A Novel Hands-On Project in Computer-Aided Manufacturing

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Abstract

This paper describes a project that involved designing and fabricating puzzle-type parts to form letters that were machined using a three-axis computerized numerically controlled (CNC) milling station. The project was part of the Design for Manufacturability course at the University of Kansas. The letters were attached to neighboring letters to form a word by using interlocking features that were hidden when viewed from the front. Additionally, each letter was comprised of two separate pieces that were connected using visible features. To provide an additional challenge for the students, each letter was machined from a different material and each piece was fabricated three times to demonstrate the concepts of mass production and interchangeability with other parts. Pairs of students were responsible for the design, tool path generation, and fabrication of each piece. The project has taken approximately one month and has been successfully completed during two offerings of the course.

Introduction

In design and manufacturing courses in an engineering curriculum, hands-on projects where students are asked to proceed from concept to production are invaluable. Frequently this type of experience may be an integral part of a senior capstone design project that may last a semester or year. Shorter projects are a common part of semester-long courses and usually focus on basic design concepts and practices that may result in production of a single item, if fabrication is required at all beyond the design analysis. At the University of Kansas the senior-level course Design for Manufacturability taught students design techniques that were important for mass production. Course topics included subjects such as reliability, quality control, robust design, and common mass production fabrication methods. A project was developed to help students experience and practice the skills required in design for computer-aided manufacturing (CAM) using a CNC mill. The primary objectives of this project were to provide students with practice and experience a) designing a part to be mass produced by automated machining, b) generating the machine instructions for manufacturing the part using FeatureCAM software, and c) fabricating the part with the help of the machinist. Students who have completed this project should be able to design mass-produced parts that interface with multiple copies of other parts using the concepts of clearance, tolerances, alignment, and fixturing as well as develop the tool path to fabricate the part on a CNC mill. Secondary objectives involved developing teamwork, communications, and creativity skills. This paper describes the details of the project that was used successfully during two semesters. The project took approximately one month from the time the assignment was given to have all of the parts machined and assembled.

Figure 1. "KUME' and "HAWKS" letters machined using a three-axis CNC vertical mill.

Project description and preparation

The project involved the design and fabrication of a series of puzzle-type parts that were assembled to form a word (Fig. 1). Each letter of the word was comprised of two pieces that fit together using interlocking features. Teams of four students were assigned to each letter with two students required to design and fabricate one of the two pieces of the letter. Adjoining letters were attached together using interlocking features that were hidden when viewed from the front of the puzzle. The assembled word was required to be stable when the word was placed in an upright orientation. Each letter was 4 by 4 inches square with a one-inch overlap with the subsequent letter in the word. All stock material for the pieces was approximately 4 by 3 by 0.75 inches and three copies of each piece were created. Each letter was fabricated from different materials such as aluminum, steel, PVC, polyethylene, etc. The materials were selected based on machinability, ease in obtaining, and cost. The length of the word to be fabricated was dependent on the number of students in the class. Two students per puzzle piece (four students per letter) was a good number because each person had to contribute significantly, although different numbers would work as well. Sixteen and twenty students were in the class the two years the project was completed so four and five letter words were created.

Each part was required to be machined using a single set-up on a three-axis CNC vertical milling station with only three tool sizes to choose from. On this type of machine the part could move in two directions on a horizontal plane and the rotating cutting tool could move up and down. To help with the fabrication, a common fixturing plate made of aluminum was used for all pieces where the plate was attached to the mill base using a vise. At least three shoulder bolts were fit through the plate and screwed into the bottom of the stock material. The threads from the shoulder bolt only extended 0.25 inches into the part so it was possible to machine over the screw locations. For materials that didn't hold threads well (e.g. certain plastics), thru holes were used for the part, although that required the fixturing holes to be in places that were not machined. The vise and stock material could then be repeatedly placed relative to the CNC. The parts were machined to a depth that just started to machine the fixturing plate. When the plate had too many machined marks on it, the whole plate was simply faced down to get a flat surface again. The possible holes through the fixturing plate that the students could use were in a fixed orientation. The instructor created the outline of the letters for the students and the possible locations for the fixturing holes (Appendix A).

