AC 2007-528: IMPLEMENTING MACHINING OF FIBER REINFORCED POLYMER COMPOSITES TO MANUFACTURING COURSES IN 2 YEAR AND 4 YEAR PROGRAMS

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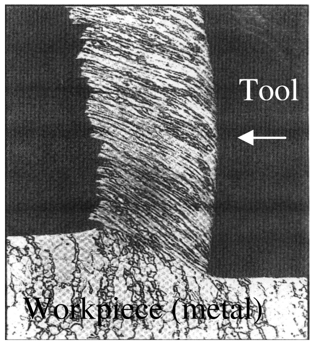
Abstract

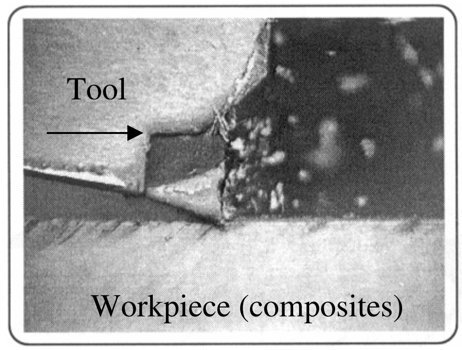
Fiber reinforced polymer (FRP) composites offer very high strength-to-weight and stiffness-to-weight ratios. As a result, the aerospace industry is making a major effort to incorporate an increasing number of composite materials into various components and structures. However, machining of FRP composites is one of the most difficult and least understood areas in manufacturing technology. Thus, it is necessary to include machining and tool regimes of FRP composites into manufacturing curricula, especially at schools in regions of the country where significant aerospace industry exist. This new topic has been applied into various programs such as Machine Manufacturing Technology Program at Portland Community College (PCC) and Mechanical Engineering Program at Washington State University Vancouver (WSUV). This report focuses on all aspects of these newly developed course materials including course content and student feedback.

1. Introduction

Fiber reinforced polymer (FRP) composites are a class of material that offer numerous advantages over monolithic metals and other homogeneous materials. Due to their greater strength-to-weight ratio, the composites are widely used in various structures and components. The aerospace industry is making a major effort to incorporate an increasing number of composite materials into various components and structures. For example, a recently developed commercial airplane will be 80% composites by volume [1]. Because the aerospace industry is a significant employer served regions of the country, there is a strong demand that education should cover net shape manufacturing of FRP composites in the curriculum, particularly in those regions.

Most manufacturing processes courses deal with metal machining only. Teaching the machining of only metallic materials doesn't fulfill the needs of the current aerospace workforce. Because the FRP composites exhibit different machining characteristics than common metal alloys normally encountered in manufacturing. They respond differently to conventional machining processes and greatly reduce the useful life of standard cutting tools due to their abrasive nature. Figure 1 shows the chip formation differences between metal alloys and FRP composites. In the metal cutting process, a continuous plastic deformation occurs with a high strain rate under the compressive stress exerted by a wedge-shaped cutting tool. The workpiece material is formed into a chip by a shearing process in the primary shear zone. The chip slides up the rake face undergoing some secondary plastic flow due to the forces of friction. As shown in Figure 1 (b), the chip formations of FRP composites are totally different from those in metal cutting. Machining of FRP composites involves shearing and cracking of matrix material, brittle fracture across the fiber, fiber pull-out and fiber-matrix debonding (by tensile fracture), and delamination prior to final fracture both in the chip and below the cutting plane depending on the fiber orientation. The chips are mostly dust type and severe tool wear can be found in FRP composite cutting.





(a) metal chip formation (b) FRP composite chip formation

Figure 1. Chip formation in metal and FRP composite cutting [2, 3]

This paper presents how this new topic has been applied in three schools in the Pacific Northwest. The experiences in the Machine Manufacturing Technology Program at Portland Community College (PCC) and Mechanical Engineering Program at Washington State University Vancouver (WSUV) will be given. All aspects of these newly developed course materials including course content and student feedback will be presented.

