IDEAS

A Senior Course in Design for Manufacturability

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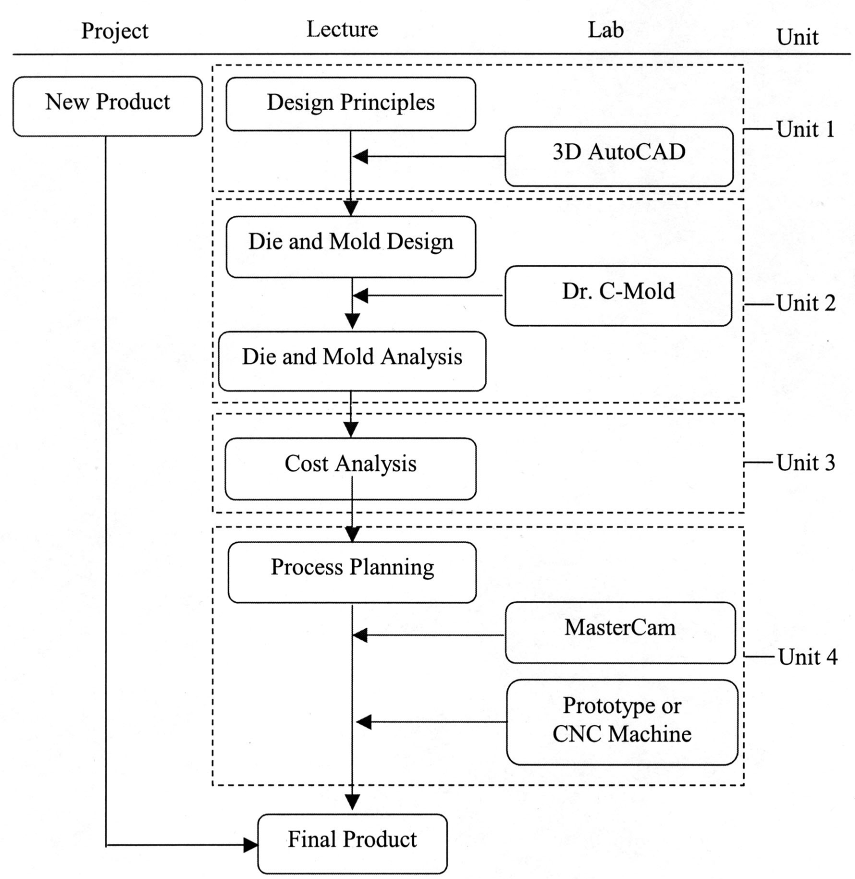
In today's fast-paced world, everyone is looking for the leading edge to become, and stay, competitive in the market. To share the market of the product, the product must satisfy and delight customers. To achieve this objective, design becomes one of the most important aspects for the product. Design is the first and fundamental step in building and constructing everything. The cost to operate the design department in each company may contain only 5% of a company's budget. However, 70% of the final product costs are influenced by the design (Boothroyd et al., 2002). In today's competitive market, the customer demands a good design with a competitive price. Therefore, in order to compete successfully, the customer has to be satisfied. With a good design, half of customer demand has already been fulfilled. Furthermore, a good design can also help enhance quality of the part, increase productivity, and reduce costs in manufacturing and assembly processes.

A manufacturing system is a complex arrangement of physical elements, such as machines, tools, people, and material handling devices, which could be measured by the production rate, inventory level, or percentage of defective rate (Black, 1991). Although the research and design department is not within a manufacturing system, the interactions between design and the manufacturing system significantly affect product cost, product quality, and productivity within a company. Therefore, a knowledge of design for manufacturing (DFM) has become a new trend for manufacturers and demands that technology educators include DFM content in their existing design curriculum. According to Boothroyd et al. (2002), DFM is concerned with understanding how product design interacts with the other components of the manufacturing system and in defining product design alternatives that help facilitate global optimization of the manufacturing system as a whole.

