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Combined Research and Curriculum Development: Nontraditional Manufacturing

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Abstract

Nontraditional manufacturing (NTM) involves nontraditional transport phenomena and often nontraditional media. Thermally based energy transfer is the main material removal mechanism for several nontraditional machining processes including electrical discharge machining (EDM) and laser machining (LM). Thermal phenomena are also central in processes such as laser forming and direct metal deposition. Substantial progress in research and development has been made in recent years. It is important to develop up-to-date pedagogic materials to help students and working engineers understand the processes and the phenomena in NTM processes. This presentation reports a collaborative effort in a web-based development supported by NSF Division of Engineering Education and Centers (EEC). The features of the development include incorporation of recent research results, web implementation with interactive capabilities, and systematic introduction. Areas of focus include EDM/ECM, LM, and abrasive water jet machining. Cross process innovation and general philosophy in NTM research are presented and needs for further pedagogic development are discussed.

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1. Introduction

NTM (Non Traditional Manufacturing) processes can be broadly categorized according to: (1) processes in which there is a nontraditional mechanism of interaction between the tool and the workpiece, and (2) processes in which nontraditional media are used to effect the transfer of energy from the tool to the workpiece. In contrast, traditional machining relies on direct mechanical contact between the tool and workpiece, which often cause undesired changes in the properties of workpiece, such as residual mechanical and thermal stresses [1].

Rising production costs dictates that production operations be automated whenever possible; innovative materials such as super-alloys, composites, ceramics and many other advanced materials, which are difficult to or cannot be processed by traditional machining methods, require new manufacturing technologies; environmental considerations require the development of environmentally conscious processes. NTM processes are often well suited to be monitored and controlled, and the processing steps can be reduced while the precision remains high. These are the impetuses for nontraditional manufacturing. In many cases, traditional manufacturing may have reached their capability limits, while NTM are offering the best resolution.

Thermally based energy transfer is the main material removal mechanism for several nontraditional machining processes including electrical discharge machining, laser machining, electron beam machining, plasma arc cutting etc. Thermal phenomena are also central in processes such as laser forming and welding based direct metal deposition. In processes such as electrochemical machining, thermal field can strongly influence the chemical reaction rate. Despite the high intensity thermal field involved, many nontraditional machining processes have good control of the thermal effects during machining. For example, laser energy can be precisely controlled to produce high machining quality with a very narrow heat affected zone. Waterjet machining and electrochemical machining are inherently less liable to induce thermal damages to the target material. Thermal effects can be useful in some cases. For example, conventional machining can be extended to the machining of ceramics with the assistance of plasma or laser beam [2].

Recently, three universities in USA, including Columbia University, University of Nebraska-Lincoln, and Southern Methodist University jointly carried out the NSF funded project: Combined Research and Curriculum Development of Nontraditional Manufacturing [3]. The project focused on nontraditional material removal or machining processes such as electrical discharge and electrochemical machining (EDM/ECM), laser machining processes (LMP) and abrasive waterjet machining (AWJM), among others. Substantial research progress has been made in recent years especially in the areas of process innovation, modeling, simulation, monitoring and control. NTM processes are diverse and multi-disciplinary, and the role of NTM is becoming increasingly important in engineering. Instead of introducing one process after another, new methodology should be founded to study and educate NTM systematically. Education of NTM at the introductory level has been appropriate. Innovations and more orchestrated efforts, however, are needed at the upper level undergraduate and introductory graduate (ULUIG) curricula. The objectives of this project are:

- To develop methodologies and educational materials to incorporate recent research results in NTM processes and systems into ULUIG level curricula
- To prepare a new generation of engineers with analytic background knowledge and process design/optimization skills by using modern tools
- To establish a national model of effective and efficient learning of multi-disciplinary subjects.

In this paper, the features of the NTM project will be presented, namely systematic introduction, incorporation of recent research results and web based and interactive tutorial. Finally the process innovation and the future directions of NTM research and education will be discussed.

