AC 2009-444: LOW-COST MICROMACHINING DEVELOPMENT AND APPLICATION FOR ENGINEERING AND TECHNOLOGY EDUCATION

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Low-Cost Micromachining Development and Application for Engineering and Technology Education

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Abstract
The goal of any undergraduate engineering or technical education program is to develop skill sets in students that allow them to be competitive in the job market; this is especially true for new emerging technologies. As companies find new modes to compete in the global market, they are always looking for a niche which will enable them to produce high quality products. Currently, there is a group of manufacturing companies in the Rockford, Illinois area that manufactures complex micro-machined parts with very tight tolerances and features. In order to move into this new micromachining area, the companies had to overcome two related issues. The first is how one can obtain low-cost, yet highly accurate micromachining equipment, and the second is finding skilled personnel to operate these new generation micro-machines. The purpose of this research was to develop a new generation of micro-machine which is financially accessible to these companies, develop a better understanding of this new paradigm in machining, and develop new student skills in this area.

In the marketplace, there are many companies which produce and sell micromachining equipment. This equipment takes two forms; either very high end, very precise equipment which typically sells for over $100,000 or hobby machines which are not as precise, but sell for about $20,000. For a company to engage in micro-part manufacturing, they must have the capacity and capital to purchase equipment for producing complex, high quality parts. Not many companies have the ability to purchase top of the line micro-machining equipment. To remedy this problem, this researched focused on the development of a unique low-cost micro milling machine which allows for high precision and ease of use. This paper reports on the development process and testing of this low-cost machine. In addition, the paper presents machinability data that will enable companies to select optimum cutting condition, thus reducing costs associated with tool breakages. Detailed educational experiences which were developed utilizing micromachining techniques are also presented. This work also details the educational work which has been developed for the program students.

Introduction

The increased need for miniaturization of parts has continued to play a major role in developing micro-manufacturing technologies. Micro-manufacturing focuses on technologies used to produce parts in the sub-millimeter range, and essentially bridges the gap between nano-scale manufacturing and macro-manufacturing. According to the World Technology Evaluation Center's (WTEC) commission report [1], micro-manufacturing has and will continue to have very significant impacts on national security, defense, energy, healthcare and domestic manufacturing base. Micro-parts are being utilized in the electronic and drive systems for small unmanned reconnaissance planes, for high precision parts used in missile guided systems, for medical devices to deliver medicines in tumors located in fragile internal organs, and many other significant applications.

There are many similarities and differences between macro- and micromachining. While the usage of solid modeling and computer-aided manufacturing (CAM) software is similar, the operations and tooling is vastly different. Current research on micro-machining has focused mainly on developing the actual machine tools. In the U.S., micro-machining centers have been developed successfully at several institutions, including the University of Illinois Urbana-Champaign [1, 2], at the Florida International University [3, 4], and Georgia Institute of Technology [5, 6]. Although these machines, and those developed elsewhere nationally and globally, have been proven to work, complete commercialization has not been realized due to several factors. Firstly, the existing machine tools cost in the region of $80,000 to $200,000, which is very inhibitive for most companies intending to enter into this lucrative business. Secondly, micromachining applications dictate high precision, often in the sub-micron range. Inspection for tolerance and tool condition in this regime requires the use of expensive optical equipment that would not be feasible to incorporate into a micro-machine tool for practical applications. Moreover, tool wear monitoring continues to be a challenging issue as there is no reported method that can be adapted to perform this task in a practical way. Most researchers [1, 3, 7] have found that in micro-machining, premature tool breakage is more is a common occurrence than tool wear. This has a significant influence on the resulting precision of the final product. In addition to tool condition, another factor that affects mach inability and precision is vibration. Vibration and chatter leads to poor surface finish. Increased vibration has been shown to increase chip load, thus significantly increasing cutting forces [2, 8]. In micro-machining, this may be a major cause for tool failure. Vibration modeling is essential to support chatter avoidance [8]. Research shows that with careful design of a rigid micro-machine, vibration can be predicted and isolation can be achieved [2, 8, 9]. However the influences of material properties at the micro-structure level, especially for steels, and cutting conditions are still uncertain and work continues to be done in these areas [2, 9, 10]. In addition to these factors, the mechanics of micro-cutting is still a relatively new area, not well understood. In micro-cutting, there is no formal explanation of scaling effects (also referred to as "size effects"), for example, in the relationship between material removal rate and the specific cutting energy [5]. Thus, there is a need for continued research in this area.

