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ADVANCED TOOLMAKING TECHNIQUES FOR DEVELOPING COUNTRIES[1]

by

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[1] The views and opinions expressed in this paper are those of the author and do not necessarily reflect the views of the secretariat of UNIDO. This document has been reproduced without formal editing.

Contents

ABSTRACT

I. Introduction

The policy of purchasing used, technologically obsolete machine tools by developing countries is questioned. The need for industrialized and developing countries to utilize toolmaking techniques which maximize productivity per scarce tool and die makers is described. Numerical control, electrical discharge and electrochemical machining are identified as new production processes for toolmaking which are valuable supplements to conventional methods. The successful development of these technologies has reduced the skill required by the machine tool operator and tool, die and mold finisher.

II. Numerical control in Toolmaking

The reasons for the superior performance of numerical control in toolmaking are defined; including productivity, accuracy, and improved quality. Reductions in worker skills are described along with recommendations for developing countries to follow in establishing training programs for the acquisition of the new programming and maintenance skills. Several examples are given which describe the use and benefits of numerical control in toolmaking. The examples are taken from industries in England, France, the United States, and Italy.

III. Electrical Discharge Machining (EDM) in Toolmaking

The recent technological advancements, which greatly reduce electrode wear and increased electrical discharge metal removal rates are described. The problems and successful procedures for shaping the important electrode are defined. The unique characteristics of the surface finish on parts made by EDM are described along with an indication of how these surfaces greatly improve die performance. EDM applications in forging dies, stamping dies, molds, die casting dies, wire drawing dies and extrusion dies are included. The advantages and problems inherent in these examples are given. The reductions in skills made possible through EDM are described.

IV. Electrochemical Machining (ECM) in Toolmaking

The profitable uses of ECM as a supplement to EDM are described. The principles of this very new process are defined and the problems involved in implementing ECM are appraised. The skills required are described and contrasted to those available in developing countries; a method is suggested for developing and introducing these skills into developing countries. Skill reductions comparable to those achievable with EDM are indicated.

V. Conclusions

The successful use of these new toolmaking technologies by industrialized countries—although largely implemented because of a profit motivation—has shown that the output of a toolmaker can be greatly increased. Because the expansion of a tool and die industry is limited by the number of qualified toolmakers available—a skill which takes four to eight years to acquire—developing countries should selectively apply numerical control, EDM and ECM to maximize the output of their precious resource of skilled toolmakers. The acquisition of used machine tools as a means to expand a developing country's tool and die industry should be discouraged because of its adverse effects upon productivity and manufacturing techniques—both of which increase the barriers to greater output from a tool and die industry. Policies for establishing an industrial development program to speed the adaptation of the new toolmaking techniques are presented.

INTRODUCTION

For economic reasons, industrialized countries have implemented new methods to increase their production of tools and dies with fewer toolmakers. Similarly, for developing countries to expand their tooling output, they too should adopt new techniques to maximize the productivity of their precious skilled labor.

The successful application of computers, numerical controls and electrical machining processes by industrialized countries shows that these new methods can now ease the shortage of critical metalworking skills.[1] The new techniques shift certain operational functions from the production floor—where job proficiency is obtained through long years of on-the-job training—to the engineering office where the appropriate skills are more speedily acquired through intensive formal technical education that is supplemented by a shorter period of on-the-job training.

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[1] For the purpose of this study, skills are defined broadly to include all levels of competence, professional as well as technical.

The relatively low labor rates in developing countries have led some to conclude that it is unnecessary to invest in automation. Thus, the use of advanced production techniques is often postponed because the direct economic incentives appear less attractive to a developing country than they appear to an industrialized country.

The use of secondhand machine tools and obsolete methods too often has been recommended as a means of expanding a metalworking industry in a developing country. Such action is logically supported by the assumption that used machine tools—often the rejected equipment of industrialized countries—may be acquired with a minimal capital outlay. An obscure, but serious disadvantage of this policy is that the developing country must then acquire an inordinate amount of additional skills to compensate for the low productivity of the obsolete machines

Productivity benefits are, therefore, of great importance to developing countries since they involve more than just reductions in cost. A policy to acquire antiquated equipment will present formidable obstacles to the development of a competitive industry, especially in the production of tools and dies, since the critical toolmaker skills are in such short supply.