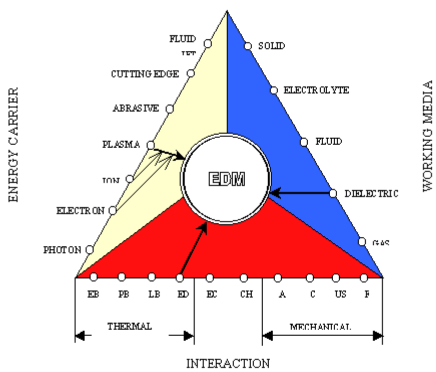
2. Systematic Introduction of NTM

2.1 Revealing the Common Features of NTM and Focus on Energy-material Interaction

During this project, we were impelled to think in depth not only the technical aspects, but also the philosophy and methodology behind traditional manufacturing and nontraditional manufacturing. One feeling of prior material on NTM study and education is that individual processes are discussed without much correlation. In fact, nontraditional processes have many common features. The approach of introducing one process after another without discussing their common features may impede possible process innovations and cross process integration. Efforts are spent to reveal the common features behind manufacturing processes and the focus is on energy-material interaction.

Having a clear overall image is important when trying to exploit various energy fields in NTM. The general philosophy of NTM study is presented in Chapter 1 of Laser Machining Processes module. The Four Attributes (Temporal, Spatial, Frequency and Amplitude) Analysis of energy field is illustrated using laser machining as an example. Following similar approaches, the reader can have a good understanding of the major process parameters of any specific process. Further discussion on process analysis and innovations are presented in Section 1 and 2 of the Cross Process Innovations module. General issues in micromachining are discussed in two sections of Micro-EDM in the EDM module. Surface integrity in NTM and conventional manufacturing are discussed in detail in EDM module. These general discussions apply to many NTM processes and help broaden the views of readers, but are rare in prior curriculum materials. Further effort should be made in the future to develop a more systematic philosophy in NTM study.

A machining process, and more broadly, any manufacturing process, can be presented by the "process conditions scheme"(PCS), which is the diagram of condition features of machining and its conjugate (Fig. 1). The base side of the conditions triangle represents the kind of *interactions* such as *Thermal* (electron beam *EB*, plasma beam *PB*, laser beam *LB* and electrical discharges *ED*), *Electrochemical EC* and *chemical CH, and Mechanical*. Note that *A* denotes grinding and abrasive flow, *C* cutting (turning, milling, drilling etc), *US* ultrasonic wave, and *F* flow fluid action (high pressure water jet, low pressure suspension jet etc.). The left side of the triangle represents the set of energy carriers: Photons, Electrons, Ions, Plasma, Abrasives i.e. random oriented cutting particles, Cutting edges, and Fluid jet. The right side of the triangle consists of types of working media: Solid particles, Electrolyte, Fluid, Dielectric, and Gas [4].



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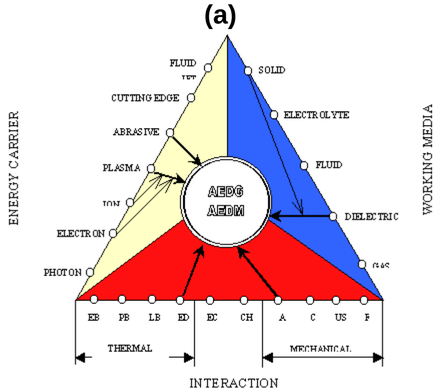


(b)

Fig. 1. Process Conditions Scheme (PCS) for (a) Electrical Discharge Machining (EDM), and (b) Abrasive Electrical Discharge Machining/ Grinding (AEDM/AEDG)

There are so many new processes nowadays, even an experienced engineer may feel lost, let alone the college students. Using the process conditions scheme, the correlation and possible integration of different processes are more straightforward than directly going into the details of individual processes. For example, in Electrical Discharge Machining (EDM) the main interaction is thermal by electrical discharges (***ED***), which leads to material removal by melting and evaporation (Fig. 1a). Dielectric is used as the working medium and energy is delivered to the workpiece and electrode by ions and electrons within the plasma channel during discharge in the dielectric media. Normal EDM process produce a layer of material with altered properties, such as recast layer and heat-affected zone. These layers should be removed in stress and fatigue critical applications. Application of powder-mixed working media allows AEDM to obtain mirror finishing of complex shape and more uniform and crackless affected layer. Therefore, AEDM produces a die without the need of removing the affected layer. Fig. 1b illustrate the process analysis of abrasive EDM and EDG. The main thermal interaction (bold line) is assisted by abrasion-mechanical interaction, and energy is carried by plasma and by abrasive grains. Working media consists both dielectric and solid particles.