Through funding provided by the U.S. Army, TACOM, Northern Illinois University (NIU) engineering and technology researchers developed a new generation low cost machine tool. In the same project, studies were conducted to examine material removal rates for different types of cutting tools at various speeds, feeds and depths of cuts for different materials. Lastly, this paper also presents an educational perspective for training engineers in this new field of micromachining.

Development of a Low-Cost of Micro-machine

a) Hardware

CNC machining at the macro level has been in existence for many years. Much has been learned about the process in relation to cutting parameters for different materials and different types of operations. However, compared to macro-machining, less is known about micromachining. As manufacturing needs have changed, and as parts grow smaller, there has been a major shift in how machining is accomplished on a micro scale. While macro-machining uses large tooling to cut material, in micromachining the tools are much smaller and the cutting process operates on different mechanics; thus there must be an understanding of this process. In the micromachining realm, cutting accuracies are on the micron level, and thus vibration and rate of travel have a large effect on the accuracy produced. Figure 1 shows examples of parts produced in micromachining.

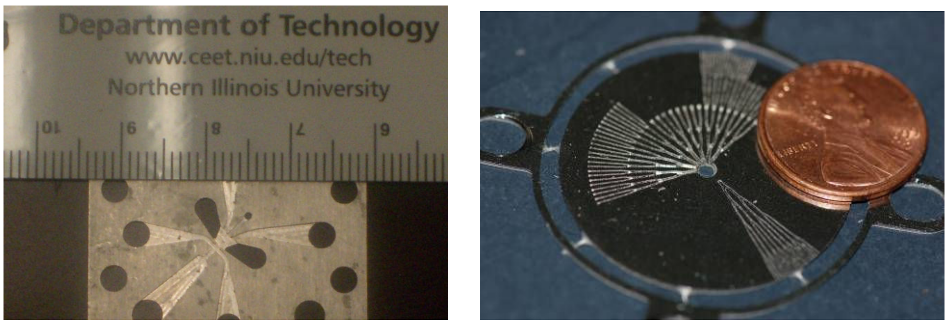

Figure 1 - Example of two micro-machined parts

Micromachining is not a new technology; it has been in existence for many years. However the technology is still being researched and many micromachining companies are still in a transition to commercialize the process. Typical micro-machines are priced from $80,000 to well in excess of $200,000, depending on the usage and accessories that are required. This high cost places the machines outside of the budgets of many schools, small companies, and R & D laboratories. In this project, NIU engineering and technology researchers were given the task of developing a new generation of low-cost micro-machine (LCMM) which would be affordable and yet provide the required accuracies. It should be noted that the design engineers were given a time frame of approximately four months to outline, research, design, and construct the first generation LCMM. Below are the constraints that were placed upon the initial design:

- Material Costs - $12,000
- Spindle speed – Between 10,000 - 100,000 rpm
- Accuracy – Between 0.001 inches – 0.0002 inches (25 microns - 5 microns)
- Work Area – 2 inch cube
- Open loop control – accurate without feedback
- Actuation – step motor/ lead screw drive
- Programming –G & M codes
- Tool Changer – 5 tool
- Number of Axes – 3 (x, y, and z)

The development of the first generation LCMM included the mechanical, electrical, and control aspects of the machine, as well as selecting the appropriate CAM software needed for solid modeling the operator interface. There were two aspects of the machine that were at the forefront of the development – cost and accuracy. Since the overriding consideration in the development was cost, all components, software, and assembly needs were optimized, and off-the-shelf components were used whenever possible. The consideration of accuracy was more difficult since it is a compilation of many different tolerances. The accuracies are dependent on spindle run-out, actuator and motor resolution, and controller software, as well as the manufacturing tolerances. With all of these factors taken into account, the first generation, low-cost, 3-axis, micro-machine was designed, constructed and assembled. It is presented in figure 2 below.

