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R&D CONSORTIUM ON COST EFFECTIVE HIGH PERFORMANCE MACHINING

of Ferrous Materials

October 1997

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by

Alcoa Forged Products
Chessen Group Inc.
Cincinnati Milacron
Cummins Engine Co.
Dapra Corp.
Eaton Co.
GM North American Operations
GM Powertrain
Institute of Advanced Manufacturing Sciences
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and

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BARBER - 5.22.06r0000014

TABLE OF CONTENTS

83

BARBER - 5.22.06r0000015

I. INTRODUCTION AND BACKGROUND

There are two ways to turn a machine shop into a more profitable operation: (a) by replacing conventional processes with new processes utilizing the latest technology and by (b) complementing existing processes with the latest technology. While case studies already provide evidence that High Performance or High Speed Machining (HSM) offer great potential, several questions remain:

Business Questions

- How does my company benefit from this technology? What is my return on investment?
- What are the advantages of HSM over the present machining methods (conventional CNC machining, EDM)?
- What specific materials and machining operations will this Consortium project cover?

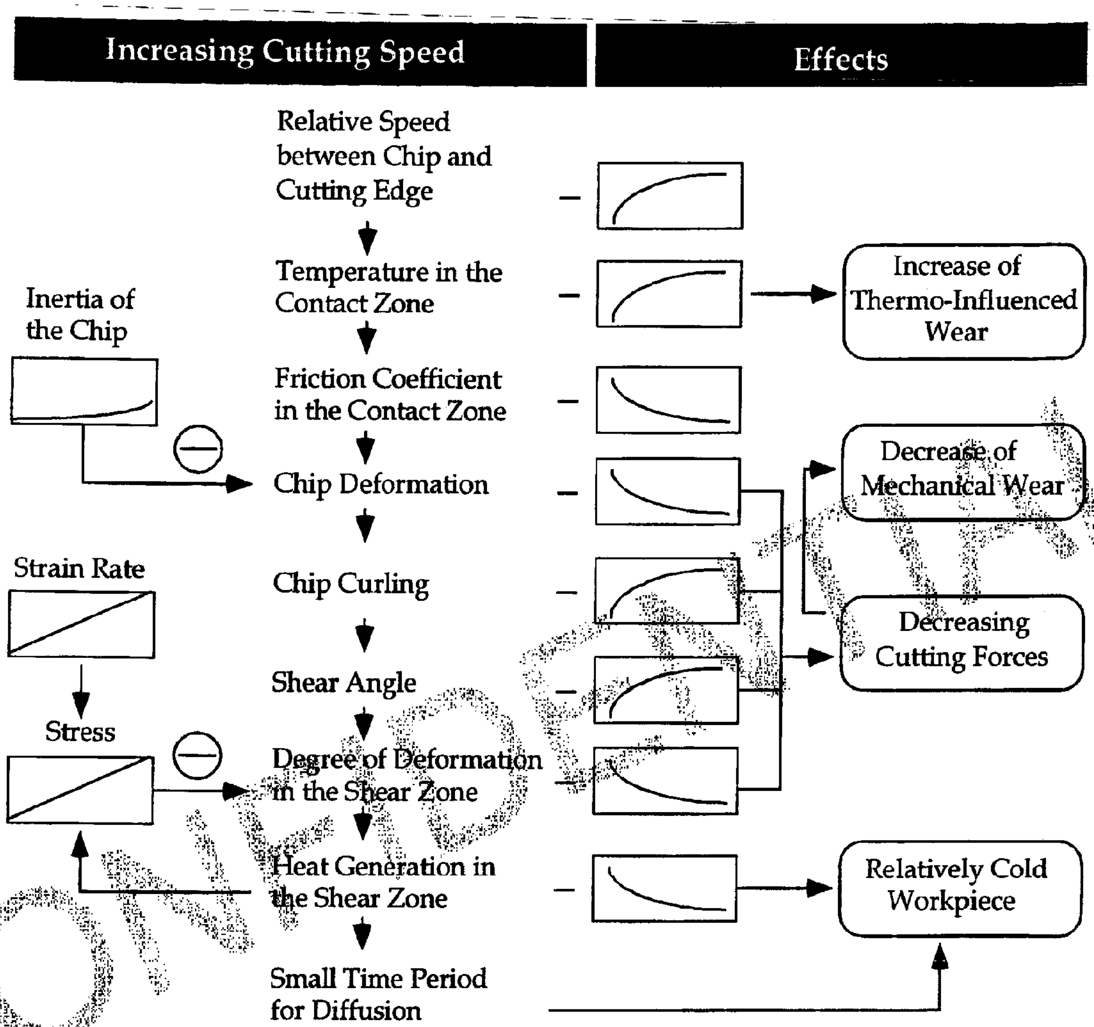
It is true that in most cases costly equipment is needed to fully benefit from new technologies such as High Speed Milling and Hard Turning. But, with appropriate implementation, the gain in productivity is so high that the breakeven point is usually reached within two years of investment. Throughput can be increased dramatically, so that additional capacity leads to higher volume, sales and profits.

