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Teaching Applications for Rapid Prototyping Technologies*

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Rapid prototyping technologies (RP) enable solid models to be obtained from designs generated using CAD applications. Their increasing popularity in industry is due to the reductions in cost and time associated with the use of these models when verifying product development stages and improvements in end quality. However, these technologies can also be applied to enhance students' active learning in the teaching of multiple subjects connected with product development. Students can bring their designs to fruition and check any decisions taken in an economically acceptable way. This work shows how RP technologies can be exploited for teaching, using the full development of a gear pump. The work has been carried out with educational aims in the Product Development Laboratory of Madrid Polytechnic University (UPM), for the subject Design and Manufacturing with Polymers.

Keywords: educational innovation; collaborative learning; stereolithography; vacuum casting; machine design; rapid prototyping

INTRODUCTION

RAPID PROTOTYPING technologies allow physical objects to be manufactured in a short period of time, starting out from computer models created in CAD systems [1]. Apart from obtaining physical models, these technologies enable Rapid Molds to be made from which pre-series of end parts can be obtained in order to check both their functional and aesthetic aspects. It is particularly useful to use these technologies as a way of checking the design stages of parts intended for mass production by thermoplastic material injection and thus optimise the process stages.

Various teaching applications have recently arisen from rapid prototyping technologies to help students learn the full product development process. Experience shows that engineering students need teaching activities that combine theory and practice in a context of real engineering application challenges. Amongst the most outstanding innovative activities are those conducted in schools such as the Western Washington University [2], Rose-Hulman Institute of Technology [3] and Massachusetts Institute of Technology [4].

In all these places, students have lived through the different stages of product development: conception, design, simulation, analysis, manufacture and testing, using mechanical computer aided engineering (MCAE) tools, and the latest rapid prototyping and manufacturing (RP&M) technologies. To summarize:

- In Western Washington University [2], rapid prototyping technologies have been applied in the teaching of subjects such as Plastics Engineering Technology and Manufacturing Engineering Technology, focussing on the development of molds for mass production.
- Students in the Department of Mechanical Engineering of the Rose-Hulman Institute of Technology [3] applied Fused Deposition Modelling technology to the production of prototypes of a 'Halo' type collar for size verification.
- Students in the Department of Aeronautics and Astronautics at the M.I.T. [4] have worked in teams to develop different bicycle frames by performing activities that include making sketches, design optimisation using CAD, CAM and CAE tools, producing prototypes and structural testing.

Furthermore, within the new European Area of Higher Education, born out of The Bologna Declaration in 1999 [5], teaching–learning methods are being implemented for encouraging active student participation. The Design and Manufacturing with Polymers subject taught in the 5^{th} course at the Mechanical Engineering Department of the Universidad Politécnica de Madrid (UPM), has been designed according to these new tendencies and to take advantage of the rapid prototyping technologies available for teaching purposes.

As an application for the use of RP technologies in teaching, this paper sets out the full development of a gear pump, with two basic educational aims:

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- To serve as an example of the process used in industry to design and manufacture a machine prototype, and which should also serve as a model to be followed for the development tasks that have to be done by students as part of their studies, and later, in their work.
- To provide practical design cases and mechanical solutions calculations that will also complement the topics explained in the subject with real examples.

Rapid prototyping technologies available in the Product Development Laboratory at the UPM have been used to make the prototypes. To be precise, *stereolithography* and *silicone mold vacuum casting*, both used as a support for the research carried out in the Mechanical Engineering Department at the UPM.

TEACHING METHODOLOGY

Active teaching–learning methods used with students boost interest, motivation, creativity, freedom of choice, communication and mutual adaptation. The teacher's role consists in teaching to learn, proposing objectives, planning, creating student responsibility, teaching decision making, listening, orienting and assessing in collaboration with the students [6]. This approach is the one used in Design and Manufacturing with Polymers taught at the UPM, in the way set out below.

At the beginning of the subject, students are divided into teams of two or three, which are given different products to be developed. Products are chosen that can be mass produced by thermoplastic materials injection and which allow the knowledge acquired in theory classes to be applied in a practical way.

Studies do not include steel mold manufacture or injection machine tests due to the high investment costs and the time that would be involved. However, all injection simulations performed using Moldflow type programs are very positively assessed.