In 1995 the American Society of Mechanical Engineers (ASME), with funding from the National Science Foundation, published the results of a study that examined curriculum changes needed to more effectively integrate elements of the product realization process into the education of engineering or technology students (Przirembel, 1995). The premise for this study was the realization that the lack of manufacturing and design capabilities in U.S. industry today is a critical factor in the decline of the nation's international competitiveness. Sixty-six senior managers from 33 companies were asked to rank a list of 56 different "best practices" as to the importance of each topic to both new mechanical engineering graduates and experienced mechanical engineers. In addition, this same list of best practices was sent to all accredited mechanical engineering departments in the United States where academic representatives were also asked to rank these topics in order of importance. Teams/teamwork was selected by over 90% of the industry respondents and the academic respondents. Eighty-eight percent of the industry respondents indicated that DFM was somewhat important or very important.

Figure 1. The DFM curriculum module.



A senior course - Design for Manufacturability

The team approach allows all employees who are working on a product to act as one team in order to achieve the common goal of manufacturing a quality product in less time and at reduced costs. If a company wants to develop a world-class manufacturing operation, it has no choice but to view design and manufacturing as a single conceptual process, which DFM can do. DFM is a cutting-edge improvement program that can reduce labor, material, and mass requirements without sacrificing the integrity of product or process (Boothroyd & Dewhurst, 1990).

In industrial manufacturing, metal casting and plastic injection molding processes are the two most common and most important techniques used to produce parts. Both techniques are used in creating the basic profile of products for advanced manufacturing processes. Before casting and injection molding can be done, a proper mold has to be designed. A good mold design can improve the ease of manufacturing and enhance the quality of a part. Therefore, the conception of designing a good mold becomes very important (Cheremisinoff, 1990).

The purpose of this study was to develop a practical curriculum module to perform the ideas of DFM. This curriculum is designed for students at the senior level. Since students have a strong background of industrial technology (IT) in the design and manufacturing phases, knowledge of DFM will enhance the students' ability to involve themselves into the strategic planning level in their future employment. For the students of IT, an understanding of DFM becomes very important for them to integrate the knowledge of design principles and manufacturing processes. This curriculum will help students understand how DFM works in the industrial field and how to construct a new product from design through the manufacturing phase.

DFM Curriculum Module

The DFM curriculum module integrates the design principles, the design of injection molding, cost analysis, and the manufacturing processes. Figure 1 shows the architecture of this module. The goal of this curriculum is to assist students in creating a new product. The principles of DFM are applied to generate the idea of the new product.

The curriculum development of DFM can be separated into four units, which contain both lecture and laboratory sessions.

Unit 1—Design principles: The objective of this unit is to illustrate the importance of design and DFM. To this end, 3D AutoCAD drawing technology is applied to assist the product design.

Unit 2—Die and mold design and analysis: The objective of this unit is to focus on the design and analysis of injection molding. The design principles of injection molds are discussed first to generate the ideas of designing an injection mold. The application of C-mold software is the focus of discussion in this unit. C-mold software is a powerful tool used to analyze the mold design for injection processes. It can analyze the pressure, temperature, cooling system, molecular orientation, weld line, and air trap of the injection mold before it is fabricated.

Unit 3—Cost analysis: The objective of this unit is to estimate the cost of fabricating the product. The differences between fixed and variable costs are introduced for the preparation of total cost estimation. The principles of engineering economy are applied to estimate the total and unit costs, identify the break-even point, and decide the proper price for selling. In the discussion of engineering economy, a cash flow diagram and interest formulas relating present and future equivalents and also annuity to its present and future equivalents are focused on to understand the method of cost estimation.

Unit 4—Process planning: The objective of this unit is to discuss the proper machining processes for manufacturing the die and mold. How to optimize the machining parameters for milling operations, such as spindle speed, feed rate and depth of cut, are discussed. The MasterCam software is applied to create the tool path of a 3D model and then generate the NC program. Finally, the NC program is installed in a CNC machine to cut the mold.