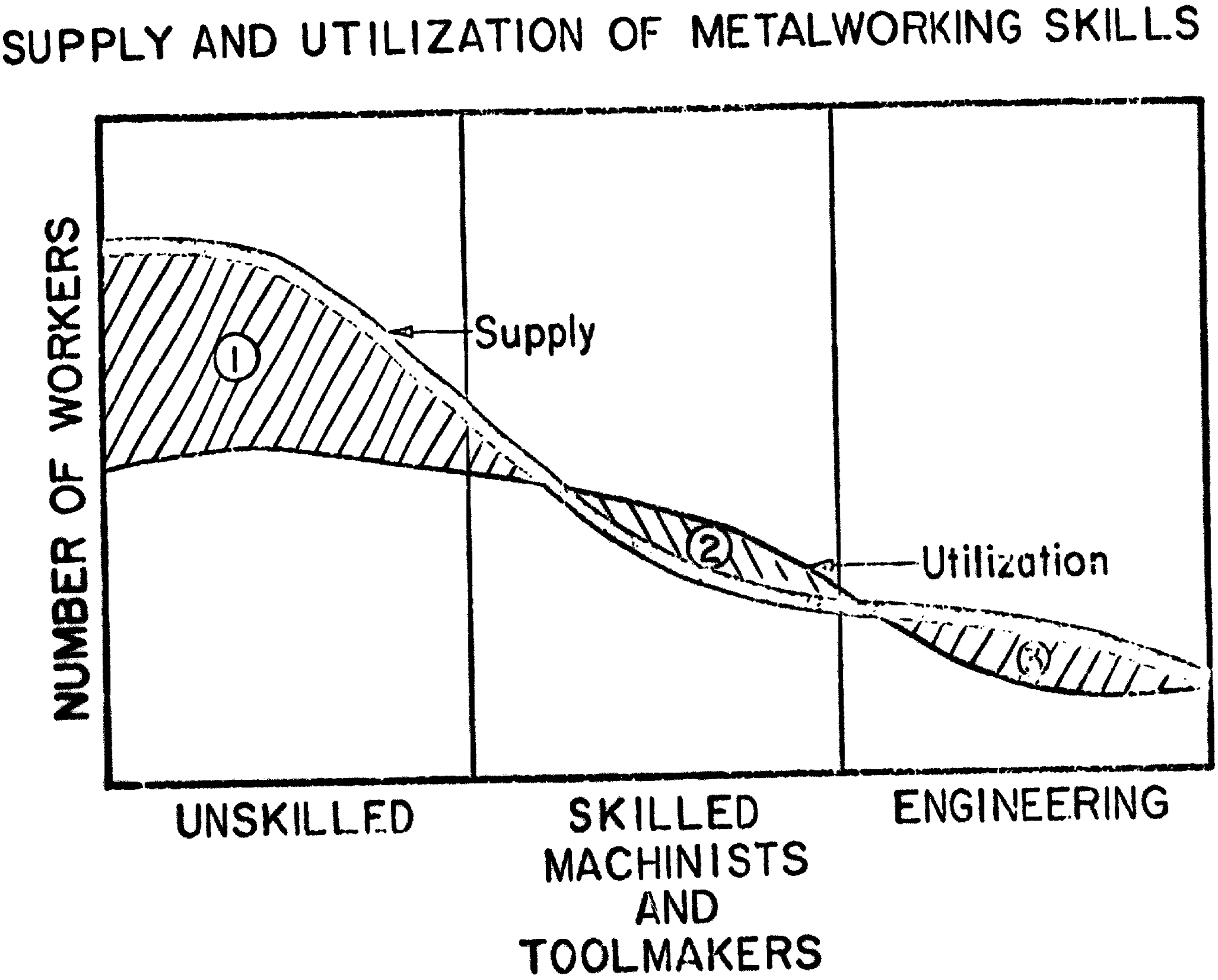
Numerical controls and the electrical machining processes facilitate greater toolmaker productivity in several ways; these include job simplification and the requirement of a different level of skills on the production floor. With numerical control, for instance, it is not the machinist, but the control tape——the responsibility of the part programmer——that regulates the machining function. Electrical discharge and electrochemical machining also reduce and sometimes eliminate many finishing operations previously required in the manufacture of several types of tooling, especially of stamping and forging dies, and molds. A beneficial shift in skills results from the use of these new toolmaking techniques; engineering specialists, including process engineers and part programmers, replace skilled machinists and assemblers.