Designing the parts

Designing two pieces to fit together to form a letter seemed easy to many students, but it quickly became apparent that the interlocking features, fixturing requirements, and internal corners made the task more challenging. There were many different types of features that could have been used to connect two pieces together but they needed to also align and hold the parts relative to one another. Requiring one set-up with limited fixturing positions also caused students to think carefully about the shape of the interlocking features as well as part deflection during the machining process. The most common design element that caused students consternation was how to fabricate sharp internal corners. A rotating tool could have easily machined external corners, but internal corners were impossible due to the finite tool radius. The solution that slowly became apparent to students was that the only way to get sharp internal corners was to have the two edges be part of two different pieces of the letter (Fig. 2). Depending on how they were drawn, some letters were harder than others; M, W, and K were difficult letters, S and U were easier. These design issues, coupled with the fact that all parts interacted with at least one other part resulted in a challenging, yet fun design experience for the students. Teamwork, creativity, and communication were essential skills the students had to use for the project to succeed. The design of the parts created excellent opportunities for students to create functional features for alignment and attachment. A simple pin and hole was easy to create but might not sufficiently constrain the two pieces together. Tolerances and fits also need to be understood and used by the students. Pairs of students were required to create their parts using a computer-aided design (CAD) package of their choice (this knowledge was a prerequisite for the course).

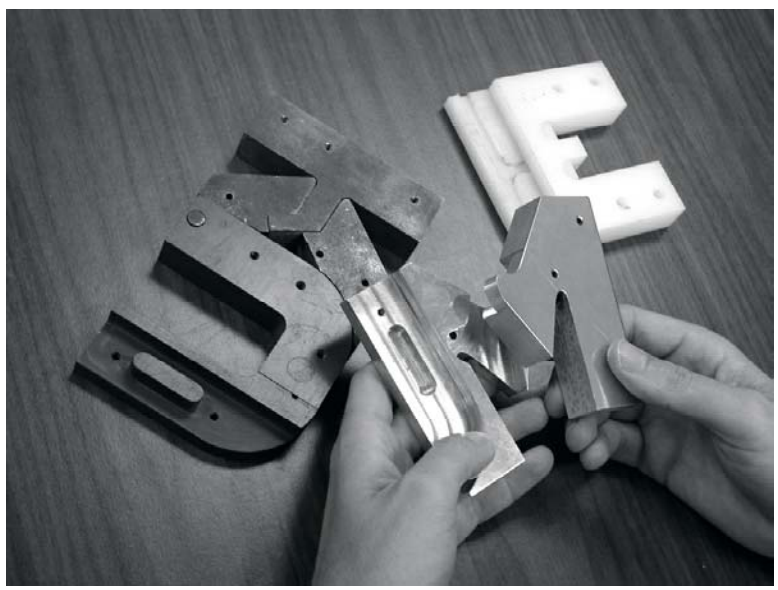

Figure 2. Each letter was comprised of two pieces with a visible interlocking feature between the two pieces of the letter and hidden interlocking features with neighboring pieces. Sharp internal corners required breaks to occur between the two pieces of a letter as seen in the letter "M".

The day the project was assigned the students were given one to two hours in class to work with their teams and the other teams their part interacted with to create their design. At the completion of this period the teams turned in hand-drawn sketches of their parts along with the location of at least three fixturing holes they were going to use. The locations of the fixturing holes were then used to create the holes in the stock material for the teams. An alternative that would take a little more time would be for the teams to also create their stock material using manual machines. Instead of spending the time to make sure the stock material had the correct final overall dimension, the material was rough cut oversized to save time during preparation. All teams then ensured that part of the tool path went around the entire piece to obtain the correct outer dimensions. At least one week was given for the students to create a solid model of their part and a properly dimensioned drawing.