Technical Questions

- For a given specific application, in addition to the machine tool, what infrastructure and technical knowledge are necessary for cost effective application of this technology?
- What is the least expensive and most effective way of implementing this technology?
- How do I train my staff for effective implementation of this technology?

Machine tool and NC technology advanced considerably during the last decade. However, in order to apply high performance machining cost effectively, two major areas still need development:

1) The actual "chip removal process" sets limits for High Speed Machining (HSM) of hardened materials and other difficult to machine alloys. Though research in the field of metal cutting has been going on for 100 years, the chip forming process is still little understood. The physical phenomena observed in high speed cutting are shown in **Figure 1**.
2) NC programs need to include process-oriented input (optimum cutting speeds and feed rates, prediction of tool deflection, elimination of chipping, prediction and increase in tool life). The amount of geometric data has to be minimized in order to allow for faster processing times by machine controllers.



Source:
Schulz, Herbert; High-speed Milling of Metalic and Non-metalic Parts, Hanser, 1989, pp 21 (in German)

Figure 1: Effect of Increasing Cutting Speed on the Cutting Process Mechanics

BARBER - 5.22.06r0000017

II. OBJECTIVES

In cooperation with the customer, i.e. members of this Consortium, the project team will evaluate, optimize and implement high performance machining processes with the goal to maximize throughput for a given manufacturing task.

To achieve this goal, many technological tasks have to be addressed, because High Speed or High Performance Machining Technology necessitates consideration of the whole operation system: data handling, cutting parameters and tool path generation, machine tool and controller capabilities, spindle/tool interface, tooling and workpiece material. This project is designed to address the most critical aspects of HSM technology. The specific objectives of the project are to:

1. Establish **optimum process conditions** (cutting speed, feed rate, cutting tool material and coating) for machining a given material and microstructure
2. Develop techniques to **reduce machining time substantially** (up to 50%)
3. **Estimate and extend tool life** to avoid premature tool failure and damage to machined surface
4. **Predict tool forces and tool deflection** and make the necessary adjustments in the NC program to improve dimensional accuracy
5. Establish **relations between process conditions and properties** of machined surface to improve surface integrity and quality
6. Develop **educational modules and seminars** to transfer the technology to the customer.

Towards achieving these objectives, the proposed work will focus on:

a) Workpiece materials: steels, cast iron
b) Machining operations: High speed milling of sculptured surfaces, end milling, hard turning, drilling
c) Tool materials: carbide and coated carbide: (TiN, TiCN, TiAlN, AlTiN, AlO_2), ceramics, Cermets, and CBN
d) Tool geometries: all
e) Cutting edge geometries: angles, tool tip, chip breaker, edge preps, etc.
f) Part geometries: flat and sculptured surfaces
g) Cutting conditions (chip thickness, cutting speed, feed rate, depth of cut, width of cut)

The level of emphasis on each task will be determined by the consensus of the member companies of the Consortium. In addition to provide funding, members are expected to participate in technical meetings and provide input in prioritizing the proposed research tasks in the project.

III. APPROACH

In outlining the technical details of this project and in conducting the project tasks, the project team will coordinate its work with Consortium members.

Phase I. Increased Throughput Leading to Higher Profits

The overall goal in this project is to increase the throughput of a machining operation in order to achieve higher profits. Project tasks will be approached from two different directions:

a) Replacing conventional machining sequences by processes utilizing the newest technology in order to increase capacity and decrease cycle time, **Figure 2**.
b) Complementing existing processes with leading edge technology:

Three machining processes with a high potential for productivity gain are High Speed Milling, Hard Turning and High Performance Drilling.

A method will be developed for estimating the cost effectiveness of HSM for a given application. Investment and maintenance costs of machine tool and cutting tools will be considered as well as reductions in machining time, improvements in surface finish and integrity. In addition, the impact of enhanced manufacturing process on part quality and life will be estimated.