The advantages resulting from a greater involvement of engineering and professional workers was apparent in a 1967 UNIDO-sponsored survey of a tool and die industry in one developing country. Because of a shortage of skilled tradesmen there was a serious need in that country to maximize toolmaker output and involve surplus engineering and related professional skills. The differences between the supply and demand for the various levels of metalworking skills in the country studied are shown in Chart I.

(CHART I)

A passage from the UNIDO report on the project more

CHART I


SUPPLY AND UTILIZATION OF METALWORKING SKILLS
NUMBER OF WORKERS
Supply
Utilization
①
②
③
UNSKILLED
SKILLED MACHINISTS AND TOOLMAKERS
ENGINEERING

specifically delineates the conditions encountered.

> Further expansion of the metalworking industries which requires skilled workers must be achieved in the face of a dearth of qualified workers. An untapped pool of skilled workers does not exist. This condition has already inhibited the development of the metalworking companies which were established recently. Several managers of these plants state that they were unable to hire qualified workers and resorted to the slow process of training programs. The work force of these plants was obviously much younger and considerably less experienced than the workers in the plants which were established in the 1950's. It was evident that these plants suffered from the inexperience of the workers, since the use of poor tooling practices was common. One manager of a plant founded in 1940 reported that the shortage of skilled workers is so serious that sometimes business only supports 50% of his staff. Yet he does not lay off experienced workers because it would be impossible to replace them when business recovers.
>
> The skilled labor shortages existed in the presence of an apparently untapped supply of well-educated but inexperienced engineers. This paradox was characterized by a manager of a relatively progressive firm which was highly active in the export market, who stated that 'there is a shortage of experienced, skilled workers and foremen, and a surplus of inexperienced engineers.' This significant observation was corroborated by several other companies visited subsequently.

The conditions found in this study are believed to be generally representative of those which are faced by several developing countries. It certainly is a dilemma faced by the more advanced countries as their society moves toward affluence. Young workers are not attracted to the sometimes dirty environment of a machine shop, and they also are less inclined to spend several years in apprenticeships at low wages when there is more lucrative, although unskilled work immediately available. Engineering and professional workers also have not been lured into toolmaking. With the relatively staid technologies which until recently were employed in the production of tools and dies, graduating engineers saw few challenges in the toolmaking field.

Because a skilled toolmaker must perform a diverse set of operations which must meet high standards at ever closer tolerances, the required skills can be acquired only with technical schooling in mathematics and metallurgy. Several years of on-the-job training are also necessary.

For a tool and die industry to produce quality tooling, all the following skills are required:

> The workers in the industry must construct and repair machine-shop tools, gages, jigs, fixtures or dies for forgings, punching, and other metal-forming work.
>
> These activities involve most of the following: planning and laying out of work for models, blueprints, drawings, or other oral and written specifications; using a variety of tool and die maker's hand tools and precision measuring instruments; understanding the working properties of common metals and alloys; setting up and operating machine tools and related equipment; making necessary computations relating to dimensions of work, speeds, feeds, and tooling of machines; heat-treating of metal parts during fabrication as well as finished tools and dies to achieve required qualities: fitting and assembling of parts and selecting appropriate materials, tools, and processes.