Fig. 2. Web based systematic introduction of NTM

2.2 Complete and Leveled Coverage of Representative NTM Processes

Using the strength of three universities, as shown in Fig. 2, curriculum material of representative NTM processes including laser machining (LM), abrasive waterjet machining (AWJM), electrical discharge machining (EDM) and electrochemical machining (ECM), are put together on the web, along with the module of cross process innovations and NTM Animation Examples.

In each module, the content is focused on material and energy field interaction. The evolvement of the process, the material removal mechanism, the equipment and process parameters are covered. Process control and optimization are also important parts in each process. Great efforts are put into the analysis and modeling of the processes, and into the incorporation of recent research results. The project also tried to draw closer the gap between research and practical production. This is realized by the thorough discussion of practical problems and by including the rule of thumb data, tables and figures. Rich reference material can be found for each topic.

The complete coverage of NTM processes may be overwhelming for undergraduate students and process engineers. To serve the needs of wider readers, the contents are divided into different levels or reasonable sequences.

For example, in Laser Machining Processes module, it is presented in terms of three broad topics: Energy, System and Material. Each topic is presented in three levels: Introductory, Intermediate and Advanced, to suit different needs. The Introduction level includes the most basic phenomena, mechanisms and theories. Qualitative description is emphasized and simple quantitative relations may be included. The purpose is to give an overall basic understanding of LMP. Introductory level is for beginners or those who just want to get a general and basic understanding of the laser machining process. The contents are featured as descriptive and qualitative, mathematics is purposely reduced. The Intermediate level includes all important phenomena, mechanisms and theories. Quantitative relations are emphasized and analytical tools are provided. Some recent research results are included. This level prepares for in-depth understanding and for advanced research. Intermediate level is aimed to give a relatively complete knowledge of the laser machining process. It is self-contained, but some references are made to level one to avoid repetitions. More theoretical aspects of laser machining processes are presented in level two than in level one. This level is for upper-level undergraduates and first-year graduates. The contents is systematically organized to make it suitable for self learning, as a text or as a useful references for a university course about laser machining processes.

The advanced level includes the relatively special phenomena, mechanisms and relatively more advanced theories and analytical tools that primarily target graduate students and researchers. Recent research results are mostly be included here. These three levels can be taken sequentially or individually. This structure is convenient for cross-referencing, especially when it is implemented on the Web. Multimedia techniques are used to make the web different from a paper-textbook: you can click to see the definition of a term, you can jump to any interested link, you can try the interactive relations, etc.

In other modules, the contents are arranged sequentially from basic levels to advanced topics following the similar guidelines as in Laser Machining module.

3. Incorporation of Recent Research Results

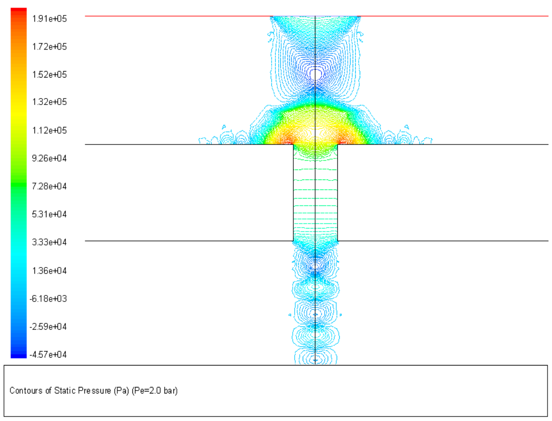
Great many important progresses are made in NTM research every year. Thus it is very important to incorporate recent research results into the curriculum to keep the student aware of the frontiers of NTM and to provide researchers a base for advanced study. However, prior texts or reference books either have a big lag in time of the contents, or do not provide a systematic introduction. This situation makes many students and researchers waste time in getting started and prepared for advanced research.

Incorporation of recent research results and introduce the material systematically is a very important feature of this project. The goal is not only to educate students the fundamentals of nontraditional manufacturing but also to train them the latest state-of-the-art technology. Representative advanced topics in nontraditional manufacturing have been discussed in detail for the following processes: Laser Materials Processing (LMP), Electrical discharge Machining **(**EDM)/ Electrochemical Machining (ECM), and AWJM (abrasive water jet machining).