2. Machine Manufacturing Technology (MMT) Program

2.1 MMT Program Overview

The manufacturing industry in the metropolitan area has experienced a steady growth, which created a tremendous demand for skilled manufacturing workers. It is the belief of the MMT department that the traditional term length structured program no longer meets the needs of the manufacturing industry and its workforce. At Portland Community College (PCC) of Portland Oregon the MMT Program is a cooperative effort specifically developed as OEOE with local key employers, local economic development committee and Machine Technology Staff. The MMT Program is designed to develop skills in reading technical language, shop mathematics, blueprint reading, metallurgy, machining processes, precision layout and measurement, organization, communication, teamwork, and programming and operating CNC equipment.

2.2 The Cutting Tool Technology (MCH240) Course

At PCC, this material has been taught in the Cutting Tool Technology (MCH 240) course, which is a sophomore class. The process conditions and tool performances were emphasized in conventional machining, CNC laser machining and superabrasives grinding of FRP composites. This is a preparatory course designed to introduce the student to the proper setups, uses and operations associated with industry standard types of cutting tools. Table 1 shows the student outcomes and skill sets for the course modules.

Table 1. The module titles, contents, and student outcomes and skill sets for MCH 240.

Module Title	Module Contents	Student outcomes and skills
Module 1 - Cutting Fluids	The student will be introduced to why Cutting Fluids are essential in metal cutting operations to reduce the heat and friction created by the plastic deformation of metal and the chip sliding along the chip-tool interface.	The student will state the importance and function of cutting fluids; identify three types of cutting fluids and state the purpose of each; apply cutting fluids efficiently for a variety of machining operations.
Module 2 - Cutting Tools	The student will be introduced to why one of the most important components in the machining process is the cutting tool, the performance of which will determine the efficiency of the operation. The student will learn the importance of selecting the proper cutting tool material and cutting tool angles required to machine a work piece.	The student will name the nomenclature of a cutting tool point; explain the purpose of each type of rake and clearance angle; identify the applications of various types of cutting tool materials; describe the cutting action of different types of machines.
Module 3 - Operating Conditions & Tool Life	The student will be introduced to why the optimization of the operating conditions of the cutting tool effect the quality, accuracy, efficiency and productivity of the work piece produced.	The student will describe the effect of cutting conditions on cutting tool life; explain the effect of cutting conditions on metal removal rates (MRR); state the advantages of new cutting tool materials; calculate the economic performance and cost analysis for a machining operation.
Module 4 - Carbide Cutting Tools	The student will be introduced to why cemented carbide tools have good wear resistance and can operate efficiently at cutting speeds ranging from 150 to 1200 SFM (46 to 366 m/min).	The student will identify and state the purpose of the two main types of carbide grades; select the proper grade of carbide for various work piece materials; select the proper speeds and feeds for carbide tools.
Module 5 - Diamond, Ceramic, and Cermet	The student will be introduced to the advantages, limitations, and applications of diamond, ceramic and cermet cutting	The student will explain the purpose and application of diamond cutting tools; state the two types of ceramic cutting tools; describe the types and

Cutting Tools	tools.	applications of cermet cutting tools.
Module 6 - Polycrystalline Cutting Tools	The student will be introduced to how Polycrystalline, Polycrystalline Diamond (PCD) and Polycrystalline Cubic Boron Nitride (PCBN) cutting tools are manufactured. The student will study why these cutting tools possess increased abrasive resistance, wear resistance, thermal conductivity, and compressive strength, and how these properties ultimately increase machining productivity.	The student will explain the; manufacturer and properties of polycrystalline tools; select the proper type and size of polycrystalline cutting tools; and setup a tool and machine for cutting metallic and FRP composite materials with polycrystalline tools.

