Enhancing Undergraduate Mechanical Engineering Education with CAM and CNC Machining

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Abstract

To effectively serve student career success, mechanical engineering programs must teach how to account for manufacturing considerations in design. The American Society of Mechanical Engineers (ASME) has identified manufacturing education as one of the greatest weaknesses as perceived by industrial employers of recent-graduate mechanical engineering hires. Additionally, in its 2014 report to the President's Council of Advisors on Science and Technology (PCAST), the Advanced Manufacturing Partnership 2.0 highlighted the need for universities to provide engineers with appropriate manufacturing education to sustain emerging technologies, a need which persists to this day. This Student Paper proposes the adoption of a laboratory course at university-level mechanical engineering programs in which undergraduates would learn and practice the basics of computer-aided manufacturing and apply that knowledge to CNC milling machines. The motivation for this course is to better prepare students for design and manufacturing careers by reconciling mechanical engineering curricula with the hiring need in the industry for engineers who understand common manufacturing processes and how to design for them.

Keywords

Manufacturing Education, Computer-Aided Manufacturing, Computerized Numerical Control, Design for Manufacturability, Student Paper

Introduction

Newly minted mechanical engineers often encounter a gap between the engineering principles they learn in school and the challenges they face in the field, and part of this gap stems from failing to understand how an engineering solution goes from model to final product [1-2]. A trope in the manufacturing industry is the young engineer who has recently spent four years at college yet is seemingly unaware of how to use a screwdriver, let alone a mill. It is crucial that post-secondary technical programs provide mechanical engineering students with an appropriate balance between developing engineering fundamentals and practical sensibilities. Introducing courses that focus on computer-aided design (CAD) and incorporating CAD software into the curriculum via design projects constitute one-way mechanical engineering programs have unified in an attempt to bridge the gap between principle and practice-based learning and meet the industry demand for engineers that are prepared for design careers. Generally speaking, mechanical engineering curricula currently has a strong focus on CAD and computer-aided engineering (CAE) that covers the creation of digital 3D models and finite-element analysis of stresses, strains, etc. on these models. However, one aspect employers value that is largely absent from engineering curricula is basic manufacturing education on topics like computer-aided manufacturing (CAM) and principles of designing for manufacturability (DFM). This is knowledge vital to understanding how to translate engineering solutions from concept to product, yet college-educated engineers are often not fully prepared for careers in design because undergraduate engineering programs fail to sufficiently teach about DFM and common manufacturing methods [3]. In reality, undergraduate access to modern manufacturing tools and processes has been scarce in the educational space in the past due to factors including class size, safety requirements, and the expense of purchasing and maintaining manufacturing equipment. However, modern advances in computer-aided design, engineering, and manufacturing along with the emergence of desktop-scale manufacturing equipment have made it practical to provide students experience with accessible, low-risk modern manufacturing techniques and alleviate the pain point of manufacturing in the mechanical engineering curriculum.

The manufacturing industry has recognized a need to improve collaboration between design and manufacturing engineers for decades. Alarmingly, in an ASME Vision 2030 Task Force survey beginning in 2008 of more than 1,400 engineering managers about the state of education and industry practice in the field of mechanical engineering, understanding "how things are made and work" was identified as one of the recent-graduate mechanical engineers' four greatest weaknesses [1]. This study "was a statistically valid and groundbreaking view of mechanical engineering education" and data from the study strongly supports the conclusion that changes in the mechanical engineering curricula to teach practical knowledge of manufacturing processes are needed to meet the expectations of the industry [4]. This discrepancy between education and the expectations of employers has been exasperated by the recent trend of over-relying on additive manufacturing as a means for students to produce the projects they design in school. Additive manufacturing is a tremendous educational tool because it is a relatively inexpensive investment for educational institutions to make and allows students exceptional freedom for their designs, but by near-exclusively relegating prototype fabrication to 3D printing, universities are inadvertently encouraging bad design habits for students' future careers and neglecting to reinforce basic DFM principles. The fundamentals of DFM are far more relevant for forming and subtractive manufacturing processes, for example, than they are for additive manufacturing, and while the drawing skills taught through computer-aided design courses are important, they typically do not inform the student of the key principles of designing for manufacturability. This, combined with the inherent design forgiveness of 3D printing as a manufacturing method, lends itself to encouraging poor CAD design both in terms of part quality and from a production standpoint when applying manufacturing methods that are more commonly used in industries such as casting, forming, and machining [5]. A simple solution that can be applied to counter this trend and emphasize manufacturing-oriented thinking in the mechanical engineering curriculum is to expose students to tangible experience with alternative manufacturing methods. Introducing a course that teaches computer-aided manufacturing (CAM) software and computer numeric control (CNC) machining will target these areas of need and ensure mechanical engineering students graduate with the knowledge needed for successful careers in design and manufacturing. CAM software and CNC milling require the user to understand essential DFM concepts such as tolerances, machining limitations, and surface finish, and with lessons tailored to get students to practice these principles, a course teaching CAM and CNC would greatly enhance mechanical engineering education.