The stages that must be got through by students are enumerated below and are those corresponding to the development of a new industrial product [7]:

1. Setting out the problem and analysing the specifications. Studying existing solutions.
2. Conceptual design and identification of basic problems.
3. Detail design, including explanation of calculations, standardised elements selection and considerations on safety and simulations.
4. Prototype manufacturing.
5. Assembly and functional tests.
6. Specifications verification and drawing up conclusions.

At the end of each stage the teams give presentations to the rest of the class explaining the basic results obtained, in line with the schedule set at the beginning of the course.

The teaching aim is outstanding, since it motivates students to use different design and calculation tools used in mechanical engineering [8], such as:

- CAD programs (Solid Edge, Catia), for 3D modelling.
- CAE programs (Moldflow Part Adviser), to carry out simulations.
- CAM programs (Catia, Moldflow Mold Adviser) for mold manufacture.
- FEA programs (ANSYS, IDEAS), for design verification.

The use of rapid prototyping technologies available in the Product Development Laboratory brings students closer to the new technologies now becoming widespread in industry, giving added value to their training, and permitting them to physically verify their CAD designs [9, 10].

Joint discussion on the different works carried out means that each team learns from the tasks of their classmates, which leads to enhanced teaching aims.

The gear pump focused in the following paragraphs constitutes an example to be followed by students doing Design and Manufacturing with Polymers, for the preparation of their applied tasks, which are a fundamental part of their assessment.

FULL DEVELOPMENT PROCESS STAGES OF A PRODUCT

The machine chosen for conducting this teaching experience is a 'gerotor' type gear pump, which allows concepts acquired in other subjects taught in the Department to be integrated into and applied to a multidisciplinary task. Subjects such as, Design and Manufacturing with Polymers, Elements of Mechanical Design, Product Engineering, Machine Design and Machine Safety and Regulations.

Prior study and specifications determination

In any development process, an exhaustive information search must be undertaken about the product (including comparison between similar solutions) so as to prepare an appropriate planning schedule and fully and exactly define the aims. The result of all this will be a list of requisites with all the basic information for the project.

The starting out specifications for the internal gear pump, which is used as an example, are:

- Flow: 1.5 litres per minute.
- Fluid to be pumped: water.
- Geometric height: 1 metre water column.

At every instant, work must be aimed at complying with these basic specifications or requirements (mandatory requirements). Moreover, it is important to make a list of pretensions (or requirements

Fig. 1. Conceptual design.

to be taken into consideration whenever possible) that will form a basis of negotiation with the client and increase competitiveness and profits.

Conceptual design

The teams carry on working on the list of requirements to identify any crucial problems and choose the best solution for each one, or in the words of Sun Tzu: 'Study until you are capable of unknowingly and intuitively applying the knowledge learnt.'

To be precise, for the gear pump presented as an example, the basic problems identified are:

- type of profile to be used for the gears to ensure perfect running when they are working and minimise wear;
- adequate choice of thermoplastic materials according to the effort exerted when working and which allow mass production by injection at a competitive price and quality level;
- need for seals that ensure complete tightness.

It is important to use a Concurrent Engineering approach that will take account of manufacturing processes to be used right from the design stage, in order to optimise the whole production process.

The first activity is to obtain a CAD model of the pair of gears that make up the core of the pump. Then, the main body of the pump is designed as simple housings for the pair of gears, as is shown in Fig. 1.

At the same time, a preliminary choice of materials is made in line with the initial estimations as to the resistance needed for the different parts. To this end, data available in the CAMPUS database (www.campusplastics.com) on plastic material manufacturers, have been used.

As a solution to ensure tightness, a seal is fitted at the shaft exit point and a tight seal between the pump body parts. The pump body parts are held together by using screws and bolts.

Detail design

To complete the machine design, different commercial components need to be chosen (motor and standardised elements), which will have influence on the size and appearance of the end product.

Once the size of the different parts has been adjusted, Fig. 2 shows what the model will finally look like.

To check that the chosen materials are suitable, the estimates made need to be compared, using simplified theoretical models, with the information provided by computer calculation programs. The use of thermoplastic material injection process simulation programs, which are often used prior to the manufacture of the molds, is also important, in order to check that the choice of materials is appropriate.