The resources used in the course are the followings:

Textbooks:
- “Superabrasives - Grinding and Machining”, by Krar & Ratterman, published by McGraw Hill, 1990
- “Exploring Advanced Manufacturing Technologies”, by Krar, Gill et. al., published by Industrial Press, ISBN 0-8311-3150-0
- “An Introduction to Composite Materials, by Derek Hull, published by Cambridge University press, ISBN 0-521-23991
- Machining of Composite Materials – Conference Proceedings, edited by Srivatsan & Bowden, published by American Society of Materials (ASM), ISBN 0-87170-459-5
- “Machinery's Handbook” by Oberg, published by Industrial Press, 27th Edition, ISBN: 0831127996

Videos:
- “Technology Shaping Tomorrow” by General Electric
- “Industry Cutting Edge” by General Electric
- “Metal Working with Compax & BZN Blanks” by General Electric
- “Man Made Diamond” by General Electric
- “ Tooling for Composites” from the SME Manufacturing Insights Series
- “Cutting Tool Materials” from the SME Fundamentals of Manufacturing Series
- “Cutting Tool Geometries” from the SME Fundamentals of Manufacturing Series

2.3 FRP Composite Machining Matter Details

The productivity gap between the United States and offshore industries is forcing U.S. manufacturers to produce better quality products at competitive prices. In order to be competitive in the world marketplace, U.S. manufacturers must use all of the new technologies available to increase productivity and gain market share on a global scale. While the cost of a tool only represents about 5 to 10% of the cost to produce a part, it is not the initial cost of the tool that is important, but the results or productivity that a tool offers. Superabrasives such as diamonds, PCD, CBN, etc. offer good results in FRP composite machining. Diamond is used to cut and grind hard, abrasive non-ferrous, non-metallic, and composite materials. CBN is used to cut and grind hard, abrasive ferrous materials. Four important characteristics of superabrasives were given to the students. The following information were handed out during the modules 5 and 6.

Four important characteristics of superabrasives:

i. Hardness - The harder the abrasive with respect to the workpiece, the more easily it can cut and remove material. The basic principle in material removal is that the cutter is harder than the material being removed. Hardness of the cutter with respect to the material allows higher cutting speeds and greater feeds to decrease the amount of time required to complete the work cycle.

- Diamond is four times harder than Silicon carbide and is used on non-ferrous materials.
- Cubic Boron Nitride (CBN) is two and one half times harder than Aluminum oxide and is used on ferrous materials.
- Due to the higher hardness, superabrasive tools last longer.

ii. Abrasion Resistance - Resistance to abrasive wear is a desirable property in a cutting tool as it allows an increase in productivity by maintaining a sharp cutting edge longer and it allows increased cutting speeds and feeds to decrease the time required to complete the work cycle and lessen the time required to maintain the cutting tool.

- Diamond has three times the abrasive resistance of Silicon carbide.
- CBN has about four times the abrasive resistance of Aluminum oxide.

iii. Compressive Strength - The physics of metal removal consists of high pressures created in the shear zone as a result of the materials resistance to rupture. These forces are transferred to the cutting tool at the chip tool interface. Resistance to compressive pressure allows the material to fracture, thus producing a chip of material removed. Compressive strength of a material is a linear relationship to its density; the higher the density, the higher the compressive strength.

- Diamond is eighteen times greater than Silicon carbide.
- CBN is about two and one half times greater than Aluminum oxide.
- Superabrasives can withstand forces of interrupted cuts and high material removal rates.

iv. Thermal Conductivity - The majority (2/3) of the heat produced in a material removal process takes place in the shear zone. The shear zone consists of the shear plane (a function of heat, depth of cut, and density of the material) and the shear angle. As the shear angle decreases, due to heat, the length of the shear plane increases, producing more heat. The source of the heat produced in the shear zone is due to the plastic deformation of the molecular structure of the material prior to rupture. The source of the other 1/3 of the heat produced is a result of friction as the chip produced slides over the tool. This is known as the chip/tool interface. High thermal conductivity is a desirable property in a cutting tool as it allows the heat to be dissipated quicker. By dissipating the heat through the cutting tool, friction is decreased at the chip/tool interface increasing the shear angle and decreasing the length of the shear plane, reducing the heat being generated by the plastic deformation of the molecular structure of the material being cut.

