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A Web-Based Curriculum Development on Nontraditional Manufacturing with Interactive Features*

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The engineering challenges faced by traditional manufacturing has facilitated the development of nontraditional manufacturing (NTM) processes. The multidisciplinary nature and the diversity of NTM education have posed more challenges than education in traditional manufacturing processes. To overcome these challenges, the different NTM processes are systematically presented from introductory to advanced levels by web implementation with interactive capabilities. Apart from text, images and sound, the interactive methods employed in this project include: interactive exploration of physical processes with JAVA applet; Macromedia Shockwave based animation; 3D virtual reality (VR) animation of NTM process simulations; and 2D movies of process simulation by finite element modeling (FEM).

INTRODUCTION

INTEREST IN nontraditional manufacturing (NTM) has been on the increase due to the vastly superior properties of innovative materials such as supperalloys, composites and ceramics, which are difficult to or cannot be processed by traditional machining methods. Environmental considerations require the development of environmentally aware processes. These engineering challenges facilitated the development of nontraditional manufacturing processes. NTM offers an attractive and often the only choice for the secondary processing of these materials. However, the new and potential applications require enhanced process capabilities. In response, substantial research progress has been made in recent years, especially in the areas of process innovation, modeling, simulation, and control. For example, laser is widely accepted as an economical, high-throughput tool for metal/ceramics cutting and drilling. Recent developments in MEMS and rapid prototyping manufacturing (RPM) would be impossible without the development of critical NTM processes.

Progress has also been made in teaching NTM processes. Education at the introductory level has been appropriate, but innovation and more orchestrated efforts are needed in the upper-level undergraduate and introductory graduate (ULUIG) curricula. The multi-disciplinary nature and diversity of NTM has posed more challenges than education in conventional manufacturing processes. Teaching UUIG students at research level requires a significant investment in terms of time and effort. With more and more new research results being incorporated into courses with fixed credit hours, teaching efficiency and efficacy need to be improved. Instead of introducing one process after another without correlation, new methodologies should be developed for the systematic teaching of NTM. Besides innovations in teaching methodologies, computer-aided tools developed in research as well as computer-aided teaching technologies offer great opportunities in this endeavor.

In a recent project [1], three universities in the USA collaborated on nontraditional material machining processes such as laser machining processes (LMP), electrical discharge and electrochemical machining (EDM/ECM), and abrasive water jet machining (AWJM). The objective of the project is to strengthen students' analytical background knowledge and their process design and optimization skills using computer-aided tools. In this paper, a web-based curriculum in NTM with interactive capabilities is presented, in order to systematically introduce NTM research and education.

STEP-BY-STEP CURRICULA DEVELOPMENT OF NTM PROCESSES

Curricular materials of representative NTM processes include laser machining (LM), abrasive

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water jet machining (AWJM), electrical discharge machining (EDM) and electrochemical machining (ECM), along with a module on cross-process innovations. The processing, process optimization, material removal mechanism, the equipment and process parameters are covered for each process. Significant effort is devoted to analysis and modeling of these processes, and recent research results are included.

Complete coverage of NTM processes may be overwhelming for upper-level undergraduate and introductory graduate students, so the contents are divided into three levels: introductory, intermediate and advanced.

Level I

The introductory 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. This level is for beginners, or those who want a general basic understanding of the subject.

Nontraditional processes have many common features. 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 the Laser Machining Processes module [1]. 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 innovation are presented in sections 1 and 2 of the Cross Process Innovations module [2]. General issues in micromachining are discussed in two sections on Micro-EDM in the EDM module. Surface integrity in nontraditional and conventional manufacturing is discussed in detail in the EDM module. These general discussions apply to many NTM processes and broaden the students' perspective.

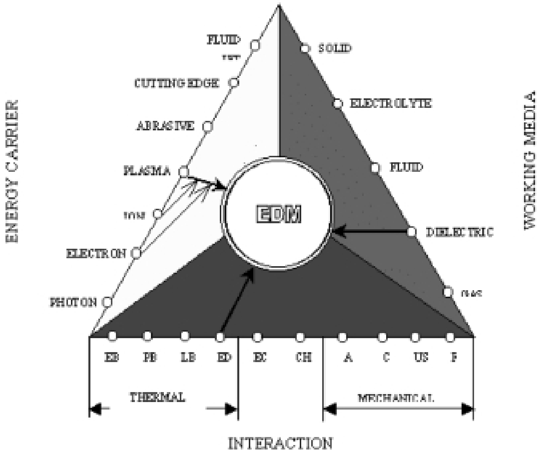


Fig. 1. Process conditions scheme (PCS) for electrical discharge machining (EDM).