The teaching aim is noteworthy since it stimulates the use of different design and calculation tools used in mechanical engineering such as CAD programs, programs for calculation by finite elements and CAM programs for parts manufacture in plastic materials.

Figure 3 shows the stresses attained when making the snap fit and permits verifying that the chosen material is sufficiently resistant. Figure 4 represents a time simulation for filling a

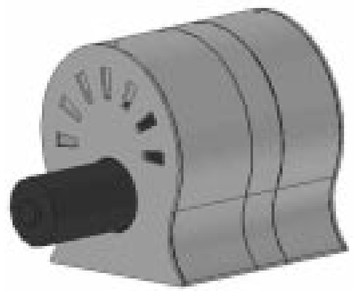

Fig. 2. Detail design: assembly.

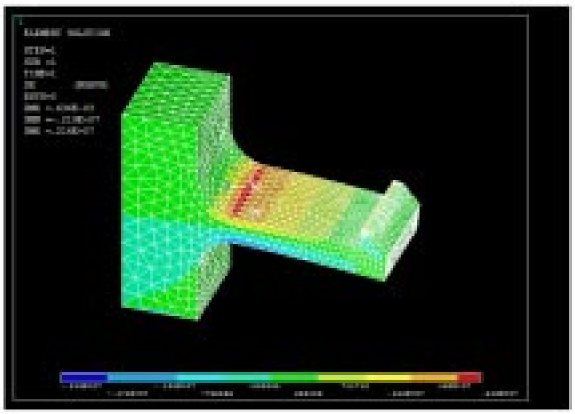

Fig. 3. M.E.F. study of a snap fit for the end covers (enforced displacement loading).

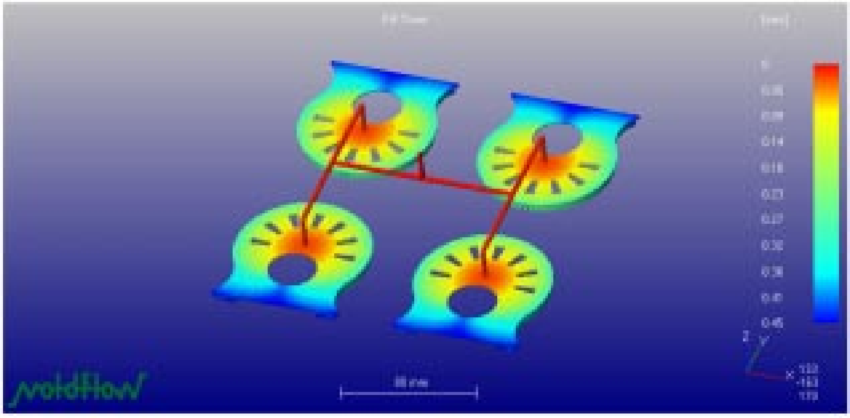

Fig. 4. Time simulation for filling a multi-cavity mold for end covers.

Fig. 5. Prototypes obtained by stereo lithography for size verification.

Fig. 6. Prototypes obtained by vacuum casting for working verifications.

4-cavity mold for mass production of the end covers and is used to compare different materials vis-à-vis production.

Prototypes and tests

Once the design and calculation stages have been accomplished, prototypes can be produced applying the rapid prototyping technologies of the U.P.M.'s Product Development Laboratory.

Firstly, prototypes are made by stereolithography. This is a method whereby action by a laser activates the polymerisation reaction of an epoxy resin and generates the parts 'by layers', according to the movement pattern obtained from the CAD files [1]. Figure 5 shows these prototypes which are used for visual and assembly checks, (known as A-samples in the world of industry), paying special attention to any possible interference and empty spaces.

In this particular case they are not suitable functional tests as epoxy resins are hygroscopic and the machine is designed to pump water. For this reason, they are used as models to obtain silicon molds, which in turn will be used to obtain some end prototypes by vacuum casting with polyurethane resins [1]. These resins possess properties that are much more similar to mass production design materials and allow prototypes to be obtained for functional tests (known as B-samples). The final prototype for the gear pump can be seen in Figure 6.