- Diamond has 27 times the thermal conductivity of Silicon carbide.
- CBN has fifty five times the thermal conductivity of Aluminum oxide.
- The superior qualities of Diamond and CBN allow cutting tools to stay sharp longer and allow free cutting at high temperatures and cutting speeds.
- Diamond and CBN increase productivity while producing dimensionally accurate parts.

The shop application guidelines were introduced to the students.

Milling

Cutting Tools GE 1500 Compax; this type of PCD uses a metallic catalyst to aid in the sintering of the 25 to 40 µm diamond crystals. Tool inserts are fabricated by brazing a single PCD cutting edge to a tungsten carbide body. The particular combination of properties of PCD makes it uniquely suited to machining composites. The machine tool should be capable of 8000 RPM, and feed of up to 4064 mm/min (160 in/min). The end mill body should accommodate standard triangular inserts (TPG-322) such as ISCAR IEM125 W1, with an axial rake of 0^0 to $+5^0$ and lead angle of 0^0.

Recommended starting parameters
Milling Mode: Conventional or CNC
Cutting Speed: 762 m/min (2475 FT./MIN.)
Feed Rate: 0.508 mm/tooth (0.200"/tooth)
Radial Depth: 0.76 mm (.030")
Insert Type: TPG-322 (Compax 1500)
Tool Geometry
Axial rake: $+5^0$
Radial Rake: 0^0
Lead Angle: 0^0

Drilling

Drilling represents one of the most important machining operations which are currently carried out on composites. Delamination generally represents the main concern when drilling composites, because of the lowering of fatigue strength as well as a poor assembly tolerance. Thrust force has been widely cited by various authors as being responsible for delamination. Konig et al [4,5] reported the values at which delamination occurred in the case of Glass Fibre Reinforced Plastics (GFRP's). Only a few works deal with modeling this phenomenon.

Various twist drill geometries have been tested for the drilling of composite materials. Among them, 8-facet split point and Jodrill with 30^o helix gave the best results in the ranges 400-20000 RPM and 0.025-0.05 mm/rev. (.001 to .002 in/rev) for the spindle speed and for the feed rate respectively the 8-facit split point appears to achieve its success by combining the free cutting characteristics of split point and a longer taper angle at the shoulder which tends to minimize fibre break out. The Jodrill point reaches the same result using a slight step instead of a taper at the drill shoulder. Polycrystalline Diamond (PCD) allows a marked increase in tool life.

Turning

Glass reinforced plastics (GRFP) have been machined using high speed steel tools with rake angles in the range of -20^o to +30^o and cutting speeds from 10 to 350 m/min and feed rates of 0.05 to 0.35 mm/rev.

3. Mechanical Engineering Undergraduate Program at WSUV

3.1 Advanced Manufacturing Engineering Course (Mech476) Overview

Washington State University Vancouver (WSUV) is located in the Vancouver/Portland Oregon metropolitan area where there is a significant presence of high tech industry and a spectrum of more traditional industries. At WSUV, this subject has been taught in a senior course, Mech476 Advanced Manufacturing Engineering, which deals with advanced manufacturing processes and systems, including interrelationships between the properties of the material, modern manufacturing systems, the manufacturing process and the design of components. Mech476 has been offered for 2 terms so far during the fall semesters of 2004-05 and 2005-06 academic years and will be offered in the fall semester of 2007. Since this course was offered in 2005, traditional/nontraditional machining processes for FRP composites have been covered in a series of three lectures. The goal of these lectures is to enable the students to identify the appropriate machining technique to shape FRP composites and understand the science behind the processes. Prior to these lectures, the students took classes and lectures on the subjects related to composite machining. In their junior year, Engineering Materials and Introduction to Design and Manufacturing were offered. So, the students already were familiar with composite materials, traditional machining processes, and non-traditional machining processes before taking Mech476. Mech476 course outline is following:

