

Table 5. Virtual simulator opinion survey

	Yes	No	Partially
Clear objectives	15	0	0
Good program structure	10	0	5
Teacher advice	12	0	3
Longer activity duration	2	11	2
Good global evaluation	14	0	1

From a detailed ANOVA analysis (Fig. 8) of the group factor (a group of 24 students not using the virtual simulator versus a 15 student control group using the simulator), it can be concluded that this factor has a statistically significant effect on marks at the 95% confidence level.

On the other hand, a significant degree of acceptance of this new learning experience has been detected among students according to results obtained in the opinion survey in Table 5, where this new learning activity was very well scored, and it was considered very useful as a complement to the course.

CONCLUSIONS

In this work a new methodology for student training in the field of plastic injection moulding has been established. This new approach allows students to carry out a technical–economic analysis of the process as well as defining the cycle parameters to get the maximum quality of injected parts. The application software developed has demonstrated its efficiency, and students have obtained better academic results and satisfaction after using it. The expert system that supports the decision criteria for the program, represents an important basis for developing other optimisation approaches for injection moulding, and for other plastic transformation processes.

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NOMENCLATURE

C	Total cost of produced batch
C_{hm}	Hourly cost of injection moulding machine
C_{ho}	Hourly cost of personnel
t_{cycle}	Injection cycle time
Lot	Batch size
C_{mold}	Mould cost
C_p	Plasticising rate on injection moulding machine
T_p	Plasticising time
W_{part}	Injected part weight
$W_{sprue/runners}$	Injected sprue and runners' weight
C_i	Injection rate on injection moulding machine
V_{part}	Part volume
$V_{sprue/runners}$	Sprue and runners' volume
F_{clamp}	Clamping force on injection moulding machine
P_{clamp}	Clamping pressure on injection moulding machine
$S_{proy/part}$	Part projected surface on demoulding direction
$S_{proy/sprue/runners}$	Sprue and runners projected surface on demoulding direction.

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