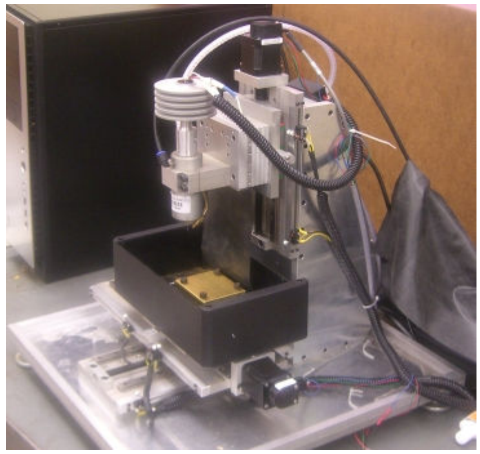

Figure 2 – Initial design of the low-cost micro machine

Feed in each of the three axes is achieved by a stepper motor and ACME lead screw combination. The lead screws are 0.25 inch (6.35 mm) diameter with a pitch of 0.05 inch (1.27 mm), utilizing an anti-backlash nut. The use of the anti-backlash nut is an important feature due to the vibrations that are encountered in the machine. The actuators have a rigid aluminum structure with roller bearing support, and thus provides the needed stability, as well as low friction motion. The stepper motors are NEMA 17 with micro-step ability, and Table 1 below shows the available accuracies for each step with and various lead screws. The stepper motor produces 6 oz-inches of torque which in hind site is more than enough to provide system motion.

Table 1 – Positional accuracy with motor/lead screw combination

		Accuracy per step							
		with 1/4 inch (6.35 mm) lead		with 1/8 inch (3.175 mm) lead		with 1/16 inch (1.5875 mm) lead		with 1/20 inch (1.27 mm) lead	
Microstep setting	Step increment (degrees)	inches	mm	inches	mm	inches	mm	inches	mm
Full	1.8	0.00125	0.03175	0.000625	0.015875	0.000313	0.007938	0.00025	0.00635
Half	0.9	0.000625	0.015875	0.000313	0.007938	0.000156	0.003969	0.000125	0.003175
1/4	0.45	0.0003125	0.007938	0.000156	0.003969	7.81E-05	0.001984	6.25E-05	0.001588
1/8	0.225	0.00015625	0.003969	7.81E-05	0.001984	3.91E-05	0.000992	3.13E-05	0.000794
1/16	0.112	7.7778E-05	0.001976	3.89E-05	0.000988	1.94E-05	0.000494	1.56E-05	0.000395
1/32	0.056	3.8889E-05	0.000988	1.94E-05	0.000494	9.72E-06	0.000247	7.78E-06	0.000198
1/64	0.028	1.9444E-05	0.000494	9.72E-06	0.000247	4.86E-06	0.000123	3.89E-06	9.88E-05
1/128	0.014	9.7222E-06	0.000247	4.86E-06	0.000123	2.43E-06	6.17E-05	1.94E-06	4.94E-05
1/256	0.007	4.8611E-06	0.000123	2.43E-06	6.17E-05	1.22E-06	3.09E-05	9.72E-07	2.47E-05

The low-cost machine has been set-up to use 1/4 stepping for a positional accuracy of 0.0000625 inches (about 1.5 microns). It should be noted that in all cases, the accuracy achieved is dependent on other considerations such as manufacture and assembly processes employed. In addition, spindle run-out is responsible for much of the inaccuracy. Typical spindles have inherent run-out in the several micron range, however, the accuracies are improving. The low-cost spindle which is being used (figure 3) in this application has a low run-out, approximately 0.00024 inches (about 8 microns).