Industrial development programs seeking to expand a tooling industry must create the means to develop these skills;

training, nevertheless, is a slow process.

The importance and interdependence of the training requirements are evident in the outline of a toolmaker apprentice program of one company, which is located in an unindustrialized area faced with the need to develop metalworking skills.[2] The broad-range of tasks that is specified and the duration of time required to attain the required proficiency illustrate the problems that will be encountered in a country's efforts to build a force of qualified toolmakers.

TOOL AND DIE TRAINING COURSE

PURPOSE

To train employees in the fundamentals and advanced skills of all types of bench and machine operations, and the repair of tools, punches and dies, fixtures, gages, and the development and construction of these items.

METHOD OF TRAINING

Actual on-the-job training is provided under close supervision and instruction. Five hours per week (12½% of total time) will be devoted to classroom instruction. Before advancing to the next training period, the trainee will be expected to meet both the shopwork and classroom requirements. The trainee is urged to keep in mind that he is entering into a period of formal education. This calls for sincerity of purpose, a willingness to learn, and a readiness to devote extra effort in his studies.

The following is a schedule of assignments while on this course:

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[2] Robert E. Rowe, "Tool and Die Training at Western Electric's Oklahoma City," Report No. MM68-133, American Society of Tool and Manufacturing Engineers, 1968.

Training Operation	Hours
1. Lathe	600
2. Mill	600
3. Grinder	600
4. Additional Machines	600
5. Jig and Fixture I	800
6. Advanced Machines	800
7. Jig and Fixture II	840
8. Punch and Die I	1,240
9. Punch and Die II	1,240
Graduation	7,320 hours

Where the standard workweek is 40 hours, approximately four years are required to complete 7,320 hours in the apprenticeship program.

Impossible as it is to expand a tool and die industry without the development of an adequate number of qualified toolmakers, numerical control and electrical machining are reducing the basic skill content for a given level of output. Although the total substitution of the new technologies for basic skills is still not feasible, a marked reduction in the number of toolmakers or an improvement in the overall quality of an operation usually results. The successful application of these advanced methods by industrialized countries has shown that developing countries too can solve some of their industrial development problems created by the shortage of skills.

1. NUMERICAL CONTROL IN TOOLMAKING

Several technological changes in low-to-medium volume applications in metalworking are tied to the use of mathematical information for design and manufacture with numerically controlled machining. Since numerical control is a machine control method, its potential impact has sometimes been assessed as similar to that created by earlier machine tool controls such as the tracer device. However, the pervasive benefits of numerical control influence every phase of toolmaking. Design, assembly, inspection, and quality control activities as well as the machining function are all directly affected. By contrast, the tracer or duplicating machine, although indeed a significant innovation for toolmaking, had only limited effects outside the machining function.

The superior performance of numerically controlled machining results from improved flexibility and longer cutting periods at increased precision standards. Furthermore, these machines show no ill effects from fatigue when properly maintained. They are equally efficient in the early morning, late afternoon, on the day or night shift, or Saturday and Sunday.

Productivity

When a toolmaker produces a part on a conventional machine, he must frequently refer to a drawing for the specified part dimensions. Interruptions to adjust the machine's handwheels, and to inspect the workpiece with gages, calipers, and micrometers are common. The machinist makes progressively smaller and slower cuts, measuring between each cut to avoid removing too much material. Such a trial and error process is time-consuming and quite susceptible to error.

Numerical control increases productivity by establishing all the machining instructions on the tape before the part is positioned on the machine tool. The interpretation of the drawing and decisions regarding the machining sequence are made by a programmer or process planner at a desk rather than by the operator in the shop. Expensive machine tools no longer stand idle during an operation which can be performed on inexpensive equipment in the office and the proportion of the machine's actual cutting time increases from a 10-30% range to one of 60-80%. Such high utilization of equipment is also made feasible because accurate estimates of machining time can actually be adhered to on the production floor. Tight schedules are maintained since the operator has relatively little control or influence over the pace of the machining sequence.