A machining process and, more broadly, any manufacturing process, can be represented by the Process Conditions Scheme (PCS), which is the diagram used to analyse the condition features of machining and its conjugate. Figure 1 shows the PCS of the electrical discharge machining process. The base side of the process condition triangle represents 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* denotes cutting (turning, milling, drilling, etc.), *US* denotes ultrasonic wave, and *F* the 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 [3]. Using the process conditions scheme, the correlations and possible integrations between different processes are more intuitive than directly examining the details of individual processes.

Level II

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. The contents of the intermediate level prepares students for in-depth understanding and for advanced research of LMP. The intermediate level aims to give a relatively complete understanding of the laser machining process. It is self-contained, but some references are made to Level I to avoid repetition. The more theoretical aspects of laser machining processes are presented in Level II than in Level I. This level is for upper-level undergraduates and first-year graduates. The contents are organized systematically to make it suitable for self-learning, as a text or as a useful reference for a university course in laser machining processes.

Level III

The advanced level includes the relatively specific phenomena and mechanisms and more advanced theories and analytical tools that primarily target graduate students and researchers. Recent research results are mostly included here.

Many important advances have been made in NTM research in recent years. Recent research results need to be incorporated into the curriculum to make students aware of the frontiers of NTM and to provide researchers with a good starting-point for advanced study. Textbooks and reference books are often out of date in terms of current research or do not cover the subject in sufficient depth. Representative advanced topics in nontraditional manufacturing are incorporated in detail for the following processes: laser materials processing (LMP), electrical discharge machining

(EDM) or electrochemical machining (ECM), and abrasive water jet machining (AWJM). The *laser materials processing module* covers advanced topics and recent research results in areas such as: the effects of the gas jet; thick section laser cutting; cutting front geometry prediction; Knudsen layer and jump conditions in laser ablation; and using the enthalpy method to deal with phase change difficulties. For example, laser cutting with a continuous wave (CW) laser is a complex physical process and the variables that determine the quality of the end product should be optimized. A gas jet that removes the debris and molten material from the cutting kerf is closely related to the cutting quality and cutting speed. Recent research advances in this topic are introduced systematically. Figure 2 shows the contours of static pressure at two different nozzle pressure levels in the numerical modeling of jet-target interaction. 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. In one part of the LMP module, the latest laser machining technologies are discussed: laser machining of ceramics; laser machining of metal-matrix composites; laser machining of supperalloys; short-pulse high-density laser machining; diode pumped laser machining of materials; ultra-short pulsed laser machining; and three-dimensional micro-structuring.

