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Combined research and curriculum development of nontraditional manufacturing

Y. LAWRENCE YAO†, GARY J. CHENG*¶, K. P. RAJURKAR‡, RADOVAN KOVACEVIC§, STEVE FEINER† and WENWU ZHANG†||

†Columbia University, New York, NY, USA
‡University of Nebraska–Lincoln, Lincoln, NE, USA
§Southern Methodist University, Dallas, TX, USA
¶Washington State University, Pullman, WA, USA
||GE Global Research, Niskayuna, NY, USA

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Nontraditional manufacturing (NTM) is becoming increasingly important in modern engineering. Therefore, it is important to develop up-to-date pedagogic materials for the area. This paper reports collaborative efforts among three universities in such a development sponsored by National Science Foundation of USA. The features of the development include systematic introduction, recent research results, and web implementation with interactive capabilities. This paper is based on an extensive web based course with animations, including Java applets, Shockwave animations, VRML animations, and QuickTime movies. The development is aimed at upper level undergraduate and introductory graduate students. Areas of focus include Laser Material Processing, Electrical Discharge Machining, Electro-Chemical Machining, and Abrasive Water Jet Machining. Cross process innovation are also presented. Needs for further pedagogic developments are discussed.

Keywords: Nontraditional Manufacturing; Cross process innovation; Curriculum development; Interactive; Web-based

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 affect the transfer of energy from the tool to the workpiece. In contrast, traditional machining relies on direct mechanical contact between the tool and the workpiece, which often cause undesired changes in the properties of workpiece, such as residual mechanical and thermal stresses (Rajurkar and Ross 1992).

Rising production costs dictates that production operations be automated whenever possible; innovative materials such as super-alloys, composites, ceramics and many other advanced

*Corresponding author. Jin Cheng, School of Mechanical and Materials Engineering, Washington State University. Tel.: 509-3357711; Fax: 509-3354662; Email: cheng1@wsu.edu

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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. These engineering challenges facilitated the development of non-traditional manufacturing processes. NTM processes are usually well suited to be monitored and controlled, the processing steps are reduced, the fixtures are simplified due to their inherent non-contact nature, and the process precision covers a wide range. In many cases, traditional manufacturing may have reached their capability limits, while NTM is offering the best solution. Engineering achievements in recent years, such as electronics industry, MEMS and Rapid Prototyping Manufacturing (RPM), are impossible without the development of critical NTM processes.

NTM processes are diverse and multi-disciplinary. It is not rare that many engineers feel not adequately prepared in finding the suitable or optimal manufacturing solutions in their works although they have received graduate level education in engineering. Substantial research progress of NTM has been conducted in recent years. The role of NTM has changed from the assistance of conventional processes to that as important as conventional processes. Currently, education of conventional processes is systematic and takes majority of the course hours. On the other hand, education of NTM processes doesn't pace up well with the new role and the new trend of NTM. The multi-disciplinary nature and the diversity of NTM education have posed more challenges than the education of conventional manufacturing processes. Education efficiency of NTM processes must be improved. Instead of introducing one process after another without correlation, new methodology should be founded to study and educate NTM systematically. Innovations and more orchestrated efforts are needed at the upper level undergraduate and introductory graduate curricula.

To meet the above challenges, three universities in USA, including Columbia University, University of Nebraska-Lincoln, and Southern Methodist University, jointly carried out a NSF funded project: Combined Research and Curriculum Development of Nontraditional Manufacturing (MRL, Columbia University Website). These universities have long-standing and on-going activities in NTM research and education. This project focused on nontraditional material removal or machining processes such as laser machining processes (LMP), electrical discharge and electrochemical machining (EDM/ECM), and abrasive water jet machining (AWJM), among others. The objectives of this project are:

- To develop educational materials to incorporate recent research results in NTM processes and systems into upper level undergraduate and introductory graduate level curricula.
- To establish a model for effective and efficient learning of multi-disciplinary subjects.
- To prepare a new generation of engineers with analytic background knowledge and process design/optimization skills in NTM.

In this paper, the features of the NTM project are presented, namely systematic introduction, incorporation of recent research results, and web based implementation with interactive capabilities. Finally, process innovations and future directions of NTM research and education are discussed.