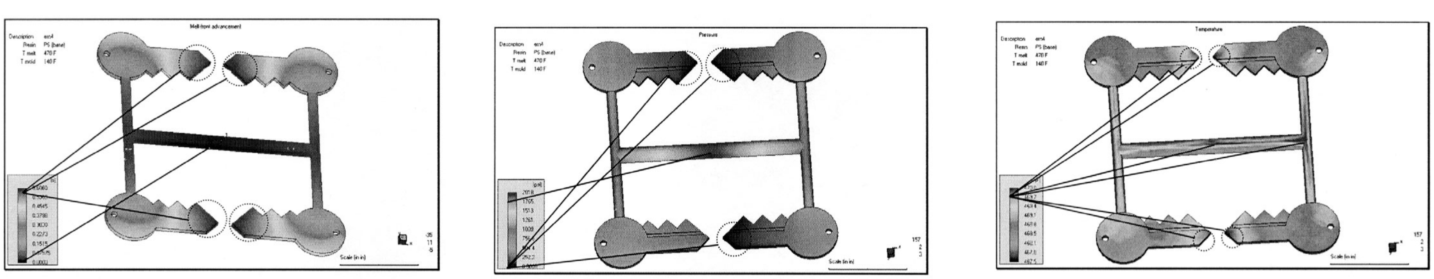
Case Study

Identify Needs

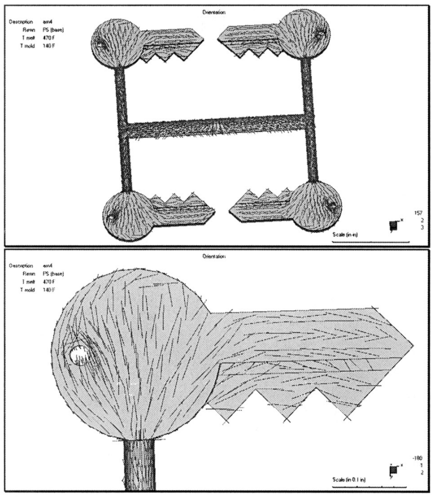
Several items needed to be considered in designing the product. The first item was to understand the need of the customers to decide the design of the injection mold. Basically, the product had to be inexpensive to make, quickly manufactured in large numbers quickly, and something that Iowa State students would like to have. With these considerations in mind, we decided to make small key chains with Iowa State printed on them.

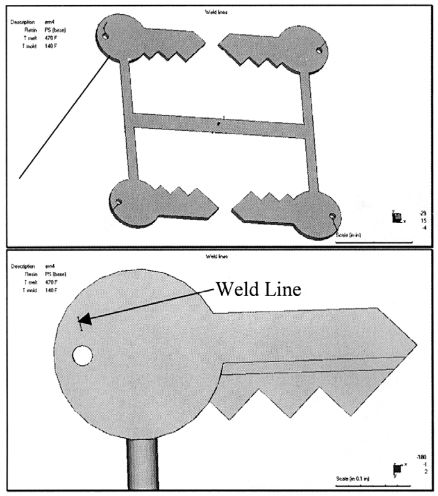
This product fit the criteria we were looking for. Once the product was decided, the design of the injection mold was considered. To quickly produce a lot of

Figures 2,3,4. Results of melt front advance (2), pressure (3) and temperature analysis (4).



Figures 5 & 6. Results of molecular orientation analysis (5) and weld line analysis (6).





key chains, a mold with four keys was designed for this project.

Die/Mold Design

The next decision was to decide what program should be used to translate the free-hand sketch to create the blueprint for further application. AutoCAD software was applied to draw the design. We chose AutoCAD because it has very good drawing capabilities and it is also very easy to export the file created by AutoCAD into MasterCam for future cutting path generation.

Analysis by C-Mold

The next step was to analyze the characters of the mold. C-mold software was applied to analyze the characters of the designed injection mold. The following steps indicate the results of each character of this mold.

Step 1—Analysis of melt front advance: The results of the melt front advance (shown in Figure 2) simply show the flow of the molten polystyrene at the completion of the injection stage. This graphical analysis allows the user to determine if the cavity or cavities have been completely filled or if a short shot has occurred. This also shows the user if any voids have been left in the part. The time required to fill each section of the cavity can also be determined by this analysis. The dashed circles indicate the corresponding time of the scale located inside the lower left corner of the figure.