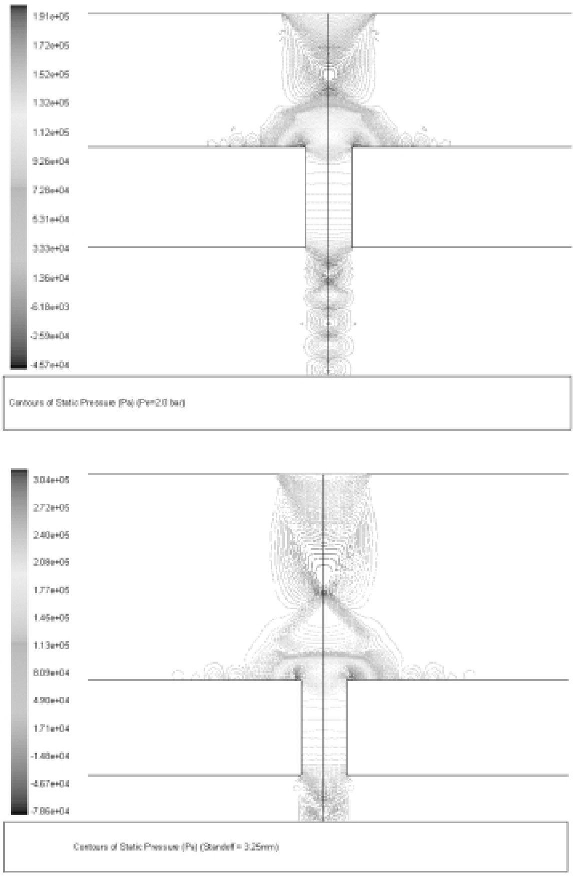


Fig. 2. Contour of static pressure for (a) $P_e = 207\,\mathrm{kPa}$ ($d = 0.711\,\mathrm{mm}$, $H = 2\mathrm{mm}$), (b) Contour of static pressure for $H = 3.25\mathrm{mm}$ ($d = 0.711\,\mathrm{mm}$, $P_e = 363\,\mathrm{kPa}$) [5].

In the *EDM module*, 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. Recent research results include the following subject areas: experimental investigation of micro-EDM parameters; integration of CAD/CAM with micro-EDM; molding of plastic components using micro-EDM tools; micro-structuring of silicon by micro-EDM; micro-electro-discharge machining of ink jet nozzles; optimum selection of material and machining parameters. For example, 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 a strong influence on the mechanical properties of the part. The subsurface altered material zones (AMZ) can be as simple as a stress condition that differs 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 nor systematically covered in existing texts and reference books. In this project, general issues regarding the process–material interaction of manufacturing are discussed systematically and in depth. The types and causes of the surface altered zone are discussed and compared for both nontraditional and traditional processes and are 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. Figure 3a shows the relation between surface roughness and the material removal rate and Fig. 3b shows the relation between the thickness of a recast layer and the material removal rate.