2. Systematic introduction of NTM

2.1 *Common features of NTM and focus on energy-material interaction*

During the implementation of 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. In prior materials on NTM study and education, individual processes are discussed without much correlation. In fact, nontraditional processes have many common features. Efforts were made to show the common features behind NTM processes and the focus was on energy-material interaction.

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, laser sintering, laser cladding, and laser material 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. 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 (Leshock *et al.* 2001).

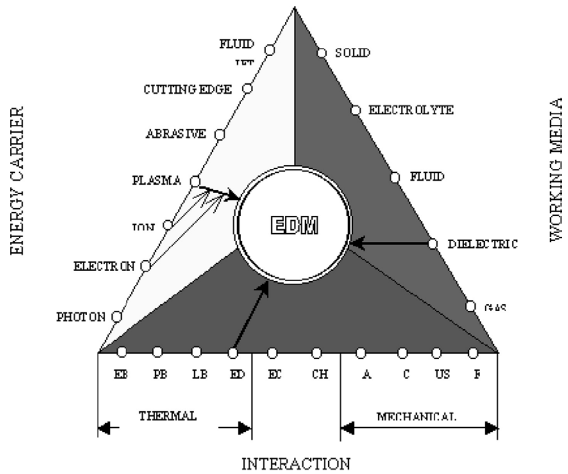
Having a clear overall picture is important when trying to exploit various energy fields in NTM. The general philosophy of NTM study is presented in Chapter 1 of Laser Machining Processes module (MRL, Columbia University Website). The Four Attributes (Temporal, Spatial, Frequency and Amplitude) analysis of an 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 (MRL, Columbia University Website). General issues in micromachining are discussed in two sections of Micro-EDM in the EDM module. Surface integrity in nontraditional and conventional manufacturing is discussed in detail in EDM module.

A machining process, and more broadly, any manufacturing process, can be represented by the Process Conditions Scheme (PCS), which is the diagram used to analyze the condition features of machining and its conjugate (figure 1). The base side of the process condition triangle represents the kind of interactions such as Thermal (electron beam *EB*, plasma beam *PB*, laser beam *LB* and electrical discharges *ED*), Electrochemical (*EC*), 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, Cutting edges, and Fluid jet. The right side of the triangle consists of types of working media: Solid particles, Electrolyte, Fluid, Dielectric, and (Gas Rajurkar *et al.* 1999).

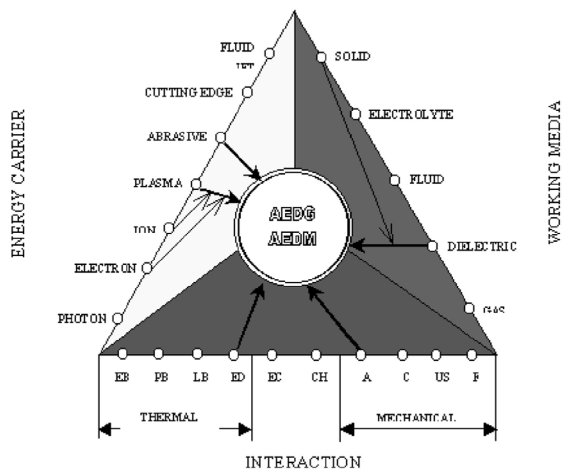
Using the process conditions scheme, the correlations and possible integrations between different processes are more intuitive than directly going into the details of individual processes. For example, the main interaction in Electrical Discharge Machining (EDM), energy carrier and working media are illustrated in figure 1a. Application of powder-mixed working media allows abrasive EDM (AEDM) to obtain mirror finishing of complex shapes and crack free machining surfaces. Therefore, AEDM produces a die without the need of removing the affected layer. For the process analysis of abrasive EDM and EDG, thermal interaction (abrasive-mechanical interaction), and energy carrier (plasma and abrasive grains), and working media (dielectric and solid particles) are illustrated in figure 1b.

2.2 *Complete and leveled coverage of representative NTM processes*

Capitalizing on the strength of three universities, curricular materials of representative NTM processes including laser machining (LM), abrasive water jet machining (AWJM), electrical discharge machining (EDM) and electrochemical machining (ECM), are developed, along



(a)



(b)

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

with the module of cross process innovations and NTM Animation Examples, as shown in figure 2. As seen, the total number of modules is six.