Course Objectives

The topics the proposed course would cover include manufacturing processes, product design fundamentals, and CAM/CNC. In a report summarizing the implementation of a similar course at the University of Iowa in 2004, it was concluded that “students best learn how to use CAD/CAM software by completing a carefully planned sequence of laboratory exercises and hands-on involvement with manufacturing processes” [6]. The facilities the proposed lab course would be taught are recommended to include a manufacturing laboratory with student-use desktop CNC machines and a computer lab with PCs installed with Autodesk Fusion 360. Fusion 360 is cloud-based, 5-axis capable CAM software that is common in the private sector and educationally free-to-use, which makes it a natural choice to teach a computer-aided manufacturing course. Based on the current market, the Pocket NC V2 (Figure 1) stands out as a suitable CNC model for educational purposes due to its price, easy-to-use UI, and ability to mill in 5 axes continuously. Other good options for educational 3-axis milling include the Tormach xsTECH Router and Haas Mini Mill-EDU. The course is anticipated to be equivalent to 1-2 credit hours over a 16-week semester and will have a lecture and lab section that meets weekly to instruct on how to use CNC and Fusion 360 CAM software and give class time to work on assignments, respectively. Computer-Aided Design should be a prerequisite to this course as the goal of the course is to expand on design principles taught in CAD, and making the most of CAM software requires a firm understanding of how to use CAD.

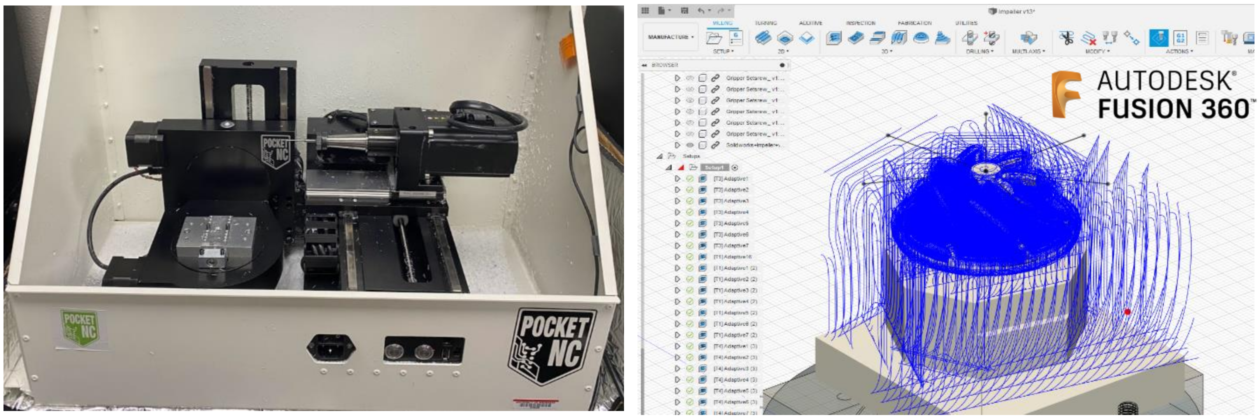

Figure 1. *Pocket NC V2 5-axis desktop CNC Mill (left) and simulated toolpaths for a part generated in Fusion 360 (right).*