The *abrasive water-jet machining (AWJM) module* first introduces the history, basic machining mechanisms, process parameters and equipment used in water-jet machining, after which recent research results on jet formation and characteristics, modeling, control and optimization of the AWJM process are discussed in detail. The introduction covers practical implementation of the process in considerable detail – for example, the fluid mechanics behind the formation of high speed water jets and the issue of abrasive particle fragmentation [4] – and provides a sound base for advanced research.

Cross-process innovations are also introduced. The integration of two or more processes, either traditional or nontraditional, has produced many

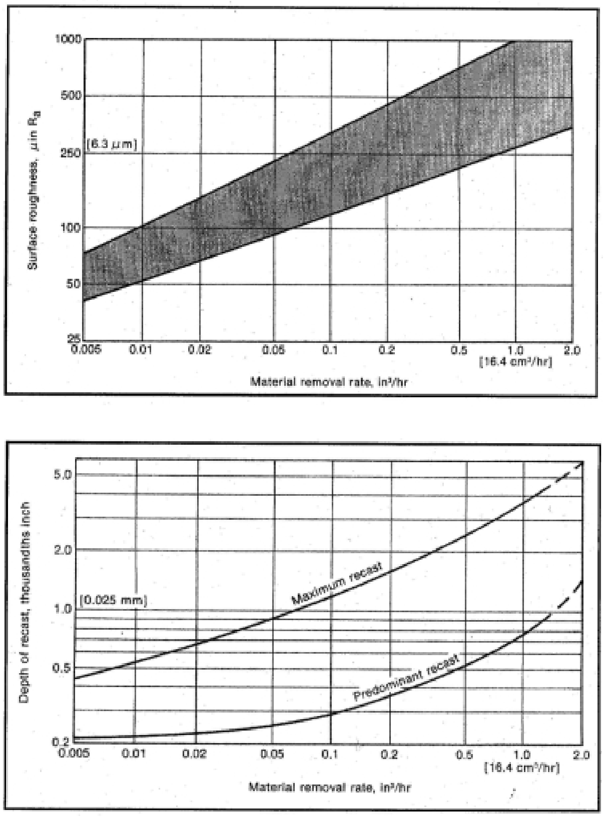


Fig. 3. Surface integrity investigation in EDM a) Relation between surface roughness and material removal rate; and b) Relation between the thickness of recast layer and material removal rate.

inspiring results. In order to use the full potential of various manufacturing processes, it is important to optimize the engineering solutions by systematically utilizing various energy fields. The general methodology behind these cross-process innovations is discussed in the Cross Process Innovation module [2]. The reason for developing cross or hybrid machining processes is to make use of the combined or mutually enhanced advantages, and to avoid or reduce some of the adverse effects produced by the constituent processes when they are applied individually. Representative examples are described, such as abrasive EDM [5], laser-assisted ECM [6], EDM with the assistance of ultrasonic vibration [7], laser/plasma-assisted conventional machining [8], and underwater laser machining [9].