The complete coverage of NTM processes may be overwhelming for the intended readership, that is, upper level undergraduate and introductory graduate students. To ease the process, the contents are divided into different levels or follow reasonable sequences. For example, Laser Machining Processes (LMP) module is presented in terms of three broad topics: Energy, System and Material. Each topic is presented in three levels: Introductory, Intermediate and Advanced, to adapt to 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. The Intermediate level includes all important phenomena, mechanisms and theories. Quantitative relations are emphasized and analytical tools are provided. Some recent research results are

Figure 2. Web based systematic introduction of NTM.

included. The contents of intermediate level prepare the readers for in-depth understanding and for advanced research of LMP. 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 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 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. One can click to see the definition of a term, and one can jump to any interested link. With multimedia techniques one can try the interactive relations, and view animated examples. 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

Many important progresses have been made in NTM research in recent years. Recent research results need to be incorporated into the curriculum to keep the student aware of the frontiers of NTM and to provide researchers a good starting point for advanced study. However, prior textbooks or reference books either have long time-delay in contents, or do not cover them in sufficient depth.

Incorporation of recent research results and introducing the materials systematically are important features of this project. The goal is not only to educate students the fundamentals of nontraditional manufacturing but also to familiarize them with the state-of-the-art technology. Representative advanced topics in nontraditional manufacturing are incorporated 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 module, the contents are divided into three levels. Advanced topics and recent research results are mainly covered in Level 2 and 3. 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 mathematically simple. Level 2 gradually introduces the contents of advanced modeling. Then cases with analytical solutions are presented to help the reader understand the influence of different process parameters. Numerical methods are then introduced, which is widely adopted to study this complex process. The rest of Level 2 and 3 in chapter 3 then focus on more recent research results including:

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

In this way, the modeling of laser material processing is introduced systematically, covering both the fundamentals and the advanced topics.

In chapter 5 of the LMP module, some basic topics are discussed first, followed by discussion of some recently developed laser machining technologies including:

- Laser machining of ceramics
- Laser machining of metal-matrix composites
- Laser machining of superalloy
- Short pulse high density laser machining
- Diode pumped laser machining of materials
- Ultra-short pulsed laser machining
- Three dimensional micro-structuring

In EDM module, after the theory and process mechanisms are introduced, three types of EDM processes (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
- 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

Surface integrity is a common concern 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 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. The influence of process parameters on the surface integrity in EDM and micro EDM is then presented.

In Abrasive Water-Jet Machining (AWJM) module, after the history, basic machining mechanism, process parameter and equipment of water-jet machining are introduced, recent research results on jet formation and characteristics, modeling, control and optimization of the AWJM process are discussed in detail. 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. Currently, there is only limited knowledge on heat generation and thermal energy distribution through the workpiece in AWJM, while the discussion in this module provides valuable insight on this issue. The infrared thermograph has been used to provide the following (Leshock *et al.* 2001):

- Thermal energy distribution in workpiece cut with AWJ by changing cutting conditions and workpiece material. This information is used to determine the heat flux at the cutting zone.
- Visualization of the AWJ cutting mechanisms in opaque materials.
- Temperature distribution in AWJ cutting nozzle and thereby indirectly monitor the nozzle wear.
- Quantitative comparisons of the infrared thermograph results with those obtained using thermocouples and the moving line heat source model.

The results of thermograph measurements in AWJ cutting titanium alloy (R58640) and aluminum alloy (Al 2024) are shown in Figures 3a and 3b respectively. It is interesting to notice that the temperature rise is less than 80 °C in abrasive water jet machining, while the