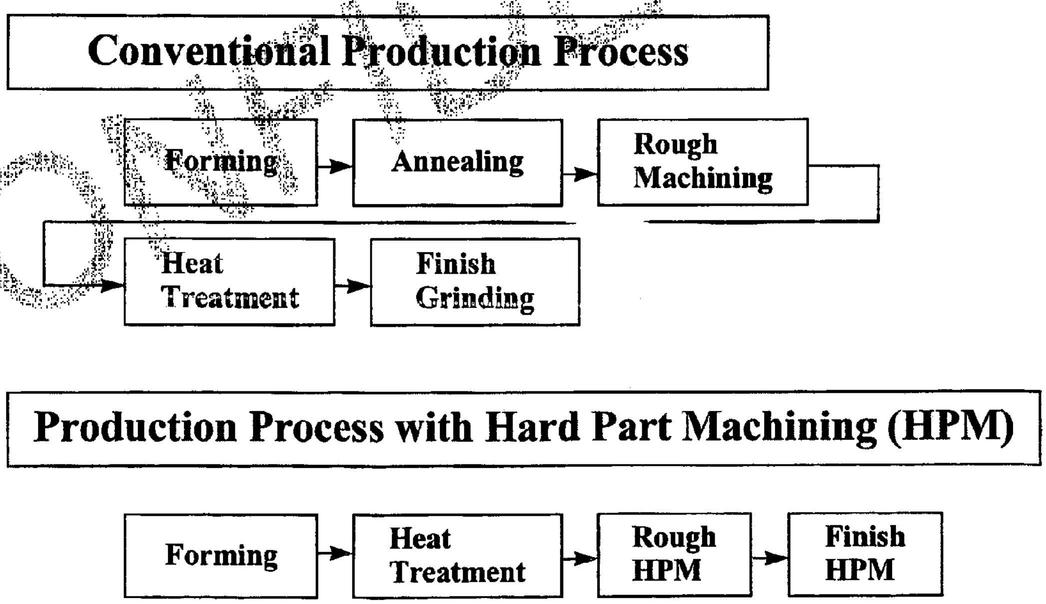


Figure 2: Hard part machining replaces conventional machining methods

Phase II. Optimization of Process Conditions and Tool Geometry

Task 2.1. Determine Process Conditions for High Performance Machining

Conduct experimental studies using different workpiece materials and tool materials such as carbide, coated carbide, Cermets, ceramics and PCBN. See **Figure 3** as an example for a study run with PCBN tools in P-20. Coatings that will be considered are TiN, TiCN, TiAlN and multi-layer coatings with combinations of these with the main focus of this study being on the more advanced cutting materials.

Process parameters such as chip thickness, cutting speed, feed rate, depth and width of cut will be optimized with regard to maximum Material Removal Rate (MRR) in roughing and optimal surface integrity in finishing. The expression surface integrity includes aspects such as dimensional and form accuracy, residual stresses and changes in microstructure.

Task 2.2. Design of Tool Geometries for Optimum Machining Conditions

Experience gained under Task 1.1. in conjunction with Finite Element Analysis (FEA) will be used to determine the optimal tool geometry for a given tool material and application. The investigation will be based on commercially available tools (inserts) and tool geometries. Suggestions will be given for design changes if necessary. **Figure 4** illustrates an example for predicting chip flow and temperatures using FEA.

Task 2.3 Tool Balancing and Run-out

Discussions with ERC customers revealed that in some cases balancing problems occur well below 10,000rpm. In addition, run-out on indexable tooling of more than 0.001" has been reported. In conjunction with participating cutting tool manufacturers, guidelines will be developed to determine when balancing problems occur and how to resolve them. Furthermore, run-out has to be considered when establishing design guidelines for cutting tools under task 1.2.

Task 2.4. Develop a Method for Estimating and Eliminating Tool Failure for Given Cutting Conditions

Conduct cutting tests as well as finite element analysis for establishing the relations between tool failure (wear or chipping) and cutting conditions when using uncoated solid carbide tools, coated carbides, cermets, ceramics and PCBN.

In High Performance Machining, using brittle cutting materials (such as CBN and ceramics), tool failure is mostly by chipping and not by abrasive or adhesive wear. Consequently, the effect of static and dynamic chip loading upon tool (insert) failure must be established. Thus, cutting conditions can be modified to reduce or eliminate tool failure by chipping.