WEB-BASED CURRICULUM DEVELOPMENT

The three levels described here can be studied sequentially or individually. This structure is convenient for cross-referencing, especially when it is implemented on the web. One of the advantages of web-based education is that a variety of information can be conveyed to readers all over the world with little cost and minimum time-delay. It is possible to click to see the definition of a term and to jump to any other link that is of interest. In this project, one can browse at own's pace and cross-reference numerous figures, pictures, tables, links, references, animations, videos, audios, and tests. Difficult or boring subjects can be delivered with more interest and efficiency. For example, nine colorful slides were used in the EDM module to explain the multiple steps of material removal in EDM. Figure 4 shows two of the slides: the first one shows what happens when the charged electrode is brought close to the workpiece, and the second one illustrates what happens during removal of the material. With the combination of the textual description and nine graphical illustrations, the student can quickly understand the complex machining mechanisms and may retain a vivid and hopefully permanent impression of this mechanism.

Using multimedia technology, the student can experiment with the interactive relations and view animated examples. To achieve more effective and intuitive learning, rather than just reading text, multimedia methods were adopted for this project. Generally, the creation of media files requires development of media editing and generation software. The various media types used here include text, images and graphics, sound, animation, video and virtual reality. Apart from text, images and sound, the interactive methods employed in this project are: a) the interactive exploration of physical processes with a JAVA applet; b) Macromedia Shockwave animation; and c) 3D virtual reality

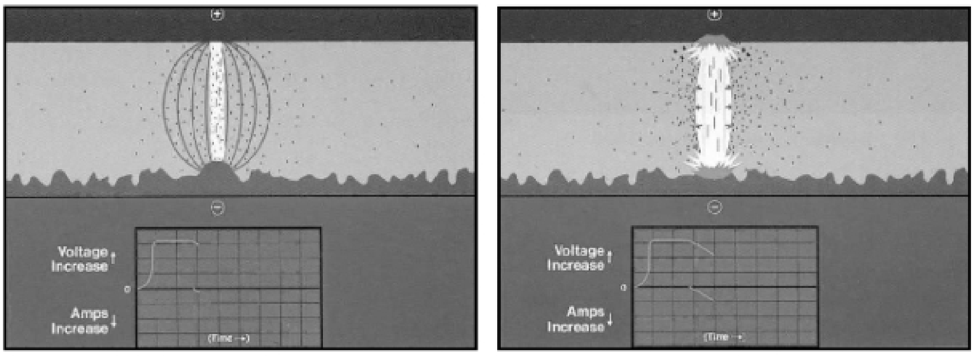
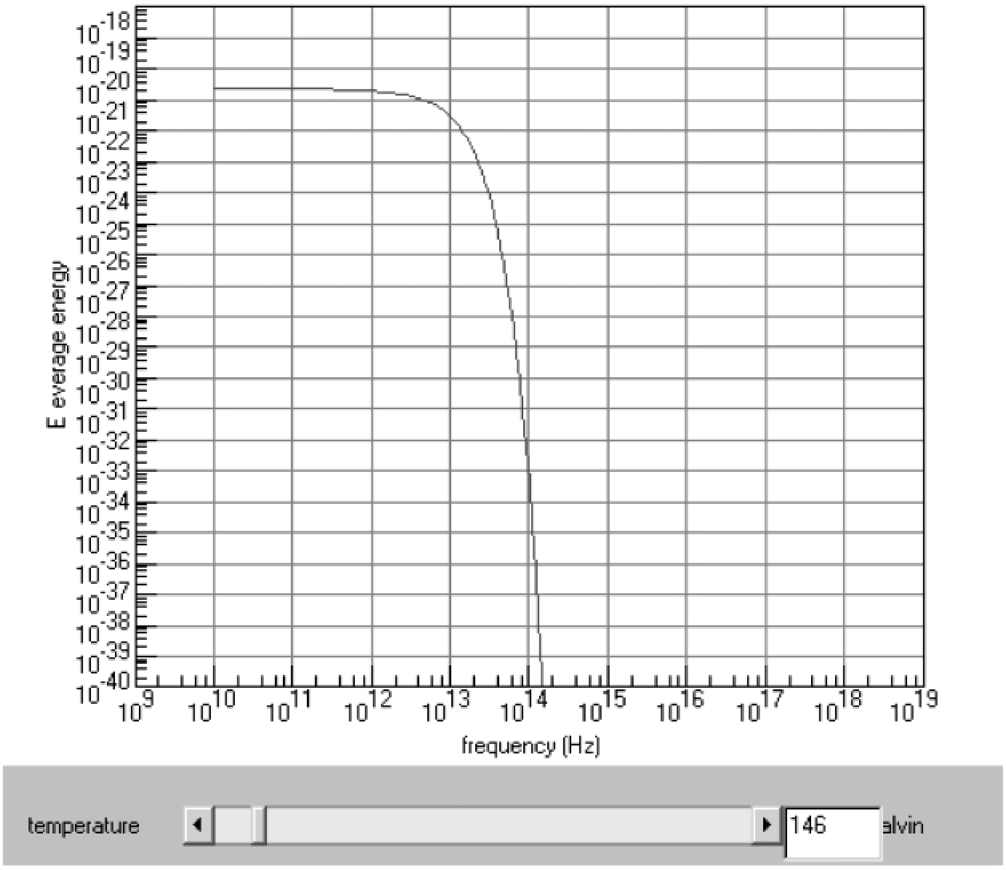