The motivation for proposing this course, above all other reasons, is to teach how to design for manufacturability. “Manufacturability, which plays a significant role in determining the cost of the engineering product, has not been widely incorporated [into design education] for structural optimization” [7]. The aspects of DFM that will be addressed in this course are targeted so as to teach a particular mindset of predicting problematic geometry and being mindful of good practices when designing a new part to maximize quality in the final product. Things to consider when designing a part for manufacturability on a CNC mill include features like raised bosses, deep pockets, narrow regions, sharp internal corners, inaccessible features, exterior fillets, thin walls, and flat-bottomed holes. Figure 2 illustrates how some of these features might adversely affect milling processes. These issues have the potential to make a part significantly more difficult or time-consuming to machine, or even make it impossible to manufacture entirely. Additionally,

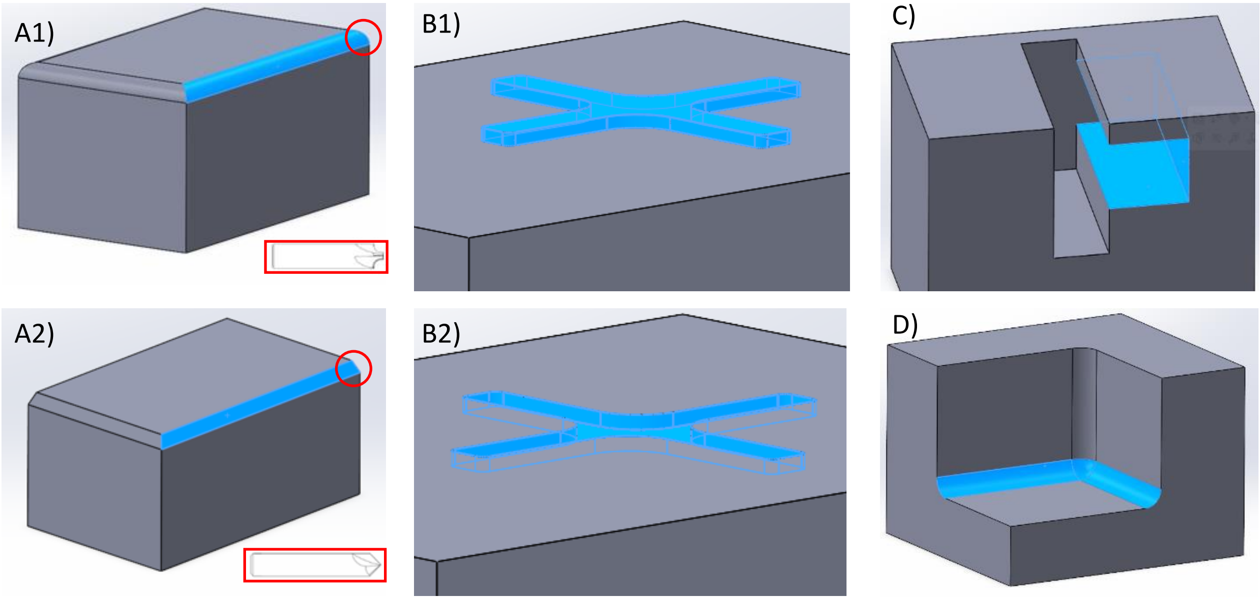

Figure 2. *Example models demonstrating features relevant to DFM for CNC milling. In Figure A1, the fillet on the model would require a custom tool to machine whereas a chamfer of the same size like in Figure A2 would only require a fairly standard, straight-sided chamfer tool. A machining strategy for the part in Figure B1 would require all of the surround material to be removed from the stock to leave behind the raised boss whereas depressing the boss in the model like in Figure B2 would mean a much smaller amount of material would need to be removed. Figure C illustrates a part that would not be possible to be machined due to a feature that can't be reached and sharp interior corners. Figure D meanwhile would require a very specific radiused end mill in order to machine the bottom fillet, and, if the fillet is not of a standard size, a custom end mill would be need to be used.*

many of the same problematic geometries and principles of designing for manufacturability that apply to subtractive manufacturing also carry over to other manufacturing techniques such as forms of molding, forming, and extrusion. By teaching what problems can arise when attempting to manufacture a new design and how to address these issues, the proposed course will promote problem-solving skills relevant to design and force students to be conscientious about how their designs will actually be produced.