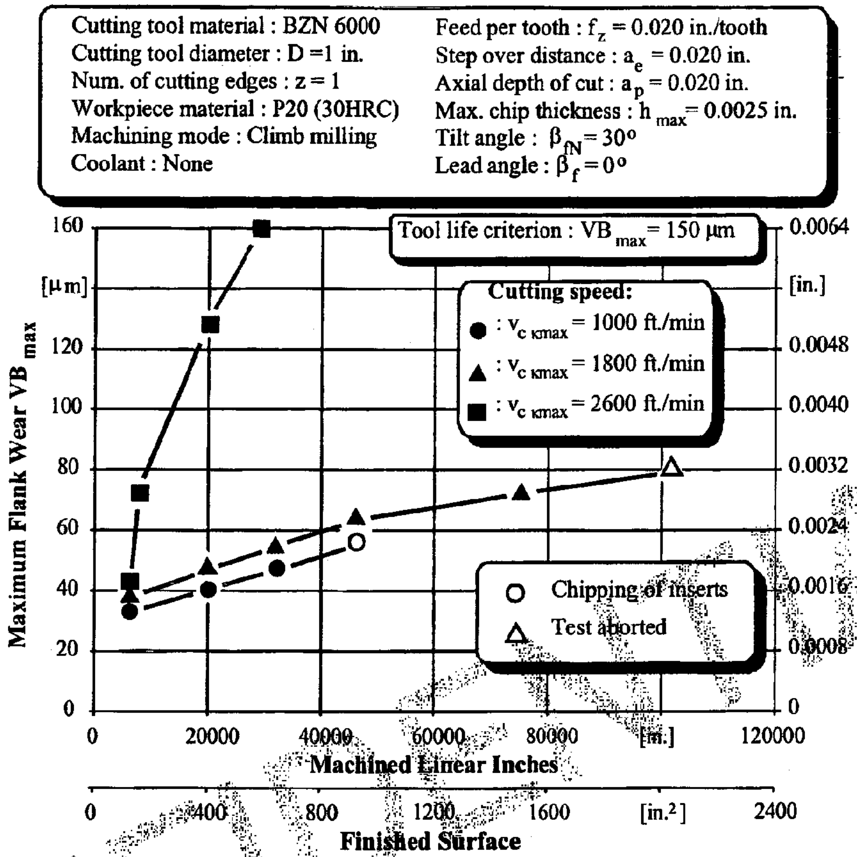


Figure 3: High Speed Machining of P-20 with PCBN Cutting Tools

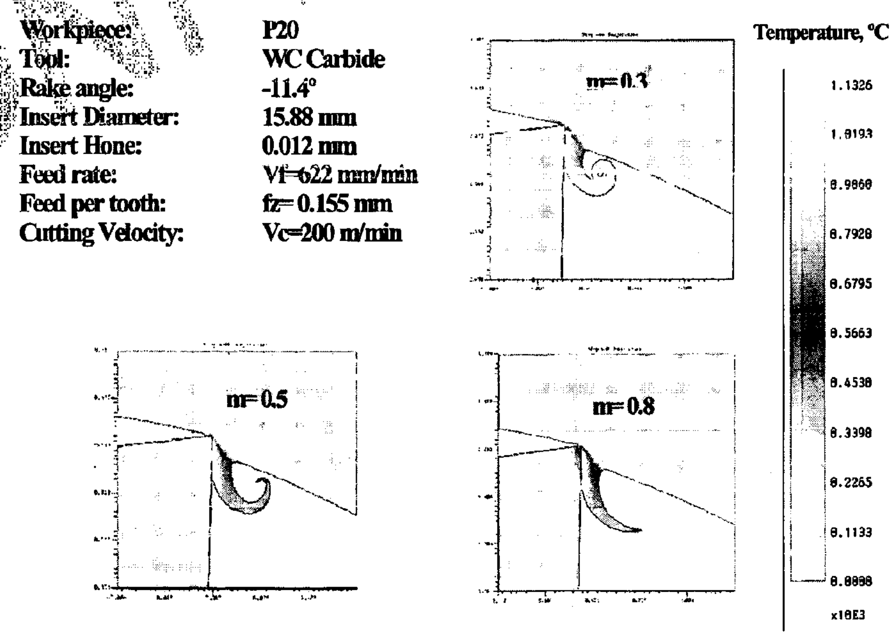


Figure 4: Influence of Friction Factor m on Chip Formation and Temperatures

Phase III. Advanced NC Programming

Task 3.1. Technological Aspects in NC Programming

Technological aspects of the machining process will be incorporated in NC programming. Local engagement conditions change constantly during milling sculptured surfaces. Spindle speed and feed rate have to be adjusted to keep the load on the tool within defined limits to reduce machining time and to minimize tool failure and tool deflections, **Figure 5**. To address these issues a software package has been developed at the ERC/NSM. The software is called OPTIMILL. It takes CAM output files and analyzes the tool engagement conditions. Optimization of feed rates and spindle speeds is done by adding feed rate and spindle speed commands to already existing geometrical information. OPTIMILL will be further improved within this project.