In laser material processing, the contents are divided in to three levels. Level 2 and 3 cover the advanced topics and recent research results. For example, modeling of laser material processing is presented in Chapter 3. Level 1 describes the most fundamental aspects of process modeling while keeping the contents descriptive and simpler in mathematics. Level 2 gradually introduces the contents for advanced modeling. Then cases with analytical solutions are presented to help the reader understand the influence of different process parameters. These are well known prior results in this area. Numerical methods are then introduced, which is widely adopted to study this complex process. After laser energy modeling, laser energy absorption by target material, and laser machining are discussed, the rest of Level 2 and 3 in Chapter 3 then focus on more recent research results:

- Effects of gas jet
- Thick section laser cutting
- Cutting front geometry prediction
- Using enthalpy method to deal with phase change difficulties
- Knudsen layer and jump conditions

Laser cutting with a CW laser is a complex physical process and the variables that determine the quality of the end product should be optimized. Gas jet that removes the debris and molten material from the cutting kerf is one of these important factors, which is closely related to cutting quality and cutting speed. Recent research progresses on this topic are introduced systematically. Nozzle geometry is discussed, then the numerical modeling of gas jet effects is introduced in multiple steps. Fig. 3 shows the contours of static pressure at two different nozzle pressure levels in the numerical modeling of jet-target interaction. The interaction of a gas jet with the workpiece in laser machining is investigated by systematically studying the influence of the processing parameters on the shock structure of the gas flow. The numerical simulation of a transonic, turbulent jet impinging on a plate (workpiece) with a hole concentric with the jet is presented, revealing the effects of gas pressure and nozzle standoff distance on shock structure [5].



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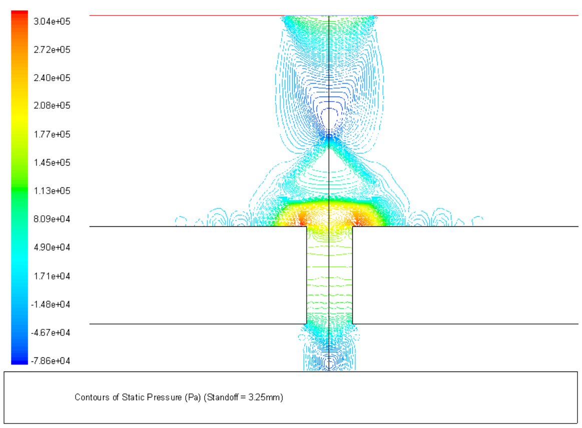

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Fig. 3. Contour of static pressure for (a) P_e = 207 kPa (*d* = 0.711mm, *H* = 2mm) (b) Contour of static pressure for *H* = 3.25mm (*d* = 0.711mm, P_e = 363 kPa) [5]

In LMP chapter 5, Materials, some basic topics were discussed first, then some recently developed laser machining technologies are discussed:

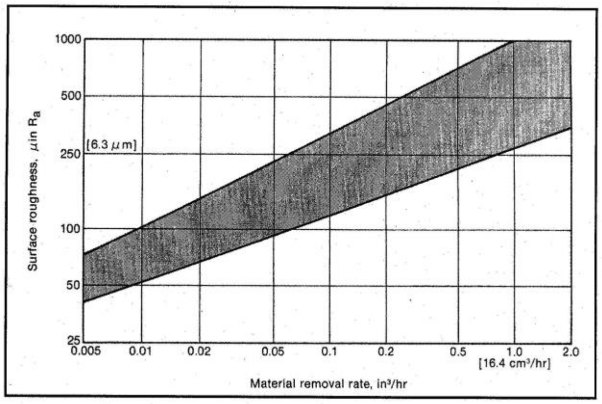
- Laser machining of ceramics
- Laser machining of metal-matrix composites
- Laser machining of superalloy
- Laser machining by Doubled and tripled frequency YAG lasers
- Short pulse high density laser machining
- Diode pumped laser machining of materials
- Diode Laser machining Overview
- Ultra-short pulsed laser machining
- Three Dimensional Micro-structuring in material.

This approach of incorporation of advanced materials with the help of visual aid and multi-media makes the contents less overwhelming, less boring, and provides the reader sufficient background to get ready for advanced research. Similar approach is taken in EDM/ECM and AWJM modules.