Computer aided manufacturing and fabrication

Part design using computers and manual machines are common elements in many engineering curricula, but experiences with computer-aided manufacturing (CAM) are not as typical. Once a part is designed a manufacturing plan must be created for the selected machine. On a CNC machine this includes tool selection, tool path, and feed and speed of the tool. Tool path is the actual path the rotating cutting tool will travel to machine the material and the speed and feed refers to the velocity of the tool and the depth of cuts. At the end of the process a text file, or code, is generated that provides instructions to the CNC machine. There were numerous excellent pieces of software to create the machining tool paths for the designed parts. With mechanical engineering students, the focus of the instructor was not to make the students experts with CAM, but rather to give them a good exposure and experience with what was involved in the generation of code for a CNC machining center. The fabrication plan was relatively simple because the parts were fabricated on a three-axis machine, a single common fixturing method was used for all parts, and a common set of cutting tools was provided to the students. On a CNC mill it is common to have a series of different machining tools in an automatic magazine called a tool crib so that different diameter and shaped cutting tools can be changed during the machining operations. For this project only cutting tools with diameters of 0.25, 0.5, and 0.75 inches were available for the students to use. The program FeatureCAM (Delcam USA, Salt Lake City, UT) was selected because it was easy to learn and relatively cheap compared to other similar pieces of software. Students were able to import the parts they had previously designed using CAD. Stock material was selected and the 3 by 4 inch geometry created around the finished part. The features were attempted to be automatically recognized by the software with a number of curves having to be redefined using the software. FeatureCAM was used to generate the tool paths that could then be animated so that students could see how material would be removed and the part fabricated. This served as a good basis from which the students were able to make modifications based on how they wanted the part to turn out. The tool crib was specified by the instructor, as were all of the maximum spindle speeds, cutting rates, and depths of cut for the different materials. A professional machinist trained to use the software was available to help the students with their parts and he checked every part before it was accepted for fabrication. This exercise was helpful to the students because it gave them an opportunity to talk with a machinist and hear his concerns and suggestions about the design and manufacturing plan. During the CAM phase of the project, students hopefully obtained a good feel for how decisions made during design directly affect the fabrication of the part.

The second week of class was used to introduce the students to the FeatureCAM software by having them work through some sample parts. The instructor and the machinist helped the students work through the tutorial and answer any questions they had. Most students picked the CAM software up quickly and were quick and proficient with simple operations by the end of the class. This class was also used to go over the design of the parts and suggest any changes that might make the part better. The third week of class was used to have the students generate the tool path and machining plan using FeatureCAM.

Figure 3. Each pair of students watched their part get machined on the mill.

After the parts were designed and the tool path generated and approved by the machinist, each pair of students helped fabricated three copies of their part (Fig. 3). The machining of the parts frequently yielded surprising results for the students where things like tool or part deflection may not have been taken into account. The machinist made sure that the students were never going to harm themselves or damage the equipment, but he also allowed them to see what happened when the machining was too aggressive. In many cases the machining plan was modified between the three parts to produce a better final product. Smaller depths of cut or different tool selection were commonly modified between parts. As subsequent pieces of the word were completed it was possible to assemble adjoining parts to check for a good fit. Invariably some parts didn't fit together as well as planned and students were forced to identify whether the problem was in the design, the fabrication, or simply communication between the teams. Later teams occasionally made changes to their part so that it would assemble with previously machined pieces. Students did not operate the CNC machine directly but rather helped the machinist with simple tasks like fixturing and cleanup. During fabrication the students were encouraged to ask questions to better understand the capabilities of the CNC mill. Each pair of students had a series of questions to answer about the fabrication and assembly of their part. A typical machining question was to compare the length of time to fabricate the part using both the CNC and manual machines. A more design-based question was identifying the most difficult feature to machine and describing how they might modify the part to make it easier to machine on the CNC. As with the CAM experience, the goal for mechanical engineering students was not to make them proficient in operating the equipment, but give them an opportunity to see the equipment in use on a part they designed. Had a smaller tabletop CNC mill or router been available it would have been possible to have the students fabricate prototypes of their pieces on their own and they might have learned a little more about machining. At the conclusion of the project there should be three word assemblies that make excellent demonstration pieces for an office or display case.