Task 3.2. Control Tool Deflections and Machining Accuracy

Enhance existing techniques to control tool deflection and improve dimensional and form accuracy which are not only functions of system rigidity and tool geometry but also dependent on cutting parameters and cutting strategy.

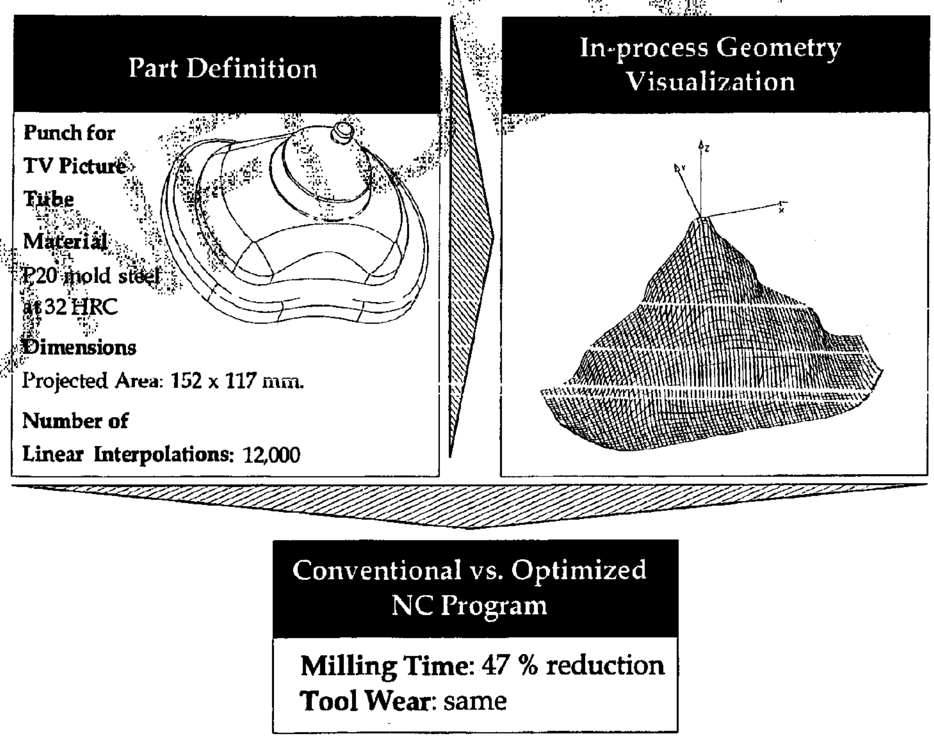


Figure 5: Picture Tube Die Machined with Program Optimized by Optimill

Task 3.3. Minimize Geometric Information in NC Programs
The cutting strategy that is chosen to machine a surface influences the amount of generated data tremendously. Conventional point-to-point motions require more geometric information to meet desired tolerances than motions that utilize circular interpolation, G02 and G03 commands, or even spline interpolation. The information that is generated in the CAD system has to be processed by the machine tool controller and influences the processing time considerably.

Phase IV. Control and Improvement of Part Quality

Task 4.1. Definition of Optimal Surface Integrity
Depending on the application, "optimal surface integrity" may be interpreted in different ways. In applications for die casting for example, compressive stresses in the die surface are desired since they prolong die life. With regard to the workpiece materials that will be chosen for this project and their application, optimal surface integrity in terms of surface finish, residual stresses and micro-structural changes will be defined. 83

Task 4.2. Determine Relation between Cutting Conditions and Surface Integrity
Use FEM techniques to predict temperatures, residual strains and stresses as well as surface microcracks. The theoretical analysis will be verified by experiments. An important parameter in this investigation is represented by the flank wear on the milling cutter. An increase of the rubbing action leads to increased friction energy and temperatures that in turn may damage the machined surface.