Over the course term, students will learn the fundamentals of computer-controlled machining, how to use CAM software, and key principles of designing for manufacturability. Through lessons in using the full extent of Fusion 360's CAM toolbox, assignments that gradually escalate with the students' understanding of CAM, and a hybrid learning approach between hands-on and computer-based experience, the course will grow students' understanding of computer-aided manufacturing and teach them to cope with the challenges of designing parts for manufacturability.

Sample CAM/CNC Course Learning Objectives:

1. Become familiar with the degrees of freedom of CNC mills as visualized in Figure 3 and learn how to account for CNC machines' travel limitations such as z-axis overextension and shaft collisions with stock material.

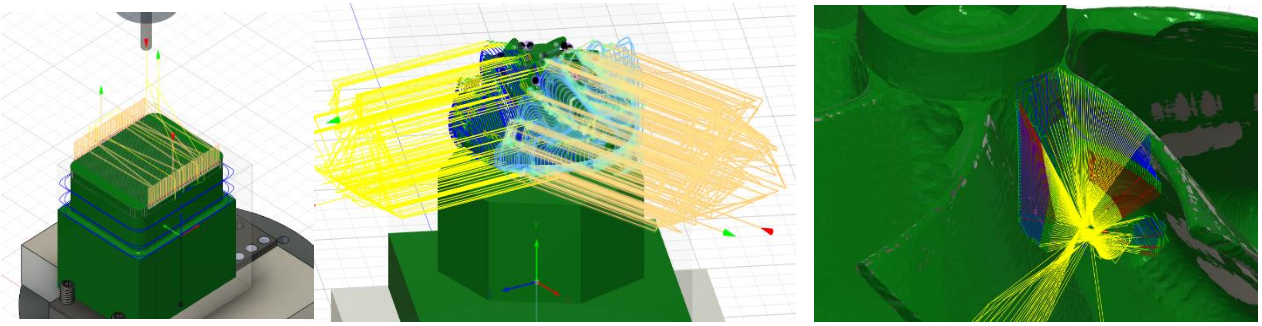

Figure 3. *3 axis toolpaths (left), 3+2 axis toolpaths (middle), and continuous 5 axis toolpaths (right). Yellow/orange lines represent tool lead-ins and lead-outs while the blue/cyan lines represent tool cutting motions. In 3 axis milling, the orientation of the tool is fixed and can only move relative to the part in the x-, y-, and z-directions. 5-axis milling has the advantage of two added rotational axes that allow the tool to move omnidirectionally. In 3+2 axis machining, the CNC only mills in one set of three axes at a time before machining another face of the part in the whereas in continuous 5-axis milling the tool is able to move in all 5 axes simultaneously.*

2. Become familiar with end mill types, terminology, and the main types of milling operations. Learn to choose an appropriate end mill for a given operation, desired finish, deflection tolerance, and material. Understand the effects tool choice can have on cycle time and tool life. Practice installing bits and adjusting tool runout or the wobble of the tool relative to the stock.