During the fourth week during the project, regular class was canceled and students scheduled time in the machine shop throughout the week with the machinist to fabricate their parts. Three hours was scheduled to machine all three copies of each part. Usually this was enough time, although occasionally with the tougher materials it took longer. Ideally time would have been spent in class after the parts had been machined talking about where problems occurred and how the pieces fit together on assembly. Unfortunately, both times the project was run it occurred during the last four week of the semester with the machining occurring during the last week of class so an effective reflection on the project was not possible.

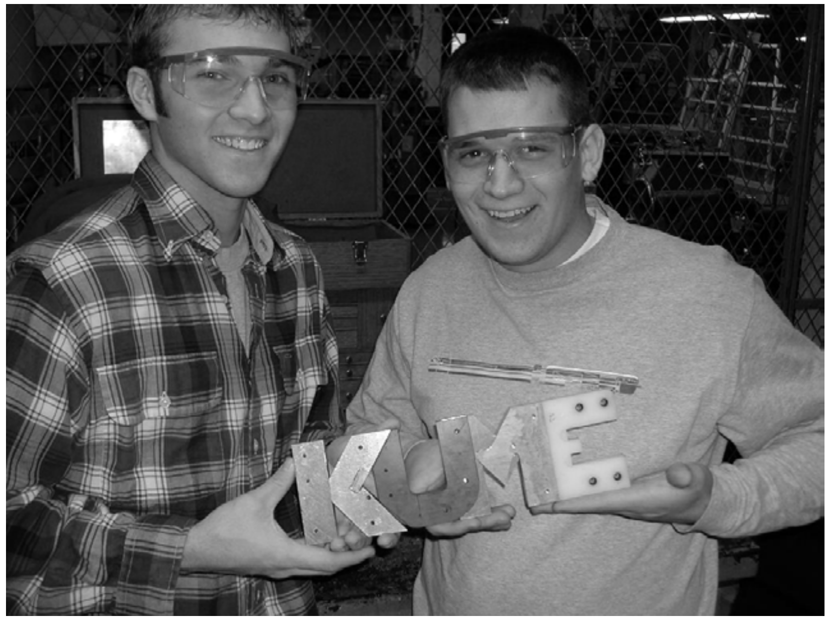

Figure 4. Students with their completed letter piece and the entire "KUME" assembly.

Conclusions

Grading was based on part drawings, how well students answered questions about the process, and whether their part was designed well and fit with the neighboring pieces without significant modification. Based on anonymous student course reviews the students enjoyed the project and appreciated that they were able to practice techniques they had learned in class to produce parts on the CNC (Fig. 4). Some students suggested having more time in class or lab to work on the project. Many students wished that more time was spent on certain aspects of the project: becoming more proficient with the CAM software; practicing with clearances, fits, and tolerances more; or spending more time working with the CNC machine. Both times the project was undertaken it was improved and was a success meeting all of the objectives identified. Students gained experience designing a piece that was reproduced only three times but still let the students see the challenges with making a part to fit a set of other pieces. All students spent time using a CAM software and learned about reasons for tool selection and problems if the wrong tool or settings are used. Finally, all of the participants actually produced their parts and had something tangible to examine at the end of the course. Students learned enough of the process to help them with other projects they completed for school. Hopefully these experiences made the students more marketable as engineers to potential employers. The project was an important part of the Design for Manufacturing course and will be used again whenever the class is taught.