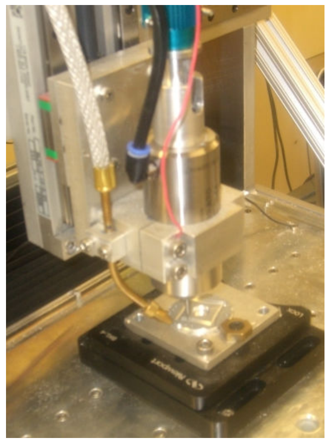
Figure 3 – Spindle in operation

b) CAM software

One of the initial design constraints developed for the LCMM was that of software and the human-machine interface (HMI). At the start, the machine was designed to utilize commercially available, low-cost CAM software that has the needed flexibility to produce three dimensional parts efficiently. Since the machine utilizes linear actuators on each of the three axes through stepping motors, the software needed the capability of providing control to each of these motors with the needed accuracy. It also needed to have the capability of micro-stepping the motors and have the ability to alter acceleration profiles. In addition, the CAM software which was used must allow the transformation of 3-D part geometry into common G and M codes. The software also needed to interface with popular CAD and solid modeling packages like AutoCAD, Solidworks, and Pro Engineer. Initially, MACH-3 was chosen as the control software, and the output was sent to a stepper motor driver controller. The results were very desirable at the start of testing, however, it was quickly learned that the Mach-3 driver was resident on the controlling computer. Since the computer was running the driver software and CAM software, the commands were not occurring in "real-time", and thus, there was a slight time lag due to the multiple computer processing needs. Figure 4A shows a complex precision part cut using the Mach-3 software and the resultant stair-stepping on the cutting surface. This issue was fixed through the implementation of Flash-cut control software. It is a "real-time" control software which is not run on the controlling computer. The Flash-cut is run on a separate micro processor, thus, the software does not exhibit any time lags, resulting in better accuracy. This is shown in figure 4B. The software also integrates with the motor controller, and is relatively cost

Figure 4A – Part cutting using Mach-3 software

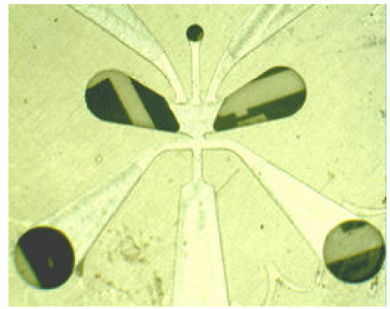

Figure 4B – Part cutting using Flash-cut software

effective. The use of Flash cut also allows for auxiliary programming to incorporate spindle motor speed control into the user interface screen. In addition, the use of the Flash-cut software allows some important parameters which greatly enhance the control and precision aspects of the machine developed. The new software and controller will allow an additional 4th axis to the system, importation of common CAD and solid modeling packages, digital inputs and outputs for limit/home switches and sensors. Figure 5 shows the user interface for the Flash-cut control software. In Figure 5, the operator can see the tool path, coordinates of the cutter, G-codes, spindle speed, as well as other controlling interface buttons.