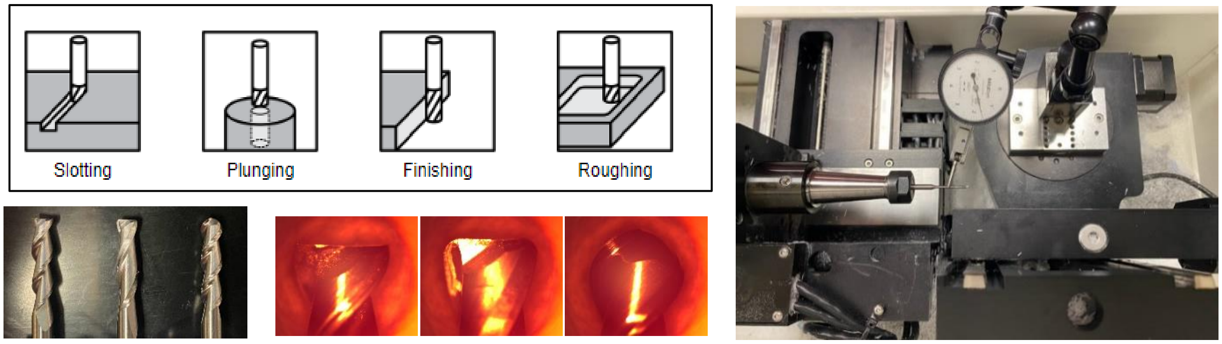

Figure 4. *Illustration of common machining strategies (top left), comparison between flat, bull, and ball end mills under different magnifications (left to right, bottom left), and example of a tense indicator being used to measure tool runout (right).*

3. Learn how to calculate appropriate speed and feed rates for CNC recipes, first by hand from the manufacturer's data table and then by substituting values into a program like HSMAdviser or FSWizard. Understand the importance of selecting appropriate values.

4. Manufacture a CNC part from scratch using the workflow shown in Figure 5.

    a. Given a freeform, 3-axis example part to machine, apply prior CAD knowledge to create a 3D model of the part-stock-vise setup in Fusion 360's Design tab for CNC milling.

    b. Create a machining "setup" in Fusion 360's CAM tab. Choose an appropriate end mill and use an adaptive clearing strategy to rough out the top face of the part. Then, apply a subsequent finishing strategy with a finer tool to machine the remaining stock from the part.

c. Successfully run a simulation of the operations in Fusion 360 and sim.pocket.nc.com without errors. Finally, set up the CNC mill for the operation, mount the stock, tare the tool, and run the process.

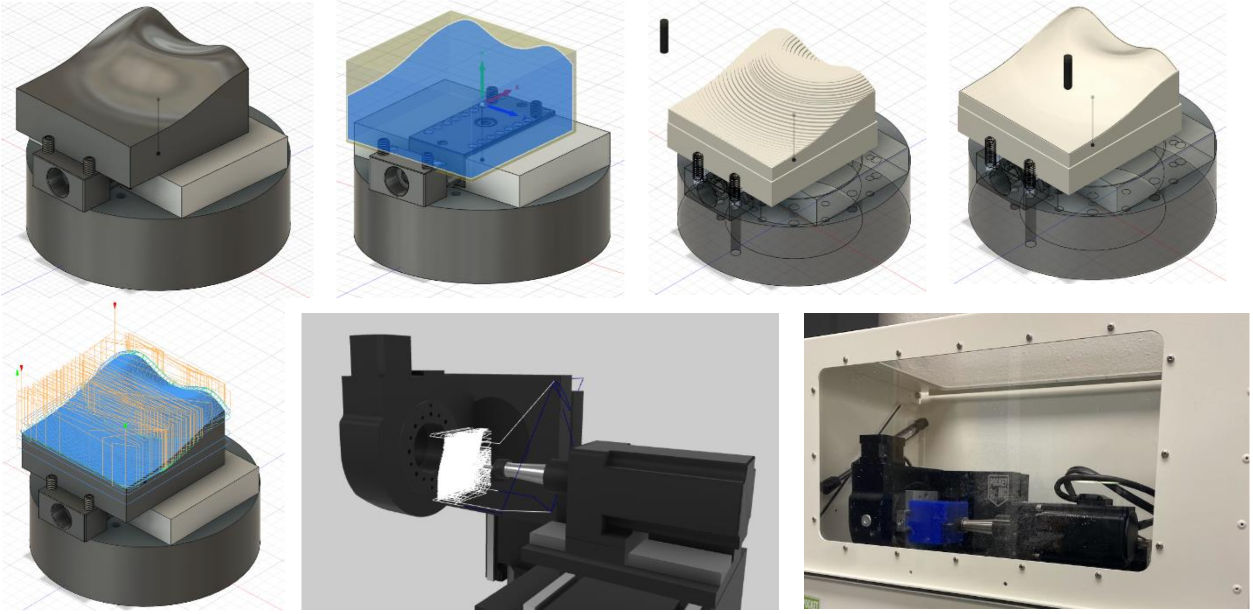

Figure 5. *Typical 3-axis machining workflow of a part. Shown above are (from left to right) a 3D model of a work-holding setup, Fusion 360 machining setup, roughing operation, finishing operation, Fusion 360 process simulation, Pocket NC process simulation, and Pocket NC machining the part in machining-grade wax.*