APPLICATIONS OF DESIGN AND MANUFACTURING THEORY WITH PLASTIC MATERIALS

The second teaching aim is to obtain practical examples for the different topics dealt with in the subject, by carrying out the different parts design in accordance with the design recommendations explained in the theory.

The virtual molds and injection simulations performed with help from the Moldflow programme can be used as an application for the topics: Transformation Process Simulation, Manufacture Processes: Injection and Design of Injection Molds. Figure 7 represents a study of the channels and cavities in a mold aimed at the mass production of end covers for the gear pump.

The design of the different parts can be used as models for the topic devoted to Design Process and Material Selection. For the different justifiable calculations made, knowledge acquired from the following topics in the subject programme is used: Stress Analysis, Mechanical Joints, Pressure Joints, Flange Joints, Use of Adhesives and Gear Design and Calculation

Figure 8 shows a contact study between the pair of gears and the stress concentration at the base of the tooth due to the presence of the pin housing. It also shows the stress produced in a pressure assembly, between the pinion and the shaft, as an alternative to a pin joint. The study was performed

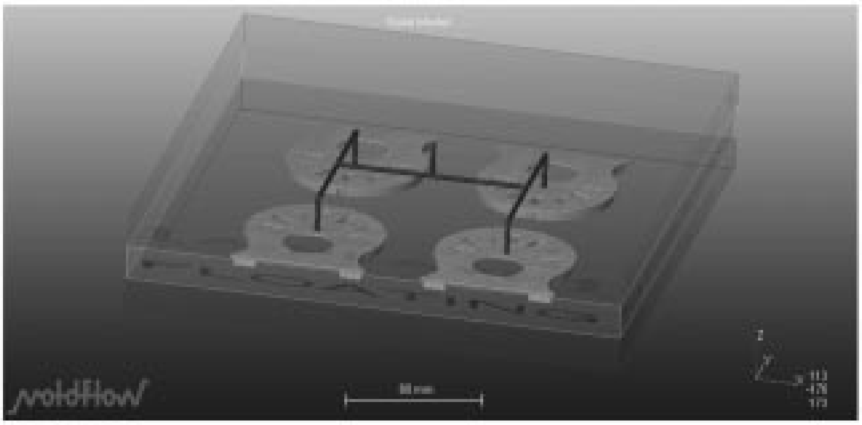

Fig. 7. Study of a three-sheet multi-cavity mold for end covers manufacture.

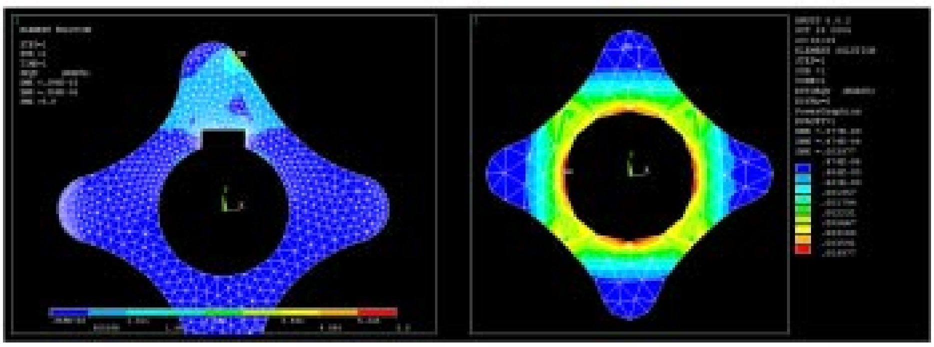

Fig. 8. Comparative study between a pin joint and a pressure joint for the pinion.

with the help of the ANSYS finite element calculation program.

Finally, the development process and the two prototype production stages serve to complete training with some notions about rapid prototyping technologies needed for working in teams on the subject tasks.

RESULTS OF THE FIRST EXPERIENCE WITH 'DESIGN AND MANUFACTURING WITH POLYMERS'

At the beginning of the course 32 students were divided into 11 teams that would develop different assigned plastic products during the module:

- wall clock
- radio housing
- alarm clock
- mobile phone housing
- wrist watch
- speaker housing
- air freshener
- computer mouse
- correction tape
- calculating machine housing
- toothbrush housing.