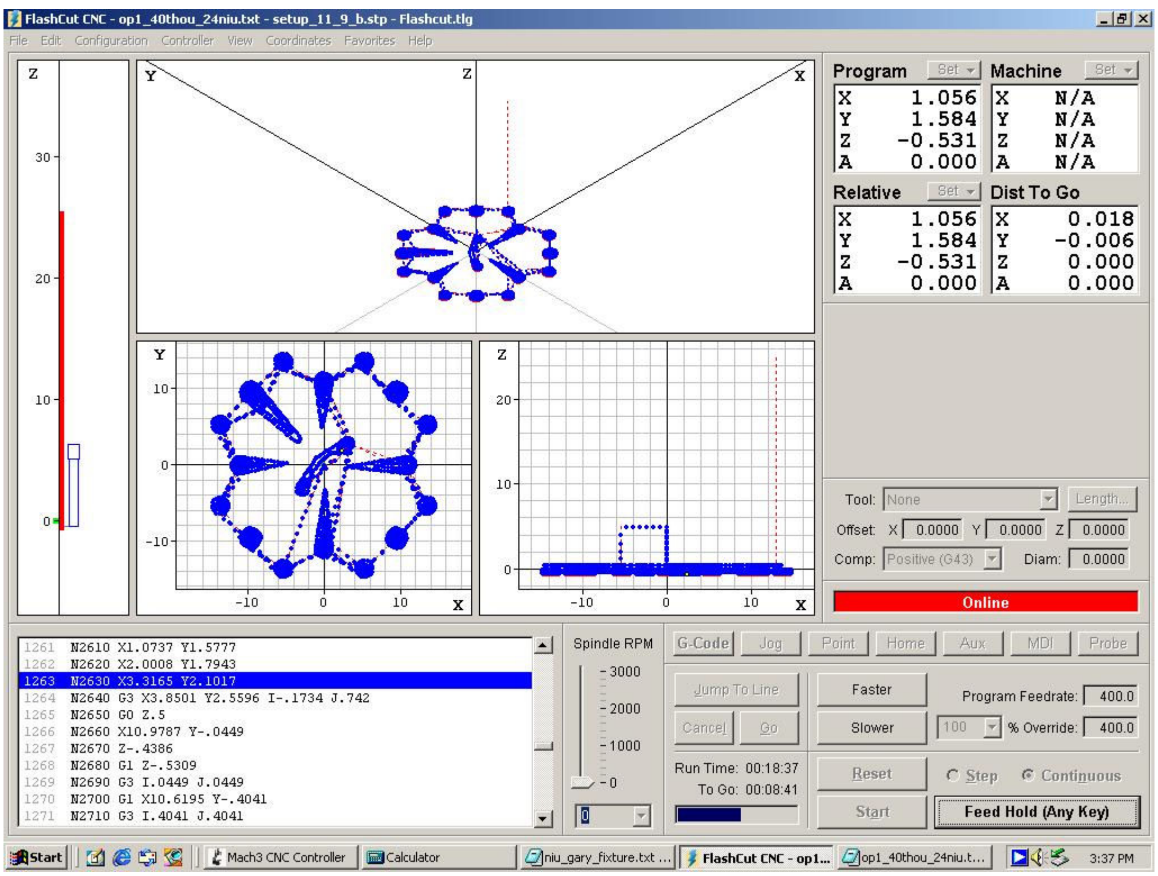

Figure 5 – Flash-cut User Control Interface

Based on a 4-month fast development time for this first-generation NIU low-cost micro-machine, the authors have developed a unique machine with many capabilities. With respect to the initial constraints, which were outlined, the authors have found that the final phase I machine has the following design values:

Final Results - Summary

- Component and material cost – $7000 (at present)
- Work envelop – 4 in x 4 in x 4 in - (100mm x 100mm x 100mm)
- Portability – Weighs less then 30lbs, with a 18in x 18 in x 18 in (450mm cube) outer envelop.
- 3-axis machining – 4th axis will be added in the near future
- Accuracy – about 0.00012 inches (3 micron)
- Components – all off the shelf, and the reliability has been proven through 1 year of testing and part production.
- Actuation – Stepper motor (NEMA 17)/ lead screw drive with a 0.05 inch (1.27mm) lead using ¼ stepping (0.225 deg/step)
- Spindle speed – 40,000 rpm maximum.
- Low spindle run-out – about 8 micron.
- Software – ability to import many different CAM files. Relatively easy for operator to learn use of software. Allows the use of limit, home, and part height sensors. Flash cut software will support many import file types.
- Open loop control – accurate without feedback
- Actuation – step motor/ lead screw drive
- Programming –G & M codes
- Tool Changer – 5 tool

In general, the design team met or exceeded all of the initial design parameters.