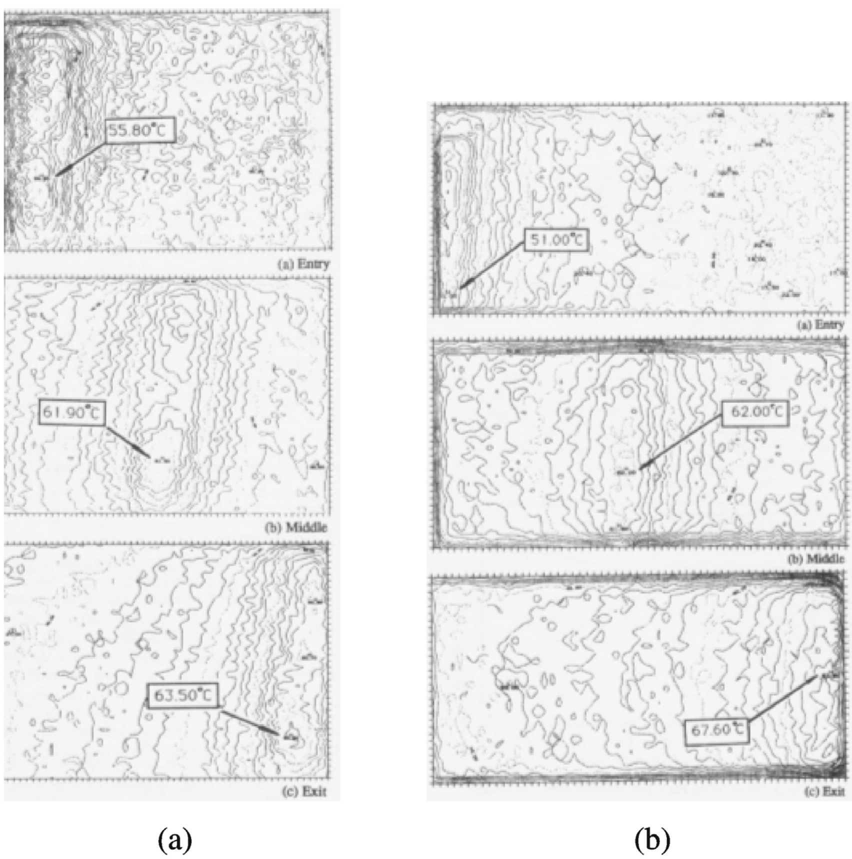


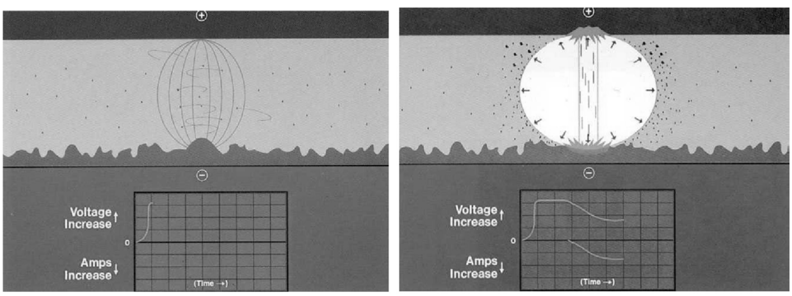
Figure 3. Thermograph measurements in AWJ cutting (a) titanium alloy (R58640), and (b) aluminum alloy (Al 2024).

EDM the temperature rise can be as high as 3000 °C, and in laser machining, materials can be melted and vaporized under even higher temperature.

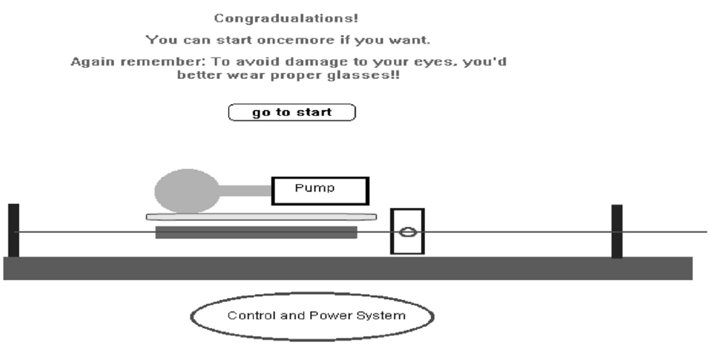
4. Web based interactive features

A prominent advantage of web-based education is that variety of information can be conveyed to the reader all over the world with little cost and time-delay. In this project, one can browse in own pace and cross reference numerous figures, pictures, tables, links, references, animations, videos, audios, and tests, etc. Difficult or boring contents can be delivered with more interest and efficiency. For example, in the EDM module, nine colorful slides were used to explain the multiple steps of material removal in EDM. Figure 4a shows two of the slides, the first one shows what happens when the charged electrode is brought close to the workpiece, and the second slide in Figure 4a illustrates what happens during the material removal. With the combination of text explanation and nine graphical illustrations, one can quickly understand the complex machining mechanisms and leave a vivid and maybe permanent impression of this mechanism.