In EDM module, after the theory and process mechanisms are introduced, three types of EDM process (Die-sinking EDM, Wire EDM and Micro EDM) are discussed in terms of equipment, process parameters, flushing techniques, electrode material and electrode wear. Micro EDM is one of the most important micromachining methods recently developed. Topics of recent research results include:

- Experimental Investigation of Micro-EDM Parameters
- Integration of CAD/CAM with micro EDM
- A Micro-EDM/Assembly System Unit for Microparts Fabrication
- Molding of Plastic Components Using Micro-EDM Tools
- Microstructuring of silicon by micro-EDM
- Micro electro-discharge machining of ink jet nozzles: optimum selection of material and machining parameters
- Molding of Plastic components using micro-EDM Tools
- Control Feature Identification in Micro-EDM

Surface integrity is important in all manufacturing processes, especially in thermally based NTM processes such as EDM, laser machining, electron beam machining, Ion beam machining and plasma arc machining. The nature of the surface layer has been found in many cases to have a strong influence on the mechanical properties of the part. The subsurface altered material zones (AMZ) can be as simple as a stress condition different from that in the body of the material or as complex as a microstructure change interlaced with inter-granular attack. This topic is important for both practical applications and advanced research, but it is not sufficiently and not systematically covered in prior texts and references. In this project, general issues regarding process-material interaction of manufacturing are discussed systematically and in depth. For example, the types and causes of this zone is discussed and compared for both NTM and traditional processes, which is categorized into mechanical, metallurgical, chemical, thermal and electrical. The influence of process parameters on the surface integrity in EDM and micro EDM is then presented. Fig. 4a shows the relation between surface roughness and material removal rate, Fig. 4b shows the relation between the thickness of recast layer and material removal rate.



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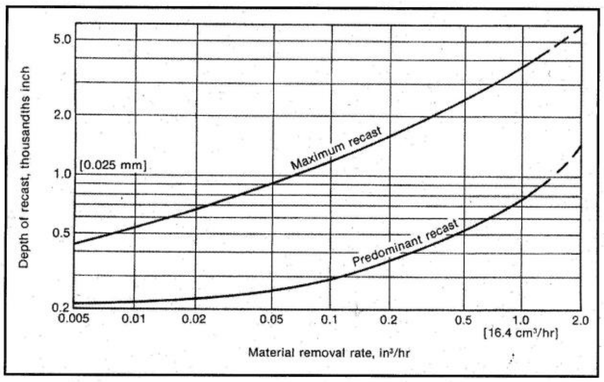

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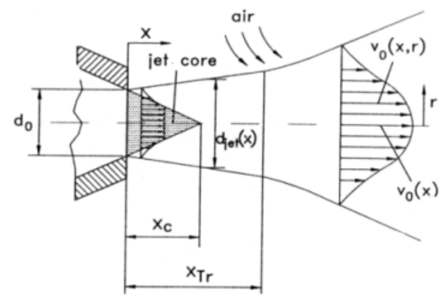
Fig. 4. Surface integrity investigation in EDM a) Relation between surface roughness and material removal rate; and b) Relation between the thickness of recast layer and material removal rate.

In AWJM module, after fundamentals of abrasive water jet machining, including history, basic machining mechanism, process parameter and equipment, are introduced, recent research on jet formation and characteristics, modeling, control and optimization of the AWJM process are discussed in detail. The introduction covers many aspects for practical implementation of the process and provides a sound base for advanced research.

For example, the fluid mechanics behind the formation of high speed water jets and the issue of abrasive particle fragmentation are discussed in detail. Fig. 5a illustrates the different zones of a high speed water jet. Heat generation during abrasive water-jet cutting occurs due to friction between the impinging abrasive particles and the cutting front, as well as due to plastic deformation during the material-removal process. Presently, there is a limited knowledge about the generated heat and thermal energy distribution through the workpiece during cutting with an abrasive water jet, while the discussion in this module provides valuable insight on this issue. Fig. 5b illustrates the influence of traverse velocity on the temperature rise in abrasive water jet machining. It is interesting to notice that temperature rise is less than 100 degrees in abrasive water jet machining, while in EDM the temperature rise can be as high as 3000 degrees, and in laser machining material can be melted and vaporized under even higher and instantaneous temperature rise.