Task 4.3. Prevent Recutting of Chips
Recutting of chips represents a problem in machining cavities or gummy materials. Since the chip has been heated and cooled down quickly, it gets heat treated and, therefore, often inhibits a much higher hardness than the workpiece material. It sticks on the rake face of the tool or remains in the cavity and damages the surface in the following cut. High pressure air will be applied to the cutting edge through the spindle and the tool, and tested as a means to prevent recutting of chips.

Task 4.4. Guidelines for Achieving Optimal Surface Characteristics
Results of this study will be used to establish guidelines for selecting cutting conditions to obtain desired integrity and properties of the machined surfaces.

BARBER - 5.22.06r0000023

PHASE V. Technology Transfer - Communication of Results and Training

Task 5.1 Tool Performance Analysis (TOOL-PAL)

TOOL-PAL is an interactive program that will deliver information for drilling, milling and turning operations. It will assist users in selecting tool geometry, tool material and cutting conditions for particular applications. TOOL-PAL will function as a database for experimental results generated at the ERC/NSM.

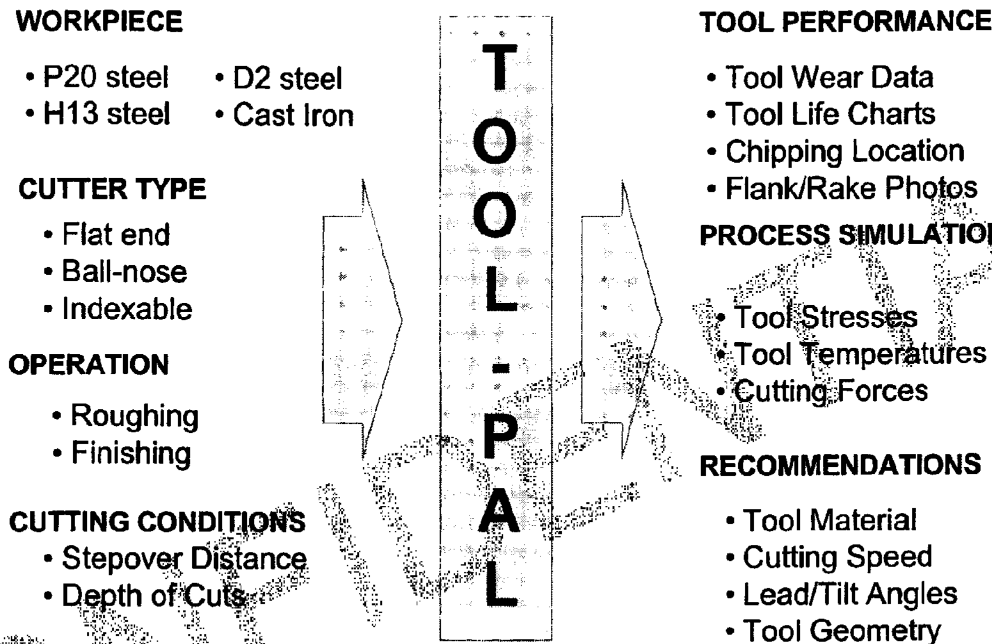


Figure 6 Structure of the Tool Performance Analysis Software (TOOL-PAL)

Task 5.2 Training Material and Seminars

Development of training material, for example an interactive CD-ROM, that can be used either for individual study or in classroom setting for training engineers and technicians of member companies.

IV. WHAT DOES MY COMPANY GET OUT OF IT?

1. INCREASED THROUGHPUT LEADING TO HIGHER PROFITS

a) Focus on key processes that consume a high percentage of the cycle time in a machining operation
b) Increase throughput by substitution and/or improvement of processes
c) Deliver complete process knowledge (such as machines, tooling and process mechanics) to the customer

2. LET THE INTERACTIVE COMPUTER PROGRAM *TOOL-PAL* HELP YOU IN SELECTING:

a) Tool material/coating
b) Insert geometry / cutting edge preparation
c) Machining parameters and strategies

Your Tool-Pal will be available on CD Rom.

3. COMPUTER PROGRAM *OPTIMILL* AND OTHER SOFTWARE

a) Prediction and **compensation of tool deflections** for any tool geometry and application
b) **Optimization of spindle speed and feed rate** in ball and flat end milling as a function of max. chip thickness and cutting speed to eliminate/reduce tool wear/failure and machining time
c) A method and the associated computer program for **tool wear estimation and advanced tool management on the shop floor**
d) A method and computer program for **designing cutting tools/inserts.**

4. TECHNOLOGY TRANSFER

a) **Machining of sample parts** provided by customer
b) **Training Seminars** in your company for presentation of project results and other issues
c) **Meetings** with project participants every **3 months**
d) **Annual reports**

Note: Deliverables listed above are tentative.
Companies participating in the project will have significant input in establishing the direction of the research and the priorities for various tasks.