To achieve more effective and more intuitive learning rather than just text reading, multimedia methods were adopted in this project. Generally, the creation of multimedia requires media



(a)



(b)

Figure 4. Examples of multimedia (a) Illustration of EDM material removal mechanism with multiple slides, and (b) Macromedia animation of laser principles.

editing and generation software to develop media files. The various media types include text, images and graphics, sound, animation, video and virtual reality. Other than text, images and sound, the interactive methods employed in this project are: a) JAVA applet based interactive exploration of physical processes; b) Macromedia Shockwave based animation; and c) 2D and 3D Virtual Reality (VR) animation of NTM process simulations by finite element modeling (FEM). Animation can be a powerful tool for instruction. It can enhance the presentation of concepts by activating graphics (charts that grow, mechanical objects that function, etc.) to illustrate a point. Animation can also be used to create attention, visually enhance a site or on-line course. This project utilizes interesting mixes of HTML text, with embedded animations to deliver self-instruction over the Web.

4.1 *JAVA applet*

Many applications that create animations for the web are Java-enabled. This development also used JAVA to enable readers to learn physical phenomena and effects of 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. Figure 5 shows the Demo of the relation between energy difference, temperature and population inversion. It will allow students to adjust the energy difference and observe the effects on the electron population distribution.

4.2 *Macromedia shockwave*

Macromedia Shockwave is a browser plug-in, which has become almost an Internet standard to enable downloading and playing of multimedia interactive contents and animations. Interactive Macromedia Shockwave animations are used in this development to illustrate the basic principles of different nontraditional manufacturing systems. For example, figure 4b shows a snapshot of a macromedia shockwave animation to show laser principles. In this Macromedia animation, a laser system is assembled step by step, and finally a working laser system appears with all the necessary components in place. The following link will lead you to

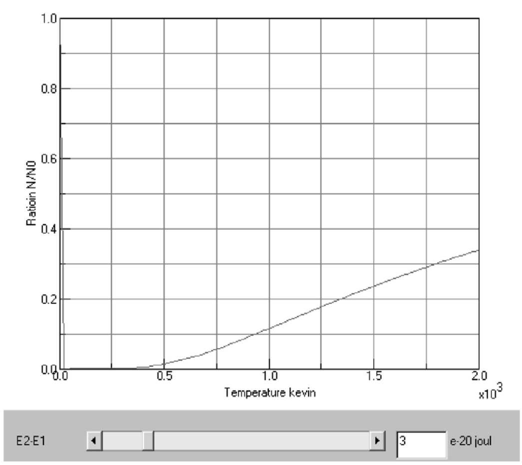


Figure 5. Demo of the relation between energy difference, temperature and population inversion using Java applet.

the animation of Laser System Demo: (http://www.columbia.edu/cu/mechanical/mrl/ntm/level1/ch02/media/laserdemo.htm). Many of us can learn more efficiently with visual or audio aid.

4.3 *2D and 3D VRML animations*

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 2D movie of process simulation results from FEM. These simulation results are available in QuickTime format. For example, the temperature history, stress and strain distributions are available upon request for certain process conditions. Figure 6 shows a snapshot of a QuickTime movie of Von Mises stress during laser forming of a rectangular plate.

The ability to produce and display three-dimensional images and animation over the Web creates educational opportunities to display full-featured 3D models and worlds to illustrate difficult concepts and principles. An emerging Web standard of 3D Formats for the Web is VRML (Virtual Reality Modeling Language), which is served to a VRML browser plug-in. The VRML browser then does all the legwork to render and support the navigation of the 3D world on the local system.

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 are based on recently developed web-based 3D graphics software, VRML. 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, VRML worlds are inherently interactive – it is filled with objectives that mutually 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 figure 7, which is a snapshot of the temperature history in the laser forming of a circular plate. Laser is a very flexible and well controllable high intensity thermal source. By scanning laser energy across metal plate, the resulting thermal stress can bend the material in predictable

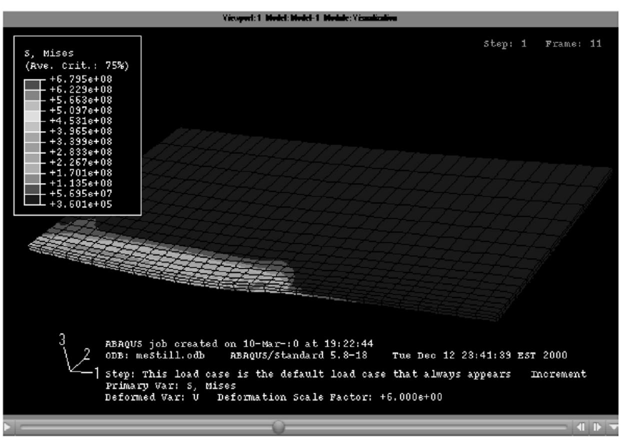


Figure 6. An example of QuickTime movie of Mises stress during laser forming of a rectangular plate.