The increased productivity of numerically controlled tools not only reduces labor costs per part but makes a 24-hour operation of the tools feasible. In developing countries where skills and precision machine tools are scarce it becomes vitally important that the utilization of these scarce assets be maximized.

Table I shows the average productivity gains experienced by users of numerical control in a wide range of American industries and operations. In this survey, productivity was synonymous with savings in the floor-to-floor time of the machined part.

TABLE I

PRODUCTIVITY GAINS REPORTED BY SURVEY FIRMS

	AVERAGE PRODUCTIVITY INCREASE WITH N/C				
Industry	**Drilling**	**Boring**	**Turning**	**3-Axis Milling**	**5-Axis Milling**
Metal Cutting Machine Tools	153%	81%	128%	325%	470%
Electrical Machinery and Equipment	152	106	15	---	---
Aircraft and Parts	149	125	193	287	293
Tool and Die	49	31	---	20	---
Office, Computing and Accounting Equipment	57	96	30	50	---
Special Machinery	103	44	86	60	---
Other Metalworking Machinery	46	55	123	---	---
Missiles and Ordnance	115	106	93	258	420
Average for Survey*	113	84	107	197	267

Source: Numerical Control Society

*Includes returns from industries not shown in table.

The productivity trends apparent in Table I show that metalworking operations which involve sophisticated cutting motions, such as multi-axis milling and turning, produce greater productivity increases as the complexity of the cutting path increases, i.e., from 2-axis to 3-axis to 5-axis work. In point-to-point drilling or boring applications, productivity is closely related to the positioning efficiency of the process. Boring operations, where precise positioning accuracies rather than rapid process cycles are critical, show the lowest productivity increase, while drilling is somewhat higher.

In this survey, the aerospace and machinery industries reported large productivity increases in nearly all types of operations. In contrast, the tool and die industry and the special equipment manufacturers, where both the number of reporting firms and the machines they own are relatively small, show smaller improvements. The lack of sophisticated highly productive continuous-path machines is a major reason for the low gains shown by the tooling firms using numerical control. The low lot sizes also discourage devoting the time and money expended by the other industries to optimize manufacturing methods for a single part.

Both numerical control and EDM have produced attractive savings in the production of tooling over and above that achieved by the reduction in machining time. For instance, the amount of benchwork and hand finishing required is often reduced by half and the need for templates, patterns, and models are greatly lessened.

Accuracy

Even though cutting rates are accelerated with numerical control, its use often has produced a twofold improvement in accuracy over conventional toolmaking machines. Previous improvements in metal cutting accuracy were usually achieved by retarding the pace of machine operations. Since numerical control usually eliminates cutter guides, errors accumulating in the design and construction of tooling aids for conventional machines are also avoided.

Because of the accuracy limitations on conventional machines and associated tooling, parts with undesirable tolerances had to be accepted because these nevertheless met the best achievable precision standards. In the less highly developed tool and die industries where both the skills and the machine tools are not as refined as those in advanced countries these undesirable tolerances can represent substantial liabilities to the metalworking industries. The users of the tooling and the product designers facing this obstacle will welcome the accuracy improvements from numerical control, since they will be able to specify shapes and dimensional tolerances previously not feasible.

The primary reason for the great improvement in accuracy is that numerical control operates from electronic commands and through a closed-loop system.[3] As well, the information carried by the electronic signal is translated into machining directions with less chance for error in interpretation.

The finite numbers appearing on a part drawing represent discrete values with no intended tolerance, but by the time the machinist interprets and transmits the numbers to a conventional machine tool through manual controls and checks the setting with mechanical metrology devices, errors often modify the discrete value. When a part dimension is expressed by an electronic signal from a numerical control system, human errors cannot degrade the reproduction fidelity of the value and the command is accurate to better than 0.0001 of an inch and is repeatable to at least 0.0002 of an inch. Since the accuracy of the machine is much below that of the control unit's electronic signal, final part tolerances reflect limitations of the machine tool.