Fig. 4. Examples of multimedia: Illustration of EDM material removal mechanism with multiple slides.

(VR) animation of NTM process simulations; and d) 2D movies of process simulation 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 attract attention or to visually enhance a site or on-line course. This project utilizes an interesting mix of HTML text with embedded animations to deliver self-instruction over the web.

Interactive exploration of physical processes with Java

This project uses JAVA to enable readers to learn physical phenomena and the effects of process parameters interactively. JAVA is a programming language which can be used to deliver animation over the web (and much more; virtually anything multimedia can be delivered using Java). JAVA has been used in many applications to create interactive animations. In this project, JAVA applets are developed to enable students to learn these complex relations interactively and intuitively. For example, the laser theories of spontaneous emission, stimulated emission and population inversion are not easy for students with an engineering background to understand. Figure 5 shows an interface of a Java applet demonstrating the relation between average energy, temperature and frequency. This will allow students to adjust the temperature and observe the



temperature 146 alvin

Fig. 5. Interactive demo of Plank's Law using Java applet.

effects on the relation between average energy and frequency. The interactive interface makes it easier for students to understand Plank's law, which is essential for learning the principles of lasers.

Macromedia Shockwave based animation

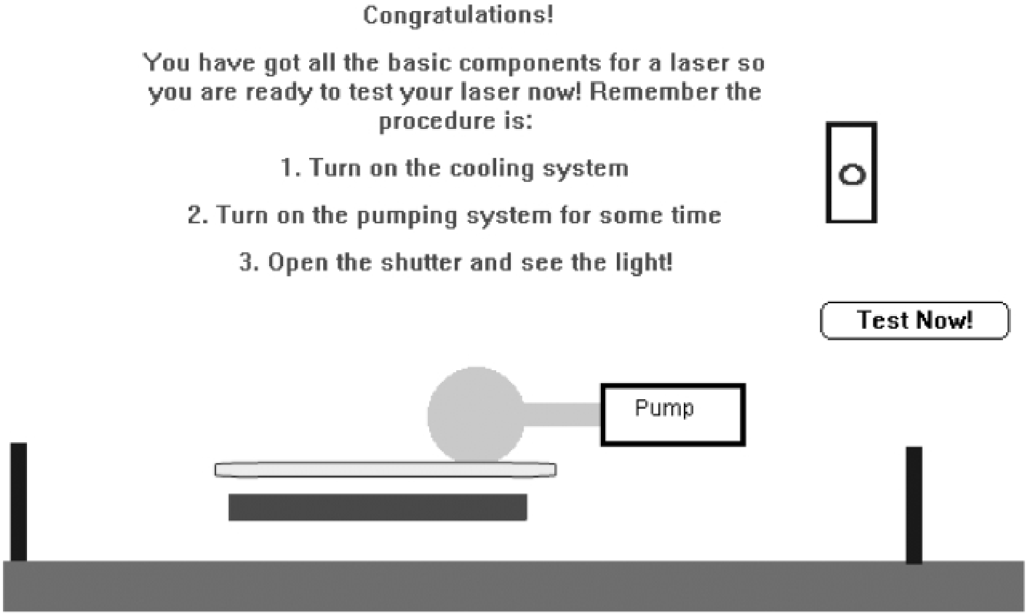
Interactive Macromedia Shockwave animation is used in this project to illustrate the basic principles of different nontraditional manufacturing systems. Macromedia Shockwave is a browser plug-in, which has almost become an Internet standard for using multimedia interactive contents and animations. In order to show the laser principles, a Macromedia Shockwave animation is used to show laser system assembly. Figure 6 shows a snapshot of this animation, in which a laser system is assembled step by step, finally resulting in a working laser system with all the necessary components in place. The Laser System Demo can be found at the following link: (http://www.columbia.edu/cu/mechanical/mrl/ntm/level1/ch02/media/laserdemo.htm).

Many of us can learn more efficiently using visual or audio aids. With the help of such interactive features, even undergraduates can understand the basics of lasers in a relatively short time.

3D interactive animations of process with VRML

An emerging standard for 3D formats for the web is VRML (virtual reality modeling language), which is employed by means of 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. 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 is a file format that defines the layout and content of a 3D world with links to more information. Unlike HTML, however, VRML worlds are inherently interactive – filled with objects that mutually interact with users. This ability to display interactive three-dimensional images and animation on the web offers educational opportunities for illustrating difficult concepts and principles. The advantages of using VRML technology for distance learning are enormous, with students being able to avail of the opportunity to share space and time in a virtual environment. No longer will students have to view the instructor from a distance. For example, a group could effectively tour around a virtual manufacturing process online together, thus providing for interaction between the participants. Face-to-face communication becomes possible and groups can collaborate on projects, even if there are miles or oceans between the students and teacher.

In this project, 3D virtual reality modeling of nontraditional manufacturing processes is developed using VRML to stimulate students' interest and offer them the opportunity to look at the 3D simulation results. Animated 3D visualization of the simulation data allows the user to change camera parameters (view the simulation from another position, zoom in on specific regions of interest, etc.) and start and stop the animation or change its speed. For example, a student can see 3D interactive animations of the laser forming process, as shown in Fig. 7, which is a snapshot of the Von Mises Stress history in the laser forming of a 1/4 circular plate. Laser is a very flexible and easily controlled high-intensity thermal source. During the laser forming process, a large thermal gradient is generated along the plate thickness direction by scanning laser energy across a metal plate. The resulting thermal stress can bend the material in predictable ways. It is a noncontact and easy-to-control process, and the bending can be



Congratulations!

You have got all the basic components for a laser so you are ready to test your laser now! Remember the procedure is:

1. Turn on the cooling system

2. Turn on the pumping system for some time

3. Open the shutter and see the light!

Fig. 6. Examples of multimedia: macromedia animation of laser system assembly.