The analysis of the melt front advancement for our design was ideal. The melt front advancement was equal in all four cavities for all times, indicating that the design was well balanced and that there should be no problems filling or over packing the mold. Also, the time required to fill the mold was relatively short, leading to a low cycle time.

Step 2—Analysis of pressure: The pressure analysis (shown in Figure 3) indicates the amount of pressure at specific parts of the molded part at the end of the injection cycle. It is ideal to have a gradual increase in pressure at the injection point as the part begins to fill.

The analysis of our design was acceptable. We had a maximum pressure reading of 2018 psi at the injection point. The other parts of the design had a gradual reduction in pressure as the flow length increased. This was not a problem because there was not a large amount of variation in the pressure readings of each cavity (approximately 500 psi).

Step 3—Analysis of temperature: The temperature analysis (shown in Figure 4) points out the spatial temperature variation throughout the part at the end of the injection stage. Generally, the greater the variation the greater the amount of warpage that can be expected.

The analysis of our design showed an overall temperature difference of 2.5 ∞F. With such a small change in temperature distribution, we expected to have a part with little or no warp.

Step 4—Analysis of cooling: The cooling analysis provides information about the time required for a material to reach its heat deflection temperature based on the design. This is important because cooling time is the most time-consuming stage of the injection process. The ability to optimize the cooling time by changing the mold design can be achieved through this analysis.

The analysis of our design revealed virtually no difference in the cooling time for any part of our design. We achieved this by keeping a uniform thickness throughout the part whenever possible.

Step 5—Analysis of molecular orientation: The molecular orientation analysis (shown in Figure 5) shows the orientation

Figure 7. Result of air trap analysis.

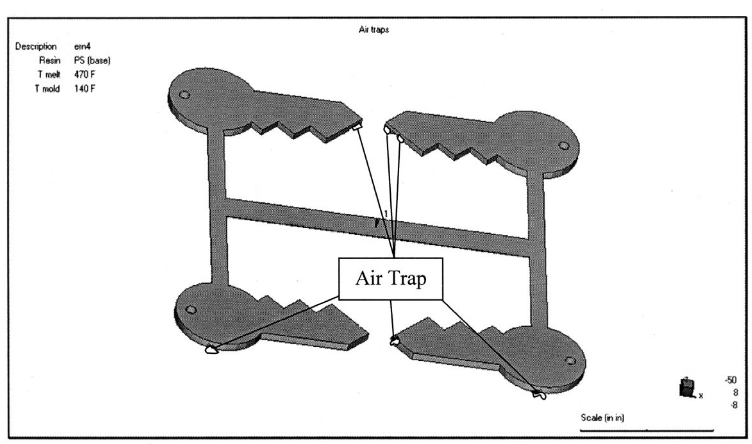


Table 1. **Summary of Cost Estimation**

Cost Item	Total Cost	Annual Cost	Frequency per Piece	Unit Cost
1. Machine	$45,000	$14,376*	50,000	$0.2875
2. Die and mold	$4,500	$1,440*	50,000	$0.0288
3. Design & analysis	$480	$160*	50,000	$0.0032
4. Maintenance		$1,000	50,000	$0.0200
5. Setup		$60	50,000	$0.0012
6. Machining	$20/hr	$2650	50,000	$0.0530
7. Material	$0.7/lb		0.2 oz	$0.0200
Total unit cost				**$0.3937**

* Indicates the interest formulas relating present and future to its annuity equivalent values are applied to calculate the annual cost (Paul Degarmo et al., 1997). The effective interest rate per interest period is set at 20% and the service life of this product is 5 years.

Table 2. **Matching Parameters and Sequences**

Sequence	Description	Spindle Speed	Feed Rate	Depth of Cut
1	Rough cut the whole mold (1/4≤ end mill tool)	2290 RPM	15 in./min	0.050 in.
2	Finish cut the key part (1/8≤ end mill tool)	4580 RPM	5 in./min	0.010 in.
3	Finish cut the running system (1/8≤ ball mill tool)	4580 RPM	5 in./min	0.010 in.
4	Finish cut the letters (V-mill tool)	8000 RPM	5 in./min	0.005 in.

of the polymer molecules on the surface of the part at the end of the filling stage. Essentially, extreme differential of orientation will cause a differential in shrinkage, thus causing the part to warp.