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[3] A system in which the output, or some result of the output, is relayed back for comparison with the input to reduce any difference between the input command and the output functional response is known as a closed-loop system. Positional information indicating the precise position of the cutting tool relative to the workpiece is continually sensed and fed back to the comparative element of the control system. So long as a disparity exists between the command and the indicated position of the machine's slide or spindle, the controller continues to issue new commands to the machine tool until the specified position is achieved, or until it stops the action if a null condition in the comparator cannot be achieved.

The accuracy of electronic commands and the closed-loop monitoring system, coupled with the capability of more exact duplication, has significantly improved part quality and uniformity. Fewer random errors reduce the need for finished part inspection. Frequently only the first part of a given production lot need be thoroughly inspected.

Many of the aspects of numerical control which contribute to increased accuracy and flexibility also shorten lead times. Machining instructions stored on tape eliminate the need for tool guides and jig plates; therefore, the lengthy delays for their design and construction can be avoided. Programming the machining instructions with high-speed computers can also be done in a fraction of time conventionally spent in tooling construction or part layout. Besides being prepared quicker, tapes can be easily revised to accomodate last minute engineering design changes.

The versatility provided by numerically controlled equipment is especially important to the small shops in developing countries. Independent operations previously performed on separate machines can now be consolidated on a multi-purpose numerically controlled machine. Some machines equipped with index fixtures and tool changers can mill, precision bore, drill, ream, and tap on one setup of the workpiece, eliminating the need for several other machines and fixtures for previously independent operations. Such a consolidation is extremely beneficial in toolmaking where the frequent transfer of tool components between machines and work stations is not only costly, but often downgrades precision standards.

The high precision standards achievable at increased machining rates with minimum setups has greatly reduced inspection, hand finishing, and rework and assembly labor in the fabrication of tools and dies. In jig and fixture applications, the accuracy and repeatability of numerical control greatly simplifies assembly, and provides for substantially better performances by the jigs and fixtures when they are delivered to the customer. Consistent dimensional uniformity between die and mold components not only reduces hand fitting but also permits design modifications, thereby simplifying assembly. These advantages, are extremely valuable in situations where toolmakers capable of precision benchwork are scarce.

Economic Factors

The advantages of numerical machining for complex, mathematically definable parts, or for medium-volume runs, if the capital and programming costs are justified have been very attractive for highly industrialized countries where labor rates for toolmakers are relatively high. But if the part is small and uncomplicated, setups may be simpler and more economical with conventional machines such as the tracer or the duplicator. However, even in such applications the use of tracer equipment is declining because more skillful operators are required and the tool assembly and finishing operations are more arduous and costly.

The economic advantage of numerically controlled machines over conventional machines will often be determined by comparing the cost of making a master model for the conventional or duplicating machine with the cost of the numerically controlled tape—minus the savings in machining, finishing, and assembly labor. In some applications where right- and left-hand tooling are to be machined, cost can be reduced because only one tape need be programmed. Most numerical control systems on large milling machines provide for mirror image machining by simple controller adjustment. For such an application, two models would normally be required by the tracer or duplicating machine.

Until recently, the cost of defining the instructions to regulate the machining of an acceptable part has retarded the spread of numerical control. This is understandable since no problem is more central to its economic use. The creation of control tapes has generated an entirely new technology for which the necessary techniques and skills are still developing. Associated operational costs have, therefore, been high and sometimes difficult to amortize on one-of-a-kind applications. In low-to-medium volume machining jobs, however, the cost of tape preparation for mathematically definable parts is frequently less than half the cost of constructing tooling, laying out the part, or producing a pattern.

Tapes for numerical control and toolmaking applications are usually prepared in one of two ways. In the first, the die, mold, or other tooling surface is described by several statements of a special numerical-control part-programming language. A manuscript of abbreviated English-like statements is prepared and converted to coded information which is processed in a computer to calculate the required cutter path. Because die, molds, and some other tooling often are not true geometric shapes, the value of these part programming languages has been limited for some toolmaking applications. Consequently, an alternate method for tape preparation has been developed.