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

ways. This process is called Laser Forming. Similar effort should be applied to other NTM processes in the future.

In addition, with students being able to actually share space and time in a virtual environment, the capabilities of using this technology for Distance Education are enormous. No longer will students have to view the facilitator (instructor) from a 'distance'. For example, a group could effectively tour inside a Virtual manufacturing process on-line together, providing for interaction between the participants. Face to face communication becomes accessible and the capability of group collaboration on projects is now possible, even if there are miles or oceans between the students and teacher.

5. Cross process innovations

Constant innovations are needed in manufacturing engineering to meet various challenges. One can be an expert in one process 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 (Cross Process Website). Representative examples are described, such as abrasive EDM (Kotlar and Szczerbak 1974), laser assisted ECM (Kozak *et al.* 1999), EDM with assistance of ultrasonic vibration (Kramer *et al.* 1989), laser/plasma assisted conventional machining (Leshock *et al.* 2001), and underwater laser machining (Zhang and Yao 2001).

The authors feel that in order to use the full potentials of various manufacturing processes, it is important to optimize the engineering solutions by systematically utilizing various energy fields. The general methodology behind the cross process innovations is discussed in the Cross Process Innovation module.

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. Energy fields have their advantages and disadvantages. The more energy fields considered, the more freedom and potential may be revealed in the optimization of processes. Traditional machining commonly involves stress field and thermal field. Of course, gravitational field and environmental pressure field are always affecting any processes. In addition to commonly utilized energy fields, such as mechanical force, sound energy, photon energy, electromagnetic fields, thermal fields, particle flows (such as electron

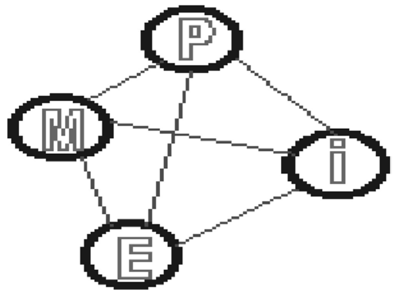


Figure 8. Three flows in Energy Field Manufacturing.

beams, ion flows) and fluid flows, it is convenient to treat medium environment as a special kind of energy field – *Medium Field*. Different medium distributions can be defined to be of different energy states. For example, chemical machining and EDM need special medium environment. Reactive Laser Cutting uses oxygen to assist cutting. During underwater shock assisted laser drilling. When laser drilling is carried out in water, melting and heat affected zone are greatly reduced, redeposition almost disappeared. At the same time, the machining mechanism changed to shock and plasma assisted laser machining (Zhang and Yao 2001).

6. The concept of energy field manufacturing

In this development, the future of nontraditional manufacturing is also discussed. In order to break the barriers in process innovation, it's meaningful to think 'traditional' and 'nontraditional' in relative terms, especially in the era of rapid technological advances. It is argued that the concept of Energy Field Manufacturing has a certain merits. 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. Figure 8 illustrates three flows existing in any manufacturing processes (P): information flow (I), energy flow (E) and mass/material flow (M). This forms the concept of Energy Field Manufacturing. The degree of integration of the three flows can be used as index for process optimization (Zhang 1998). Integrate information flow in the product helps realize capabilities such as self-sensing and self-repair. Education of manufacturing should reflect this direction in the future.

7. Conclusions

Nontraditional manufacturing processes are gaining increasing importance in manufacturing arena due to their capability of producing high-quality and cost-effective goods otherwise impossible. This NSF supported project results in a web based systematic presentation of NTM processes that provides up-to-date and easy-to-follow pedagogic materials for upper level undergraduate and introductory graduate curricula. It also represents a unique reference for practicing engineers. Recently completed research results are incorporated for individual and hybrid processes. Multimedia aids including Java, Macromedia Shockwave, and VRML are employed to help convey complex concepts and technologies in NTM processes more effectively and efficiently. The corresponding assessment from students and the teaching/learning aspects will be developed in a further paper.