5. Become familiar with the work holding techniques available for parts that require machining on all six faces – clamping, tabbing, window machining, and slitting.

6. Create another part setup for a model requiring "3+2 axis machining," meaning that the stock needs to be reoriented during machining in order to cut each face. The result will be a model that is ultimately separated from the stock by leaving support material, so one of the aforementioned work holding techniques like what is seen in Figure 6 will need be used.

Figure 6. *Examples of some different methods of CNC work holding: thick tabbing (a), thin tabbing (b), offset tabbing (c), and window machining (d)* [8].

7. Learn to select end mills and cutting operations based on part geometry. Given a part that is suboptimal from a manufacturing perspective, modify it in CAD by adding and removing features to increase ease of manufacturability while preserving the original functionality of the part. Even relatively minute changes to fillets, chamfers, contours, and pockets (see Figure 2) can have an outsized effect on manufacturing time and finish quality.

The course is anticipated to culminate in a multi-week design project that holistically evaluates the students' CAM skills and comprehension of DFM concepts targeted in the course. One pitch for this final project would be to assign students a complex part to machine and set a maximum allowable machining time requirement so as to challenge students to design the most optimal machining solution and account for model features that can only be machined efficiently by deliberately taking advantage of DFM principles. Another option for this final project is to assign a part function and set of design specifications and require students to design and manufacture a 3D model that fulfills them. A good example for this might be a wall bracket for a paper towel holder with stipulations on mounting holes, weight, and shear strength, thus uniting aspects of CAD, CAM, and finite-element analysis. A more complicated project for a team of three or more might be to design a vise with multiple parts that must be assembled together in the final prototype. The point of this exercise is to challenge students to apply their creativity and knowledge to a realistic product design scenario. In any case, the requirements for the final project will push students to apply the principles of work holding, DFM, and CAM workflow that motivate the proposal of this course.

Course Methodology and Resource Review

The first weeks of the proposed CAM/CNC course lab section would be taught through tutorials and remain primarily self-paced until students become proficient enough to create computer-aided manufacturing strategies on their own. There exists already an abundance of quality resources with which to teach how to use the Pocket NC, CNC in general, and CAM in Autodesk Fusion 360. It makes sense to take advantage of these resources and allow students to move at their own pace when they are starting with brand-new software. Autodesk provides excellent tutorials for teaching the basics of machining and CAM as well as what each available machining operation does in Fusion 360, including multi-axis options and how to use them. Assignments pertaining to what students should be working on that week would be given in-class, and coincide with weekly learning objectives which apply to the extent of the student's current expected knowledge. For example, an assignment asking the student to simulate toolpaths roughing and finishing the surface of a part might be given after following along and completing the tutorials detailing how to create a CNC setup in Fusion 360 and use the basic stock-clearing toolpath operations. Fusion 360's YouTube channel has a video for nearly every topic or question a newcomer to the field might have which makes it a phenomenal resource to develop a CAM course around. NYC CNC (www.nyccnc.com) has been making videos since 2007 and is an excellent resource for learning CNC, Fusion 360 and setting appropriate speeds and feed rates. NYC CNC has a wealth of videos demonstrating key CNC concepts and a wide variety of machining projects that showcase important tricks of the trade and what a CNC mill can do to take a machinist's capabilities to the next level. Developing a week-by-week curriculum of tutorials and projects that a student can complete over the course of 16 weeks, aimed at bringing them to proficiency with CAM software, is the key to the success of this course and reinforces the primary objective which is to provide hands-on experience with designing for manufacturability.