The teams passed through the different product development stages, following the gear pump example, which include previous studies, concept design, detail design, prototype manufacturing and working tests. They were encouraged to employ CAD-CAM-CAE tools for improving their designs [11], before manufacturing the prototypes with the help of the rapid prototyping technologies available in the Product Development Laboratory (stereolithography and vacuum casting with polyurethane resins).

During the first month of the course (March 2005), each team identified the basic requirements and produced a conceptual CAD design for their assigned product. The software used for this was Solid Edge, which has a short learning curve [12] and quickly allows students to model relatively complex engineering parts for simulation.

Two additional months were employed in completing mechanical and thermal finite element analysis (with ANSYS mainly) and design improvements. Manufacturing simulations were also undertaken to verify the design before prototyping the parts.

After design validation and approval by the course teacher, the 11 products listed above were manufactured by stereolithography using the SLA-3500 machine at the Product Development Laboratory. The different teams carried out assembly and functional tests and proposed design improvements to solve the main problems detected. As part of their evaluation the teams made public presentations of the complete product development, in which they explained the decisions undertaken. The principal role of the teacher during the presentations was to promote the exchange of opinions between the students, so that the experiences could be shared and the final learning outcomes increased [13, 14].

At the end of the course the 32 students were surveyed so as to gather information about their learning experience. Special attention was paid

Table 1. Summary of time devoted to different tasks

Time devoted to the different stages	**Total mean value (hours per student)**
FORMAL LESSONS (30 scheduled hours, non-compulsory attendance):	26
PERSONAL TUTORIALS:	1.4
INFORMATION SEARCH (bibliography):	1.8
INFORMATION SEARCH (web-based):	4.2
PRIOR STUDY:	4
SEARCH FOR AVAILABLE PRODUCTS:	2.6
STUDY OF EXISTING SOLUTIONS:	3.6
SPECIFICATIONS DETERMINATION:	3
CONCEPTUAL DESIGN:	4.6
DETAIL DESIGN:	6.3
CALCULATIONS:	2.1
CAD MODELLING:	6.1
MOLD FILLING SIMULATIONS:	4.3
PROTOTYPE ASSEMBLY:	1.3
FUNCTIONAL TESTS:	0.8
Time devoted to reports and presentations	**Total mean value (hours per student)**
REPORT ELABORATION:	10.5
PREPARATION OF PRESENTATIONS:	6.8
PUBLIC EXPOSITION OF RESULTS:	1.2
TOTAL	**90.6**
Balance (Individual Work /Teamwork):	%
Percentage of INDIVIDUAL WORK:	53
Percentage of TEAMWORK:	47

to the quantity of traditional teaching and individual student commitment, bearing in mind the criteria of The Bologna Declaration on the European Area for Higher Education [5]. In addition, the balance between individual and team work was studied. Table 1 shows a summary of the mean values registered after these were surveyed.

The mean value of 90.6 hours/student combines formal lessons and personal work in accordance with the three European Credits assigned to the subject. The balance between individual and teamwork is particularly noteworthy.

Among the possible improvements for future experiences the following items should be considered:

- Cooperation between teams could be promoted by assigning more similar products to the different groups.
- The first prototyping stage should be tackled earlier, so as to make possible a second such stage, in which the design improvements could be checked.

COURSE EVALUATION

In the last week of the course, an anonymous evaluation was conducted. It consisted of a brief introductory tutorial, followed by nine sections containing questions that needed to be answered by multiple choice as well as essay responses. The final results from the evaluation follow:

1. Amount I have learned, compared to other Mechanical Engineering courses. (1: little, 3: medium, 5: much) → Score: 4.4
2. My understanding of development processes has increased. (1: little, 3: medium, 5: much) → Score: 4.6
3. Knowledge acquired about the use of CAD-CAM-CAE tools. (1: little, 3: medium, 5: much) → Score: 3.8
4. Knowledge acquired about Rapid Prototyping tools. (1: little, 3: medium, 5: much) → Score: 4
5. Teamwork importance. (1: little, 3: medium, 5: high) → Score: 3.2
6. Amount of work related to the subject. (1: little, 3: medium, 5: excessive) → Score: 4.2
7. I think that I can apply this course to my work/career. (1: no, 3: do not know, 5: yes) → Score: 4.4
8. Coherence between lectures and hands-on activities. (1: little, 3: medium, 5: much) → Score: 3.8
9. Overall impression. (1: very negative, 2: negative, 3: indifferent, 4: positive, 5: very positive) → Score: 4.6