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References

Rajurkar, K.P. and Ross, R.F. The role of nontraditional manufacturing processes in future manufacturing industries. *ASME Manufacturing International*, pp. 23–37, 1992.

Leshock, C.E., Kim, J.-N. and Shin, Y.C. Plasma enhanced machining of Inconel 718: modeling of workpiece temperature with plasma heating and experimental results. *Int. J. Machine Tools & Manu.*, 2001, **41**, 877–897.

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

Rajurkar, K.P., Zhu, D., Mcgeough, J.A., Kozak, J. De Silva A., New developments in electro-chemical machining. *Annals Annals of the CIRP*, 1999, **48**(2), 569–579.

Kai Chen, Y., Yao, L. and Modi, V., 2000, Gas jet-workpiece interactions in laser machining. *J. Manuf. Sci. Eng.*, Aug. 2000, **122**, 429–438.

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

Kotlar, A.M. and Szczerbak, M.V. Experimental investigations of abrasive electrochemical grinding. *Elektronnaja Obrabotka Materialov*, 1974, **4**, 29–32.

Kozak, J., Dabrowski, L., Rozenek, M. and Zawora, J. Investigations of the effects of laser Radiation on electrochemical shaping process. *Transaction of WUT-New Technologies,* 1999, **2** (in Polish).

Kramer, D., Lebrun, B., Moisan, A., Effects of ultrasonic vibrations on the performances in EDM. *Annals of the CIRP*, 1989, **38**(1), 199–202.

Zhang, W. and Yao, Y.L., Feasibility study of inducing desirable residual stress distribution in laser micromachining. *Transactions of NAMRI/SME*, 2001, XXIX, 413–420.

Zhang, W., Study on RPM, 3DM and energy field formics. *Proceedings of International Conference of RPM (ICRPM98)*, Beijing, 1998, pp. 316–320.

About the authors

Y. L. Yao is a Professor in the Department of Mechanical Engineering at Columbia University. Dr. Yao and his team in the Manufacturing Research Laboratory (MRL) are interested in multidisciplinary research in manufacturing and design, nontraditional manufacturing processes, laser materials processing, industrial manipulators in manufacturing, and monitoring and fault diagnosis of manufacturing processes and machinery. He serves as Associate Editor of ASME Transactions Journal of Manufacturing Science and Engineering, SME Journal of Manufacturing Processes, SME Journal of Manufacturing Systems, and High Temperature Material Processes: An International Journal, France.

Gary J. Cheng is an assistant Professor in Washington State University, School of Mechanical and Materials Engineering. He received Ph.D from Columbia University in 2002. Dr. Cheng's research interest is in Non-traditional manufacturing, Laser-matter reaction, MEMS assembly, design and fabrication in MEMS, Nanofluid device.

K. P. Rajurkar is Mohr Professor of Engineering in the Industrial and Management Systems Engineering Department at the College of Engineering and Technology, University of Nebraska-Lincoln. He is the founder and Director of the Center for Nontraditional Manufacturing Research, and past Chairman of the Manufacturing Systems Engineering Program of the College of Engineering and Technology. He was working as a Program Director, Manufacturing Machines and Equipment, Division of Design, Manufacture and Industrial Innovation, at the National Science Foundation. He is a Fellow of the ASME, Fellow of the SME, and an active member of the CIRP.

Radovan Kovacevic is Herman Brown Chair Professor of Materials and Manufacturing Processes in Southern Methodist University at Department of Mechanical Engineering. His research interest is in physics of metal cutting (turning, drilling, milling, broaching) and advanced machining processes (abrasive waterjet cutting, laser machining and welding, electrical arc spraying); machinability; tribology; stochastic modeling of manufacturing processes; on-line monitoring and controlling of manufacturing processes; machine vision in quality control; adaptive control of welding processes.

Steve Feiner is a Professor of Computer Science at Columbia University, where he directs the Computer Graphics and User Interfaces Laboratory. He received a Ph.D. in Computer Science from Brown University. His research interests include knowledge-based design of graphics, user interfaces, virtual worlds and augmented reality, animation, visual languages, image synthesis, hypermedia, and visualization.

Wenwu Zhang is a research engineer in GE Global Research. He graduated from Columbia University in 2002. His research interest is in laser micro-shock processing, laser micro-machining, and cross process innovation.