1. Metrology/Geometric Dimensional and Tolerancing
2 Assembly processes/Fixture design
3. Powder metallurgy/Ceramic processing
4. Polymer processing
5. Composite processing

6. Composite machining
7. Rapid prototyping processes
8. Semiconductor manufacturing/Nanomanufacturing
9. Lean Manufacturing/Value Stream Mapping
10. Quality improvement tools/Kaizen Practices

3.2 FRP Composite Machining Classes in Mech476

Prior to taking composite machining classes, the students had chances learning polymer processing and composite processing. Therefore, the students are required to synthesize the subject matter from their prerequisite engineering courses in order to best determine the means to net shape FRP composites. Table 2 shows the topics and student learning outcomes for FRP composite machining lectures.

Table 2. Topics and student learning outcomes for FRP composite machining lectures in Mech476.

Lecture	Topics	Student learning outcomes
1	• Fundamentals of FRP composites • Rule of mixtures • FRP composite fabrication	• Classify different types of composite materials to define FRP composite materials. • Use the rule of mixtures to estimate mechanical properties of unidirectional FRP composites. • Describe various FRP composite fabrication processes.
2	• Drilling of FRP composites • Machinability of FRP composites	• Describe the characteristics/challenges in drilling of FRP composites. • Evaluate the suitability of the conventional drilling for a given application based on technical requirements.
3	• Non-traditional machining of FRP composites	• Describe the characteristics/challenges in waterjet cutting of FRP composites. • Evaluate the suitability of the non-traditional machining for a given application based on technical requirements.

The textbook of Mech476 was *Introduction to Manufacturing Processes* written by John A. Schey[2]. This book doesn't cover machining of FRP composites. Therefore, lecture notes were provided to the students. Powerpoint lecture notes can provide summaries of the topics covered on the lectures. Lecture materials were based on the author's research publications and other references [6-9]. Unfortunately, these notes could not bring "real reading materials" to the students. So students searched the webs or other references to complete their assignments. During the lectures, the students had a chance to look at some FRP composite samples and machined workpieces. The students showed great interest and asked many questions when they look at the samples. Information regarding how effective each course topic was learned by the students was collected by recorded performance on homework assignment and test questions. Three lectures were a part of the whole course so it was not possible to use students' comments in the course evaluation. There were two homework assignments and two exam questions associated with FRP composite machining. The students' performance on assignments and tests showed that the students learned the subjects well. Average homework assignment scores were 8 out of 10. Test scores were 15 out of 20. Not very high scores were found in the assignment and exams. This may be due to lack of real reading materials for the students in these topics. The assignment and exam scores of students do not constitute assessment of new curriculum content. Better assessment tools should be implanted into the course.

There is a room for improvement in the FRP composite machining lectures. First, the Powerpoint notes were not enough for the students who want to learn the subjects in depth. The instructor should prepare some reading materials so the students can explore the subjects further with reading. Second, demonstration or hands-on laboratory of FRP machining processes would give the students better insight on the subject. Third, a new course assessment can be taken to allow the students to make comments on specific course topics.

4. Summary

Machining of FRP composites is one of the most difficult and least understood areas in manufacturing technology. Thus, it is necessary to include machining and tool regimes of FRP composites into the manufacturing curricula, especially at the schools in the regions of the country where major aerospace industry exist. The Machine Manufacturing Program at Portland Community College offers the machine tool course with FRP composite machining modules. Superabrasives are introduced to the students and proper FRP composite machining technique in milling, drilling, and turning are given to the students. The Mechanical Engineering Program at Washington State University Vancouver provides FRP composite machining classes in a senior level course. Drilling and machinability of FRP composites are introduced to the students and non-traditional machining such as waterjet machining is covered during the FRP composite machining lectures.

5. Reference

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