Some of the students' comments were:

- *'I would be interesting to tackle more challenging products cooperating between teams.'*
- *'A second prototyping stage would help with verifying the design improvements proposed.'*
- *'I really enjoyed the fact that we manufactured our designs and made working trials.'*

CONCLUSIONS

The use of rapid prototyping technologies for teaching purposes in machine and product design subjects has numerous advantages, the most outstanding of which are as follows.

It allows design guideline teaching theory to be complemented with real product development following the stages used in industry, thereby helping to endow students with the ability to form part of a work team once their studies are over. Obtaining prototypes means that any decisions made can be analysed, and functional verifications performed alongside the students.

Thanks to this experience, a teaching-learning strategy is established that includes conscious decisions of when and how to use each of the skills and techniques learnt in the subjects. At every instant, students are encouraged to use critical reasoning and creativity as essential tools for problem solving. Teamwork and active student participation are also encouraged as part of their self-learning, thereby adapting to the new European Convergence guidelines.

It brings students closer to the new technologies now becoming more widespread in industry and helps them to face up to real design tasks, while giving added value to their training and paving the way to their tackling design and development tasks.

The work brought to fruition for the Design and Manufacturing with Polymers subject, can be extended to numerous other Mechanical Engineering subjects where integrated teaching is desired.

REFERENCES

1. D. Freitag and T. Wohlers, *Rapid Prototyping: State of the Art,* Manufacturing Technology Information Analysis Centre (2003).
2. J. Newcomer and N. Hoekstra, Using rapid prototyping to enhance manufacturing and plastics engineering technology education, *J. Eng. Tech.,* Spring 2004, Western Washington University.
3. R. Stamper and D. Decker, Utilizing rapid prototyping to enhance undergraduate engineering education, *30th ASEE / IEEE Frontiers in Education Conf.,* Kansas City 2000, Rose–Hulman Institute of Technology.
4. O. Weck, P. Wallace, P. Young and P. Yong Kim, A rewarding CAD/CAE/CAM experience for undergraduates, *Teaching and Education Enhancement Program, Engineering Design and Rapid Prototyping,* Massachusetts Institute of Technology (2004).

5. *Bolonia Declaration,* Joint declaration of the European Ministers of Education, 19th June 1999.
6. P. Wankat and F. Oreovicz, *Teaching Engineering*, McGraw-Hill, New York (1993).
7. G. Pahl and W. Beitz, Engineering Design—A Systematic Approach, 2nd Edn, Springer-Verlag (1996).
8. R. Devon, S. Bilen et al., Integrated design: what knowledge is of most worth in engineering design education, *Int. J. Eng. Educ.,* **20**(3), 2004.
9. O. Diegel, W. L. Xu and J. A. Potgieter, Case study of rapid prototype as design in educational engineering projects, *Int. J. Eng. Educ.,* **22**(1), 2006.
10. K. Stier and R. Brown, Integrating rapid prototyping technology into the curriculum, *J. Industrial Technology,* **17**(1), November 2000—January 2001.
11. K. Wallace, Teaching engineering design in the new four-year course at Cambridge University, *Int. J. Mech. Eng. Educ.,* 1993.
12. R. Rubio and R. Gallego, Present stage of CAD teaching in Spanish Universities, *Computers and Education,* **44**, 2005.
13. S. Sheppard and R. Jenison, Examples of freshman design education, *Int. J. Eng. Educ.,* **13**(4), 1997.
14. L. Shuman, M. Besterfield-Sacre and J. McGourty, The ABET Professional Skills—Can they be taught? Can they be assessed? *J. Eng. Educ.,* January 2005.
15. Masood Al-Alawi, The IRIS rapid prototyping system selector for educational and manufacturing users, *Int. J. Eng. Educ.,* **17**(4, 5), 2001.
16. R. Zavbiand J. Travcar, Preparing undergraduate students for work in virtual product development teams, *Computers & Education,* **44**, 2004.

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