BARBER - 5.22.06r0000025

V. CAPABILITIES AT ERC/NSM

- **Detailed knowledge of the die/mold manufacturing industry.** The ERC/NSM has been working with the forging, stamping, die casting, injection molding and die/mold industries for a number of years.
- **The software package OPTIMILL**, developed at the ERC/NSM, for optimizing the spindle speed and feed rate in ball end milling as a function of max. chip thickness and max. cutting speed.
- **Experience in chip flow simulation** using DEFORM software.

VI. FACILITIES AND EQUIPMENT AT ERC/NSM

- **Makino A55** 4-axis horizontal high speed machining center with 14,000 rpm/30 hp spindle, 1570 in/min feedrate capability
- **Makino Hyper5** 3-axis vertical high speed machining center with 32,000 rpm/2.6 hp spindle, 630 in/min feedrate capability
- **Cincinnati Milacron T10** 4-axis horizontal machining center, 4000rpm spindle
- **Okada Modelmaster** 3-axis vertical milling machine, 10,000rpm spindle
- Sheffield **Coordinate Measurement Machine** RS-30 DCC
- Measurement equipment, IBM Risc 6000 UNIX workstations, software etc.
- Analysis equipment such as **Scanning Electron Microscopes** and **X-ray Diffractometers** are available on campus.

VII. ONGOING EFFORTS RELATED TO MACHINING

- **A new proposal to NSF** on 'Mechanics of Machining as a Deformation Process - Design of Tool Inserts and Prediction of Tool Wear Using FEA in 2D and 3D Machining', will be submitted in spring 1998
- **DoE Project** in cooperation with NADCA on 'High Speed Milling and Pulsed ECM: New Machining Technologies to Increase Die Life', has started September 1996 and will be conducted until July 1998.
- **Modeling of the cutting process**, cooperation with DAPRA Corp., Ingersoll Cutting Tool Co., Kennametal Inc. etc.
- Performance of **PCBN tools** in machining hard materials, cooperation with GE Superabrasives, Diamond Abrasives Corp. (DAC) and Sumitomo.
- **NSF Project** on Development of Educational Modules titled 'An Opportunity for Supplemental Educational Initiative Funds to an Engineering Research Center'. This project has been funded and will start late 1997. As part of this work, we will develop training materials in manufacturing, including HSM.
- Several **industry projects** on high speed machining and hard turning.

VIII. PROJECT PARTNERS AND PROJECT FEE

The project consortium will consist of part manufacturers as well as cutting tool and machine tool manufacturers to assure a high level of efficiency in our effort to introduce or expand high performance machining in your operation. Membership fee is $20,000/year for a minimum of 2 years.

IX. PROJECT SCHEDULE

The project started in March 1997 and will run for a minimum of **2 years**. However, if at the end of the project the participating companies wish to address additional research topics, the cooperation will continue.

X. PROJECT PERSONNEL

The proposed research will be conducted at the Engineering Research Center for Net Shape Manufacturing. *Dr. Taylan Altan* is the Director of the Center.

The project coordinator will be *Dr. Ciro A. Rodríguez*. He will be assisted by full time staff engineers, graduate students and undergraduate students.

Dr. Nuri Akgerman, Associate Director of the ERC/NSM, will be consultant to this project.

Brief biographical sketches of the senior project personnel are given in Appendix A.

XI. APPENDIX A

TAYLAN ALTAN
Department of Mechanical Engineering
Department of Industrial and Systems Engineering
The Ohio State University

EDUCATION

Ph.D. in Mechanical Engineering	**University of California at Berkeley**, 1966
M.S. in Mechanical Engineering	**University of California at Berkeley**, 1964
Diploma Ingenieur, ME	**Technical University**, Hannover, Germany, 1962

TEACHING EXPERIENCE

1986-Present	**Professor**, Mechanical and Industrial and Systems Engineering The Ohio State University
1978-1986	**Adjunct Professor**, Industrial and Systems Engineering The Ohio State University

INDUSTRIAL AND GOVERNMENTAL EXPERIENCE

1986-Present	**Director**, ERC for Net Shape Manufacturing
1968-1986	**Sr. Research Scientist/Research Leader/Senior Research Leader** Battelle-Columbus Division
1966-1968	**Research Scientist**, DuPont Company