Undergraduate Student involvement

During the 2-year development phase of the NIU low-cost micro-machine, many undergraduate students were involved in the design, construction, testing, and modification. At all time, there was one manufacturing and one electrical engineering technology student working with the authors on this project. Students were involved in all aspects of the projects, as well as developing final cut parts for testing. At the outset, students were involved in developing control algorithms for spindle and traverse motors, as well as user interface. Since the goal of this project was to develop a machining center which was capable of near micron parts, part and machine accuracy was an area which needed to be enhanced. Using metrology techniques, the students, working with the faculty members, developed methods of measurement and providing accuracy for the machine and parts that were cut.

Technology-Based Micromachining Curriculum

This low-cost micro-machine was developed for use in the classroom, where many institutions could not afford a high priced machine. In order to instruct students on the operation of this new realm or machining, a new micromachining course had to be developed. This course is a lab/lecture course which utilizes a hybrid laboratory component; both on-line and live. The following laboratory modules have been developed for this course.

Module 1 – Introductions to Mechanical Micromachining
Introduction to mechanical, physical, chemical properties, machinabilities, and typical applications of materials in mechanical micromachining, including metals, polymers, ceramics, and glasses. Students are made aware that materials used in micromachining are required to be free of inclusions typically found in castings and forgings used in conventional machining. It also reveals the similarities and differences between mechanical micromachining and conventional machining, including the effects of tool edge radius along the cutting edge in mechanical micromachining, in which the chip thickness becomes a comparable size to the cutting edge radius. Small chip load as compared to the cutting edge radius, the size effect, and the ploughing forces are also covered as significant characteristics in mechanical micromachining. [1]

Module 2 - Process Parameters in Mechanical Micromachining
The major object of a machining process is to maximize metal removal rate while maintaining good surface finish, long tool lives and lower power consumption by minimizing cutting forces. Whether it is turning or milling, or any other machining process, the proper choice of machining parameters is essential. This module introduces important parameters including cutting speed, feed, and depth of cut within the context of micromachining, and their critical impacts on the surface finish and integrity, tool lives, energy efficiency, and process stability. Tooling used in mechanical micromachining is much more costly than conventional machining, thus, preventing tool wear and breakage is critical in mechanical micromachining. Students are shown how to select correct process parameters for different tool-process-material combinations.

Module 3 - Tooling for Mechanical Micromachining
It is important in machining to ensure long tool life for good dimensional tolerance. Proper tool selection is therefore a key component of mechanical micromachining. This module emphasizes milling as the most common process in micromachining, and the most commonly available end mills. In addition, micro drills are also be covered in this module as a most-frequently used process in mechanical micromachining. Tools in micromachining that are commercially available are introduced, including tungsten-carbide micro end mills starting at 25 µm in diameter, and examples of their applications in fabrication of micro- molds and dies from tool steels for injection molding and micro-forming processes. [2,3,4]

Module 4 - Inspection in Mechanical Micromachining
Inspection of parts for dimensional integrity and quality control in micromachining is covered in this module, including optical and high-magnification microscopes, scanning electron microscopes, and tunneling electron microscopes. Students are introduced to basic metrology methods for inspection involving high magnification microscopes.

Module 5 - Interfacing with CAM Software and Understanding of NC codes
Students going into the micromachining professions need to have an in depth understanding of the GUI interface used by the CAM system. This module develops a knowledge base for using a low cost CAM interface, such as flash cut and micro mill, which will provide the students with a starting platform for use of the mechanical micro-machine-tools. Students learn to manually move the three axes, utilize the spindle controller as well as other inputs needed to control the system, and import part file format from any compatible software and start the cutting process. Students are instructed on spindle speed control, part programming and understanding of G codes, which is fundamental in developing CAM part files for the machines, and the modification of these codes to given parameters associated with the mechanical micromachining environment.