A contour measuring device, similar in principle to a tracer duplicating device, determines the dimensions of a three-axis model by using a mechanical proximity probe to measure and punch the coordinate values on a paper tape. After the machining instructions have been added to the dimensions on the tape, the numerically controlled machine tool repeats the path of the probe as it reads the paper tape. Because right- and left-hand parts can usually be produced from the same tape, only one model need be digitized. The contour measuring device has an important advantage for developing countries—tapes can be prepared by relatively unskilled workers using this technique.

Results

Not only are time and skills saved but the numerical processing of dies, molds, and other tooling produces a surface with a higher degree of symmetry and continuity. This is one of the reasons why a numerically processed die or mold, for example, will need only 50% of the hand finishing required for conventionally produced parts.

Numerically processed tools also have smaller cusps[4] or none at all. Smaller cusps result because the spacing of the machining passes of the cutter on multidimensional work is easily regulated by the control system. Where greater accuracy and precision is required, very small cusps can be achieved by close machining passes. Wider machining passes can be used on flatter surfaces where large cusps may be readily removed by hand finishing. Machining passes also can be made perpendicular to the main flow of cuts, thereby providing a precise intersection for guidance in the finishing operations. By making the perpendicular cuts correspond to template locations of the model, the machined surface can be checked easily and at greater precision.

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[4] Cusps are the remaining ridges of metal left by two parallel passes of a milling cutter.

ACQUIRING THE SKILLS FOR NUMERICAL CONTROL

The ability to use less tool finishing and assembly labor, and semiskilled machine operators through the application of numerical control depend upon properly trained programmer and maintenance personnel; this means changes in traditional training programs. The skill shifts and their effects upon training in the metalworking trades has been analyzed in a U.S. Department of Labor study. It was recognized that although the occupations required for conventional machining (such as part designers, methods planners, tooling men, and machine tool operators) are still needed for numerical control, many specific functions, the relative level of skill requirements, and the decision-making responsibilities, however, do change. A summary of the functions performed in numerical control by the machinist, the programmer, and maintenance personnel illustrates the major skill changes that take place.

With the machining commands on the tape, the machinist need not have several years of experience to operate numerically controlled machines. His responsibility can be restricted to machine setup, recognizing operational deviations, and being alert to equipment malfunctions. Thus, once the numerical control equipment has been installed and its operation is reliably stable, the machine operator can be a semiskilled worker.

Equipment maintenance, however, becomes more demanding—

both in terms of skill requirements and responsibility. Numerically controlled equipment requires knowledge of servomechanisms, electronics, and hydraulics. Since a malfunction may be caused by one or more of these subsystems, at least one maintenance person must be able to analyze the total system and isolate the cause.

Numerical control has created the need for part-programming skills. The programmer, whose key responsibility is managing the manufacturing process, works closely with the design engineer to assure that the design intent will be translated accurately onto the control tape; the programmer also works with the machine operator to assure that all programming assumptions are understood for setup and machining operations.

A catalog of the responsibilities of the programmer, the numerical control maintenance staff and the machine operators will provide some insight into the nature and complexity of the necessary training programs. It will also illustrate the training requirements for developing countries.

Numerical Control Part Programming

The most serious training challenge arises in developing the part-programming skills. The programming activity begins with an overall analysis of the part drawing to determine if the part can be machined efficiently on the numerically controlled equipment available.

Some of the questions which need to be answered are:

1. Is the machine tool physically capable of carrying out all the required operations?
2. Can the equipment, under automatic control, achieve the desired tolerances?
3. Does the part consist of true geometric shapes which can be mathematically defined; if not, will it be feasible to use a contour measuring machine for tape preparation?