AWARDS AND HONORS

1986	**Fellow**, Society of Manufacturing Engineers
1986	**Fellow**, American Society of Mechanical Engineers
1985	**Gold Medal**, Society of Manufacturing Engineers
1983	**Fellow**, ASM International
1976	**Chairman**, Production Engineering Division, ASME

PUBLICATIONS

Co-authored more than 200 technical papers in refereed journals and proceedings, 3 books, several book chapters, and a large number of invited presentations

OTHERS

Member of the Editorial/Advisory Board of four international journals
Founding member of NAMRI, North American Manufacturing Research Institute of SME
Chairman of the Scientific Committee, 1982-1985
Active member of CIRP, Chairman of STC - Scientific Technical Committee Forming (1986-1989)
Member, R&D Committee of American Management Association, 1988-1991
Member, Manufacturing Subcommittee of Ohio Science &Technology Council

NURI AKGERMAN
Associate Director
Engineering Research Center for Net Shape Manufacturing

RESEARCH and DEVELOPMENT EXPERIENCE
Planned and conducted a variety of manufacturing research and development projects for federal and corporate clients in the following areas:

- CAD/CAM of dies and molds.
- Definition and NC machining and inspection of complex surfaces.
- Development of Specialized Computer Numerical Control units.
- Implementation of custom manufacturing systems including development of custom equipment.
- Analysis procedures for manufacturing processes such as forging and rolling.

Directed the technical development of ToolChest CADCAM product (commercialized 83 by Battelle and later sold to TC Dynamics Inc.). Was responsible for product quality, staffing, release schedules, etc. Participated in marketing and sales activities.

MANAGEMENT EXPERIENCE
- Managed, motivated and led a team of engineers.
- Responsible for hiring and periodic evaluations.
- Coordinated all technical activities, task assignments, scheduling and priorities so as to insure on time project completion.
- Participated in strategic planning and budgeting activities.
- Demonstrated ability to communicate effectively.
- Prepared proposals and presentations to clients.
- Performed cost estimates and formulated schedules.
- Coordinated contract negotiations.

TECHNICAL EXPERIENCE
Twenty plus years of experience with computers of all kinds. Familiar with the use of PC's, HP/400, HP/700, IBM RS/6000, DEC and Sun workstations and networks as well as Unix, Fortran and C. Actively involved in algorithm development and coding for ToolChest CADCAM system and other similar products and systems. Hands on experience in the design and building of production machinery and control systems. Machine shop experience with manual as well as CNC equipment.

EDUCATION
Ph.D., Mechanical Engineering, University of California at Berkeley, 1971
Master of Science, Mechanical Engineering, University of California at Berkeley, 1967
Bachelor of Science, Mechanical Engineering, Robert College, Istanbul, Turkey, 1966

BARBER - 5.22.06r0000029

CIRO A. RODRIGUEZ
Project Coordinator
Cost Effective High Performance Machining Consortium
Engineering Research Center for Net Shape Manufacturing

EDUCATION

Ph.D. in Industrial Engineering	**The Ohio State University**, 1997 Dissertation title: "Ball-nose end milling – Development of Criteria for Automatic Selection of Spindle Speed and Feed Rate"
M.S. in Mechanical Engineering	**The Ohio State University**, 1993
B.S. in Mechanical Engineering	**The University of Texas - Austin**, 1989

EXPERIENCE

1991-1997 **Graduate Research Associate**
Engineering Research Center for Net Shape Manufacturing,
The Ohio State University, Columbus, Ohio

- Research activities in manufacturing of dies / molds, rapid prototyping and rapid tooling
- Focus on tool path optimization for CNC milling operations
- Planning and coordination of research projects with graduate students, visiting scholars and undergraduate students

1990-1991 **Lecturer**
Instituto Tecnológico de Estudios Superiores de Monterrey,
Monterrey, N.L., MEXICO

- Courses: Manufacturing processes and senior design project

1989-1990 **CAD Supervisor**
PERFEK (design and manufacturing of automotive stamping dies),
Monterrey, N.L., MEXICO

- CAD: system administration, user support and software development for design automation
- Shop floor: user support for operation of CNC milling machine (FIDIA controller) and lay out machine

PUBLICATIONS

Co-authored several technical papers in refereed journals, international conferences and trade magazines

BARBER - 5.22.06r0000030