Module 6 – Maintenance Mechanical Micro-machine-Tools

Unlike conventional CNC machining centers, the new generation of mechanical micromachining centers will need different care and maintenance. This module introduces maintenance technologies specific to micromachining, as the process does not create conventional chips that a larger machine would. Techniques are introduced to handle the slurry of the removed material as a fine paste that gets into many areas of the machine. This section introduces students to general maintenance and protection procedures of micromachining centers by materials and by products of the cutting operation. Students learn about the fundamentals of electromechanical mechanisms, including those of the stepper motors and limit switches that are basic components of the mechanical micromachining centers.

Feed-Rate and Spindle Speed Research Summary for Micromachining

One of the goals of this research is to complement studies in micromachining by developing methods to determine desirable machining conditions and reliable techniques for process control. This project also aims to enhance knowledge for micro-machining processes that will enable the development of next-generation micro-machine tools. Some preliminary cutting tests have been performed to determine feasible cutting conditions for stainless steel 316L. Examples of cutting force measurements at 30,000 rpm spindle speed with a 0.2mm diameter cutting tool are shown in figure 6 below. Preliminary analyses also indicate high levels of burring at the selected cutting conditions, as shown in the high magnification image below (figure 7).

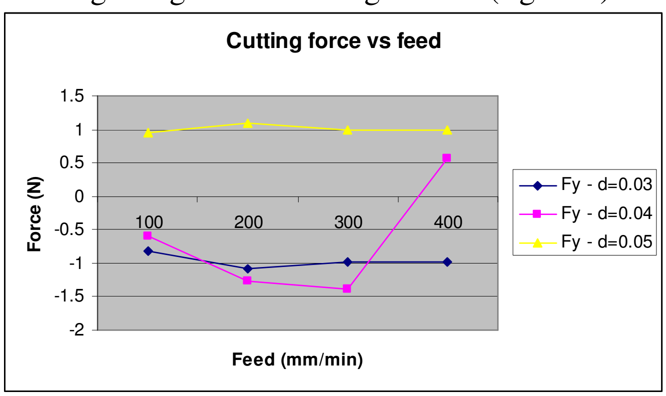

Figure 6. Cutting forces on a 0.02 in diameter cutter at 30,000 rpm

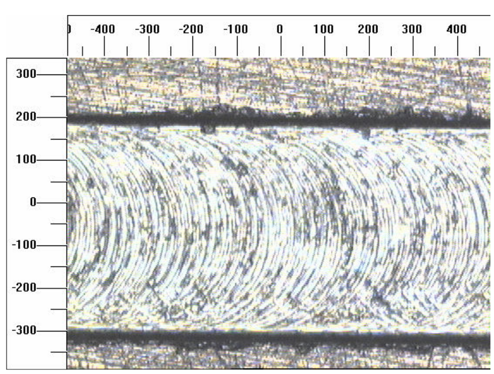

Figure 7. Burring of the sample for a 0.02 in diameter endmill at 30,000 rpm.

The preliminary results indicate that sensitivity of cutting force with depth of cut is more significant than with feed. It should be noted that the feeds chosen were based on the maximum available for the micromachine. The maximum achievable depths of cut for a 0.02 and a 0.01 inch diameter tool 50 and 25 microns (2 and 1 microinches) respectively when machining cold rolled 316 L stainless steel. It should be noted that more work is under progress the study tool lives and the machinability of other materials.

Conclusions

A low cost micro-machine (LCMM) has been successfully developed and built. Tests on this machine have indicated high levels of accuracy can still be maintained without closed loop control. The majority of the components used to build this machine are off-the-shelf components that are inexpensive and easy to install. The CAM software is easy to learn and use, and provides a very straight forward GUI. A proposed micromachining curriculum has been presented. This, together with the LCMM, offers a very affordable laboratory based curriculum to train engineers in this new area of manufacturing. Preliminary machinability studies have been carried out to determine optimum cutting conditions for stainless steel on this micro-machine. More testing is being done to generate machining data for different materials and cutting conditions.

Acknowledgement

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