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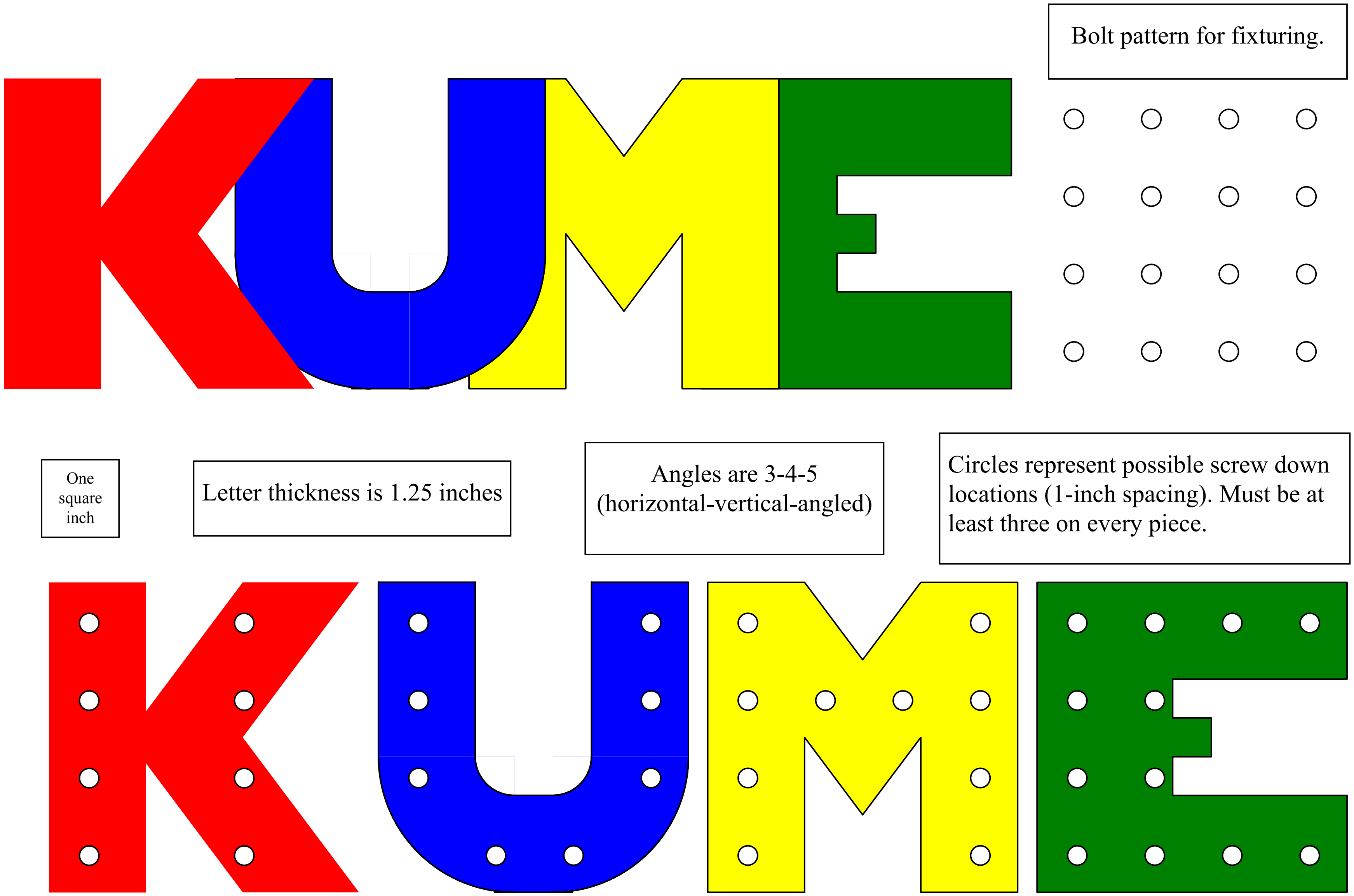

Appendix A. Handout given to class that showed the outline of the letters and the possible locations for the fixturing holes.