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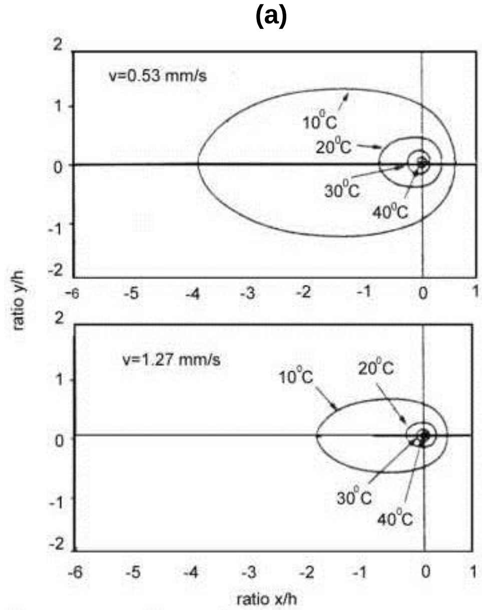


(b)

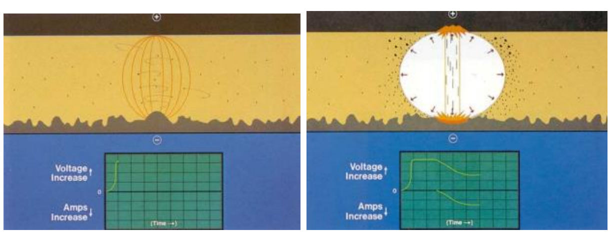
Fig. 5. (a) Zones in a high speed water-jet; and (b) Influence of traverse velocity on the temperatures rises in abrasive water-jet machining.

4. Web Based And Interactive Tutorial

To achieve more effective and more intuitive learning rather than just text reading, multimedia methods were adopted in this project. The methods had been used are: a) JAVA and Macromedia Shockwave based interactive exploration of effects of process parameters; b) 2D and 3D animation of process simulations; c) Web based interactive audio and video illustration of processes; and d) Online interactive test and terminology explanation.

A prominent advantage of web-based education is that higher level of richness and variety of information can be conveyed to the reader all over the world without much cost and with little delay. This is a trend for modern education. In this project, one can find plenty of figures, pictures, tables, links, reference, animations, videos, audios, tests, etc., in full color. They are live and more interesting. Difficult or boring contents in education can be delivered with flavor and efficiency using this style. For example, following the link of http://www.unl.edu/nmrc/Processmech/Processmech.htm, the material removal process in EDM is illustrated in using slides of multiple steps with the help of text explanation (Fig. 6a). One can quickly understand this part and leave a maybe permanent impression of this mechanism.

Interactive Macromedia animations are used to illustrate the basic principles of lasers. Fig. 6b) is a snapshot of the macromedia animation of laser system and laser principles. The following link will lead you to the animation of Laser System Demo: (http://www.columbia.edu/cu/mechanical/mrl/ntm/level1/ch02/media/laserdemo.htm). Some people are visual learner, and many of us can learn more efficiently with visual or audio aid. With the help of such interactive



(a)

(b)

Fig. 6. Examples of multimedia (a) Illustration of EDM material removal mechanism with multiple slides; and (b) Macromedia animation of laser principles.

tutorials, even the undergraduate can understand the basics of lasers in a very short period.

This tutorial also used JAVA to enable readers to learn physical phenomena and process parameters interactively. For example, the laser theories of spontaneous emission, stimulated emission and population inversion are not so easy to understand for students with engineering background. JAVA applets were developed to enable students to learn these complex relations interactively and intuitively. Audio and video are also used to enhance the efficiency of learning and to expand the information that can be conveyed traditionally. Online quiz is another feature in this web-based tutorial. After each chapter, there is a quiz for students to test themselves how much they understand the materials covered. Test results are available after student submits their answer.

FEM analyses are very important in the research of NTM processes, especially for graduate students. Undergraduate students, many process engineers and managers do not have enough background or time to do the actual modeling. It's meaningful to expose any people who are interested in NTM process to some representative FEM results. This helps them understand the power and value of FEM analysis in NTM. This is difficult to implement in paper-based textbooks. In this project, students are able to see preordered video of process simulation results from FEM. These simulation results are available in QuickTime format. The teacher or web-master can order videos of real manufacturing processes and computer simulation results. For example, the temperature history, stress and strain distribution are available upon request for certain process conditions.