Much the same as with the present implementation of the CAD course, the teacher's assistant for the proposed CAM course would preferably have at least one semester of CAM experience or have already taken the course, and they will be responsible for supervising the computer lab during lab sections and helping students as they get stuck working through tutorials or assignments. Lecture for the proposed course would mainly be supplemental to the lab with the instructor working through examples similar to the assignment for the week and explaining core concepts and expectations relating to machining strategies, designing for manufacturability, applications in industry, etc. Midterm exams for the course shall have students perform a design/machining task in Fusion 360 to assess how well they can apply the software and DFM concepts that have been taught in class up to then. This approach will allow the instructor to gauge how well students are performing at checkpoints in the semester and motivate students to learn the skills they need with Fusion 360. Once brought up to the level of competency with using CAM software, students should apply what they've learned to machine their own parts with a milling machine. At this stage in the course, their skills should be to the point where they can design a part, plan a work holding arrangement, select an appropriate machining strategy, and generate safe milling tool paths that effectively and completely machine the part. It is at this point that students should be prepared for a final project that challenges them to design a part and/or CAM machining strategy in such a way as to take advantage of the principles of designing for manufacturability. The "A-outcome" for the final project is a part/assembly that is safe to manufacture and achieves its stated function with a total machining time and a surface roughness that falls within an established range of acceptability.

Problems Facing the Course

As with any new course, it will likely take multiple semesters for everything to come together. Feedback from students and TA's should be considered by the instructor when evaluating the course after each semester, and progressive steps should be taken to mitigate the growing pains a lab section using brand-new equipment and software will undoubtedly experience. One foreseeable outcome is that students will not be able to manufacture overly-complex 3D models due to the limitations of the lab's CNC machines. However, this is one of the learning outcomes of the course. Even in industry, parts often cannot be manufactured properly in the first iterations of a product's design; students must develop an appreciation of how vital the interaction between the spheres of design and manufacturing truly is in order to grasp the importance of the DFM concepts taught in the course. Finding good TA's will also likely be a challenge as it has been in prior introductions of similar courses at various universities, at least until the course has been established for a few years [6]. In addition to active involvement, TA's will need to be familiar with Fusion 360 and competent at supervising the safe operation of the CNC mills. The Pocket NC V2, as is the case with most 5th-axis desktop CNC mills on the market, does not have sufficient failsafe to completely prevent improper use of the machine in a way that could cause collisions with itself or the work holding. Because of this, the TA will need to oversee ahead of time that the work holding arrangement and machining toolpath simulations the student generates in Fusion 360 and the manufacturer's simulator are error-free and won't cause damage to the tool or mill. Other pain points the course may experience early in its life include a steep learning curve with Fusion 360, compiling sufficient multi-media material, and establishing appropriate final project time allotment, milestones, and design specifications. These potential problems may be resolved as they might arise although it will almost certainly take a couple of years for the course to fully mature.

Conclusion

In accordance with the need to reconcile the hiring needs of industry with mechanical engineering curricula, introducing a CAM/CNC course would fill a hole in mechanical engineering education by addressing the principles of designing for manufacturability and the current lack of manufacturing education. Providing hands-on experience with CAM software, manufacturing strategies, and the connection design has with manufacturing shall provide mechanical engineering programs with an added emphasis on design-oriented problem solving and enable faculty to better teach the process by which engineering solutions are developed in the real world. In an ideal scenario that minimizes development time and cost, design engineers should be able to communicate effectively with manufacturing engineers to understand the demands that their design has on production so that development goes through fewer iterations. The proposed course would help by bringing up-and-coming engineers to speed with the knowledge needed to create designs that are conscientious of all types and stages of manufacturing. The course will also promote experience with varied manufacturing methods so that students may better analyze appropriate production strategies and have the expertise to deal with the challenges of product design in their future careers. Engineers that are conscientious of DFM principles when designing solutions are rare coming out of college, so if undergraduate mechanical engineering programs can reinforce a DFM-oriented mindset in young engineers through a course that necessitates it, it may greatly contribute to education quality.

Acknowledgments

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