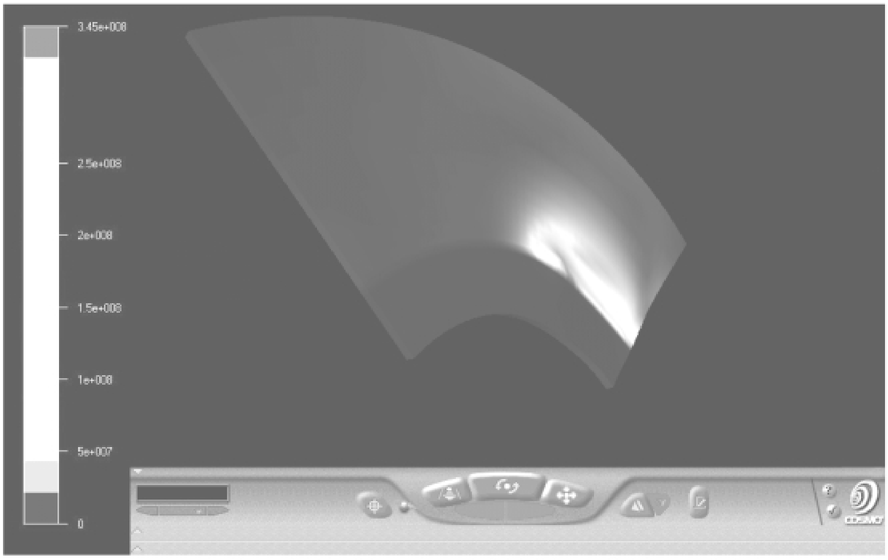


Fig. 7. Snapshot of a 3D interactive animation of Mises stress (S_{mises}) in laser forming of a circular plate.

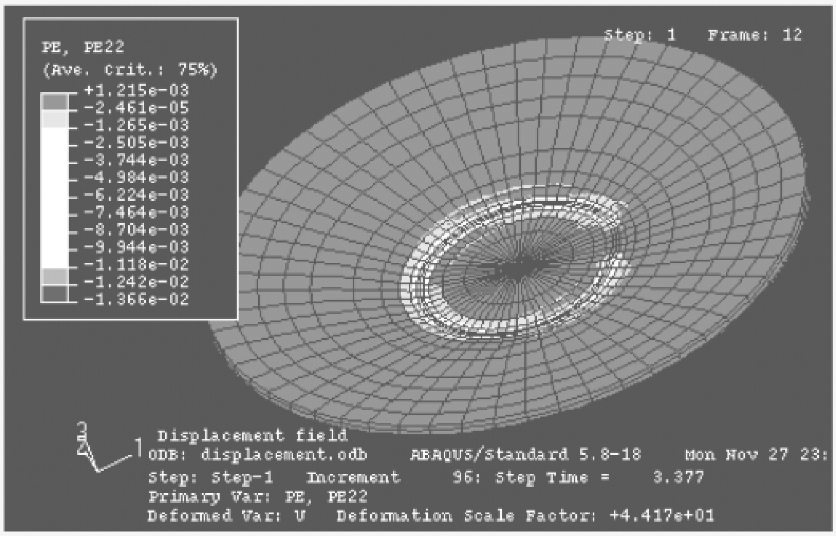
explained by studying the thermal and stress evolutions in the process. Similar efforts should be applied to other NTM processes in the future.

2D movies of process simulation by finite element modeling

Process simulation results (e.g. data for successive temperature distribution maps and residual stress) show the details of the workpieces from an angle in the NTM process. FEM analyses are very important in research and education in the area of NTM, especially for graduate students. Undergraduate students and many process engineers and managers do not have enough background information or time to do the actual modeling. It is useful to expose any people who are interested in NTM processes to some representative FEM results, to help them understand the power and value of FEM analysis in NTM. However, this is difficult to implement using paper-based textbooks. In this project, students are able to see 2D movies of process simulation results using 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 distributions are available upon request for certain process conditions. Figure 8 shows a snapshot of a QuickTime movie of plastic strain during laser forming of a circular plate.

CONCLUSIONS

The multidisciplinary nature and the diversity of NTM have posed more challenges than teaching traditional manufacturing processes. This NSF-supported project has resulted in a web-based, step-by-step presentation of NTM processes that



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 Displacement field
ODB: displacement.odb    ABAQUS/Standard 5.8-18    Mon Nov 27 23:
Step: Step-1   Increment     96: Step Time =     3.377
Primary Var: PE, PE22
Deformed Var: U   Deformation Scale Factor: +4.417e+01
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Fig. 8. An example of QuickTime movie of plastic strain (PE_{22}) during laser forming of a rectangular plate.

provides up-to-date and easy-to-follow pedagogic materials for upper-level undergraduate and introductory graduate curricula. The following web-based interactive features were adopted in this project: interactive exploration of physical processes with JAVA applet; Macromedia Shockwave based animation; 3D virtual reality (VR) animation of NTM process simulations; and 2D movies of process simulation using finite element modeling (FEM). An assessment of the developed curriculum will be presented in a future study.

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