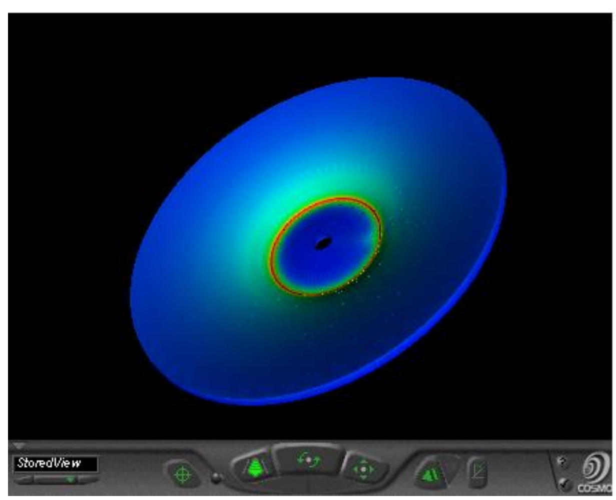


Fig. 7. Snapshot of a 3D interactive animation of temperature history in laser forming of a circular plate

3D animation and virtual reality modeling of non-traditional manufacturing processes are also employed in this project to intrigue student's interest and to offer them chances to look into the 3D simulation results, which is based on recently developed web-based 3D graphics software, VRML. Just as HTML (HyperText Makeup Language) is a file format that defines the layout and concept of a 2D page with the capability of links to information, VRML (Virtual Reality Modeling Language) is a file format that defines the layout and content of 3D world with links to more information. Unlike HTML, however, VRML worlds are inherently interactive—it is filled with objectives that interact with users. In this project, web based 3D interactive visualization and animation has been developed using VRML. Student can see 3D interactive animations of the laser forming process, as shown in Fig. 7, which is a snapshot of the temperature history in the laser forming of a circular plate. Similar effort should be applied to other NTM processes in the future.

Web-based interactive tutorial is the right direction to go for modern education, but more efforts are needed to enhance this feature in this project. On the other hand, any body can put materials onto the web, either accurate or inaccurate. Thus it is important for government to support systematic and orchestrated efforts to develop similar texts for education and for engineering references. The NTM project is a model for such efforts.

5. Cross Process Innovations and Energy Field Manufacturing

Constant innovations are needed in manufacturing engineering to meet various challenges. One can be expert in one process and use it to extreme but still may not find the optimal solution. Not surprisingly, the integration of two or more processes, either traditional or nontraditional, has produced many inspiring results. The cross process innovations are discussed in one standalone module of the project [6]. Representative examples are described, such as abrasive EDM [7], laser assisted ECM [8], EDM with assistance of ultrasonic vibration [9], laser/plasma assisted conventional machining [2], underwater laser machining [10] etc.

The authors feel that in order to use the full potentials of various manufacturing processes, it is important to purposely and systematically use various energy fields to optimize the engineering solutions. The general methodology behind the cross process innovations is discussed in the cross process innovation module. The reasons for developing cross or hybrid machining processes are to make use of the combined or mutually enhanced advantages, and to avoid or reduce some adverse effects the constituent processes produce when they are individually applied.

One common feature of NTM is the extensive use of various energy forms and energy fields. In fact, engineering is the art of energy field utilization and manipulation. Energy field is the spatial and temporal distribution of energy. Some may think that "point energy" is not energy field, but point is only a relative concept, it is merely a localized energy field. Energy field is a more general concept. A focused laser beam might be regarded as a point energy source, however, for micromachining we must consider its spatial and temporal distributions. Traditional machining commonly relates to stress field and thermal field. Of course, gravitational field and environmental pressure field are always affecting any processes on earth.

Any kind of energy fields has its advantages and disadvantages, and our aim is to find the best combination for engineering tasks. The more energy fields we consider, the more freedom and potential we have in optimizing our processes. In addition to commonly known energy fields, such as mechanical forces, sound, light, electromagnetic fields, thermal fields, particle flows (such as electron beams, ion flows) and fluid flows, it is convenient to treat medium environment as a special kind of energy field--*Medium Field*. Chemical machining and EDM need special medium environment to do their work. Reactive Laser Cutting uses oxygen to assist cutting. Different medium distributions can be defined to be of different energy states. This not only helps explain physical phenomena, but also helps quantify the effects of medium environment.

In order to break the barriers in process innovation, it's meaningful to think over what traditional and nontraditional mean, and put forward the concept of *Energy Field Manufacturing*.