The analysis of our design showed a gradual change in the direction of orientation in our parts. This was a critical issue along the flow path of the key, where the part would be likely to warp. However, the molecules orientated along the flow path of the key were almost parallel to each other.

Step 6—Analysis of weld line: The weld line analysis (shown in Figure 6) provides the formation of weld lines during the simulation. This information can be used to relocate weld lines and to eliminate them. Malloy (1994) defined weld lines as follows: "Weld lines (or weld planes) are formed during the mold filling process when the melt flow front separates, and recombines at some downstream location" (p. 47). Weld lines look like cracks on the surface of the molded part and generally are the weakest areas having potentials of failure.

The analysis of our design showed four weld lines for our design. The weld lines were caused by the hole in the end of the key. This was of some concern to us because a key ring was to be put through the hole, applying force that would cause stress on the weld line. To handle this slight problem, we had two options. First, for the small price that the part would sell for, long-term reliability was not an issue. Second, we could have found a low-cost semi-crystalline material that was not as sensitive to the structural inferiority at weld lines associated with amorphous materials.

Step 7—Analysis of air trap: The air trap plot (shown in Figure 7) shows the areas of the design that may require venting. The plot shows the areas where air is likely to be trapped inside the mold. If the air is not vented the possible defects are short shots, or burn marks, on parts.

The analysis of our design showed that we needed to vent our mold at two areas on each cavity. This was not a problem or of any concern, as all molds have to be vented to allow air to escape.

Analysis by Cost

As the design and analysis of the injection mold was finished, the next step was to estimate the cost of production and make an evaluation of the sale price of each product. For design and manufacturing engineers, the analysis of alternative production methods of a part, or a product, is faced with cost variables related to materials, direct labor, indirect labor, tooling, and invested capital (Bralla, 1999). Table 1 shows the summary of the cost estimation.

The direct unit cost of the key chain was about $0.39/unit. However, the indirect cost, such as management, transportation, and advertisement, also needed to be considered (DeGarmo, Sullivan, Bontadelli, & Wicks, 1997). We supposed that we would get a 5-year contract, which needed to produce 50,000 key chains per year. The indirect cost was set at 20% of the direct cost. Therefore, the total cost (TC) of the product now equaled:

TC = ($0.39*50,000)1.2 = $23,400.

We wanted to achieve a 30% benefit from the total cost. The total price (TP) of each year could be expressed as:

TP=$23,400*1.3= $30,420.

The price of each key chain (UP) would be:

UP=$30420/50,000=$0.61/unit.

Process Planning

The final procedure of the DFM project was to plan the machining processes to fabricate the mold. To optimize the machining processes, the proper machining parameters had to be decided first. A carbide tool was used to cut the mold. Table 2 shows the information of machining parameters and machining sequences.

MasterCam software was applied to create the cutting path and NC program for a CNC milling machine after all parameters were decided. The CAD drawing was directly imported into MasterCam to generate the cutting path. The machining parameters shown in Table 2 were used for each operation. The verification function helped us to evaluate whether the cutting path generated was proper or not. After the cutting path was decided, the NC program was obtained and then used in the CNC machine to cut the injection mold. Thus, the project was prototyped and evaluated through this process.

Conclusions

Although design and manufacturing are two different departments, the development of a DFM curriculum provides the opportunity to integrate design and manufacturing. This module was created to help students to learn how to design a product from its concept to a realization of the actual part, what to look for in the design, what type of material to use, how to estimate the overall cost of the final part, and how to produce it. For students who graduate from an IT department, it is very important for them to understand how to integrate the courses they have completed. The DFM curriculum provides the students the knowledge necessary to communicate valuable ideas to the design engineer. It also provides an opportunity for them to understand how to apply their knowledge in the future in both the design and manufacturing areas.

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