In some sense, traditional means things that are mature and widely accepted for some time. Thus the content of traditional changes over time. The strict distinction between traditional and nontraditional is not so important, but it is necessary to regard mechanical force/energy as a common kind of force/energy in parallel with light, sound, ion beam, electricity etc.

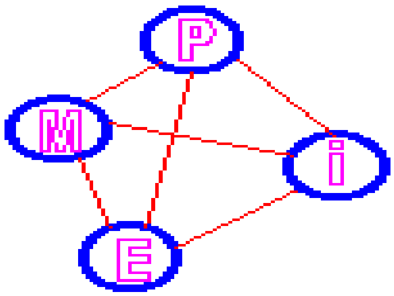


Fig. 8. Three flows in Energy Field Manufacturing

The essence of manufacturing engineering is utilizing information to control energy and mass to achieve human being's desired objectives. Energy field carries the information and convert the material into final products. Thus energy field manipulation is central in all manufacturing processes. Fig. 8 illustrates that three flows exist in any manufacturing processes (P): information flow (I), energy flow (E) and mass/material flow (M). Rather than divide manufacturing processes into traditional or nontraditional, we should treat them equally as kinds of *Energy Field Manufacturing*. The degree of integration of the three flows can be used as index for process optimization [11].

6. Conclusion

Nontraditional manufacturing processes are gaining increasingly important roles in manufacturing due to their capability of high quality and cost-effective machining of high performance materials. This NSF supported project results in a web based systematic presentation of NTM processes that is a unique reference for engineers and an easy to follow curriculum text for students. The project focuses on energy and material interaction. Meaningful results of this project include systematic presentation of common features and general philosophy of NTM, and the complete presentation of representative NTM processes. The effort for improved NTM research and education shouldn't stop at this point however. The Energy Field Manufacturing concept should be further extended and implemented. More NTM processes should be implemented similarly, computer and multi-media should be more thoroughly integrated in the education of NTM, and knowledge base of each process should be systematically built up.

References

[1] K. P. Rajurkar, and R. F. Ross, "The Role of Nontraditional Manufacturing Processes in Future Manufacturing Industries," *ASME Manufacturing International*, 1992, pp. 23-37

[2] Carl E. Leshock, Jin-Nam Kim, and Yung C. Shin, "Plasma enhanced machining of Inconel 718:modeling of workpiece temperature with plasma heating and experimental results," *Int. J. Machine Tools & Manu.*, 2001, Vol. 41, pp. 877-897.

[3] MRL, Columbia University; NMRC, University of Nebraska-Lincoln; and RCAM, Southern Methodist University, http://www.mrl.columbia.edu/ntm/index.html

[4] K. P. Rajurkar, D. Zhu, J. A. Mcgeough, J. Kozak, De Silva A.: "New Developments in Electro-Chemical Machining," *Annals Annals of the CIRP*, 1999, Vol. 48/2, pp.569-579.

[5] Kai Chen, Y. Lawrence Yao and Vijay Modi, 2000, "Gas jet-workpiece interactions in laser machining," *Journal of Manufacturing Science and Engineering*, Aug. 2000, Vol. 122, pp.429-438.

[6]http://www.mrl.columbia.edu/ntm/CrossProcess/CrossProcessindex.htm

[7] A. M. Kotlar and M.V. Szczerbak, "Experimental Investigations of Abrasive Electrochemical Grinding," *Elektronnaja Obrabotka Materialov*, 1974, Nr 4, pp.29-32.

[8] J. Kozak, L. Dabrowski, M. Rozenek, and J. Zawora: "Investigations of the Effects of Laser Radiation on Electrochemical Shaping Process," *Transaction of WUT-New Technologies*, Vol. 2, 1999 (in Polish)

[9] D. Kramer, B. Lebrun, A. Moisan, "Effects of Ultrasonic Vibrations on the Performances in EDM," *Annals of the CIRP*, Vol. 38/1, 1989, pp. 199- 202

[10] Wenwu Zhang and Y. Lawrence Yao, "Feasibility Study of Inducing Desirable Residual Stress Distribution in Laser Micromachining," *Transactions of NAMRI/SME*, Vol. XXIX, 2001, pp. 413-420

[11] Wenwu Zhang, "Study on RPM, 3DM and Energy Field Formics," *Proceedings of International Conference of RPM (ICRPM98)*, Beijing, 1998, pp. 316-320.