The programmer must then analyze the process details. This often involves making a sketch of the part in its setup position to determine the best fixture arrangement. Answers to the following questions must also be determined:

1. What cutting tools are required? (Sizes and shapes should be specified.)
2. Considering the workpiece and cutter materials and the configuration of the machine tool, what cutter feed and speed rates should be established.
3. Should the workpiece be reset to machine any areas unmachinable because of initial fixture placements?

When the tooling and methods for processing have been determined, it is necessary to establish the proper machining sequence. This is an important phase since several approaches can be used to establish the sequence of machining operations. Only one set, however is the most efficient process; there can be a costly difference between a programmed tape which produces a part and a tape which produces the part in an optimum manner. A second review to optimize the tape often reduces the process time by 20-25%, especially when several cutting tools are involved for drilling a large number of holes.

For each operation in the sequence, a programmed starting and ending point is determined, and the intermediate points collectively define the cutter path. The coordinate points for each segment of the cutter path are entered on a programming sheet and are supplemented by machine tool commands. Examples of this information are cutter feedrate, coolant flow, tool selection, spindle on-off, etc. Upon completion of the programming form, the complete record of the written program is reviewed and verified. Typical questions to be raised at this point are:

1. Are all machine tool operations such as coolant flow, spindle movements, etc. properly activated?
2. Are machinability and process sequences correct.
3. Are the cutter paths accurate?

The information on the program manuscript is then transferred onto a control tape or fed into a computer for calculation. The computer output is then entered on the control tape. The punched tape is verified through one of several methods, for example, plotting the tape information on an X-Y plotter or a drafting machine. When the part is complex, the tape may be checked by machining the first part in wood or plastic.

Depending upon the complexity of the application, there are several approaches for organizing the skills in the part-programming phase. Programming always requires three types of activities: process planning, programming the part, and transferring the proven tape to the shop.

Because the three distinct operations are easily segregated, specialization of effort is usually desirable. Such division of effort makes possible the use of more inexperienced workers and eases the training problem. It is not always necessary, however, to separate the three activities; in many smaller companies the planning, part programming, and tape transfer operations are successfully performed by a single person. The organizational technique used by one company which pioneered the use of numerical control illustrates the effective management of these three operations and demonstrates the levels of skills required.[5]

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[5] John M. Fauth, "Management Guide to Numerical Control," Numerical Control Society, 1964.

Process Planning

Personnel involved in the process planning activities establish the overall manufacturing plan by analyzing the part design data and the blueprint. Tooling, fixturing, and cutter characteristics are specified, and a process operations sheet defining the machine setup, the sequence of roughing and finishing operations, and the fixture and tool changes is prepared. The methods to be used in programming the part are determined, as is the programming language to be employed. The management plan consisting of the estimated cost, schedule, and equipment requirements for all production activities is also prepared by the process planner.

Process planners usually have at least two years of experience in tool and process design coupled with an extensive background in shop mathematics. They should be journeymen machinists or qualified machining planners. Where these skills are scarce, a machinist, machine planner, or machine fixture designer possessing a working knowledge of mathematics through geometry and trigonometry often proves qualified.

Part Programming

The programmer works from the data and instructions provided by the planning section and therefore uses a somewhat different set of skills. The programmer analyzes the blueprint, studies the tooling and cutter requirements, and evaluates the machining sequence specified on the operation sheet. Depending upon the complexity of the part, the programmer then completely defines the path of the cutting tool by developing the beginning and ending points for each segment of the tool path. The programmer codes the machining operation and records the commands on the programming form according to the conventions of the part-programming language used. Upon completion of the programming form, a tape is prepared—usually through the assistance of a computer. The tape is then verified.

Besides the tape, the programmer provides the machine tool operator with a part diagram which graphically illustrates the cutter paths and fixture procedures. The diagram includes a written explanation of the machining operations; it specifies the programmed stops, the work to be performed during the stops, and the cutting tool numbers. Descriptions of other data pertinent to the machining operation also appear on the diagram with whatever written comments may be relevant.

Provided the process has been properly designed by the process planner, no actual machine shop, machine planning, or tool design experience is required of the part programmer. The skills required of his function are much easier to meet than those of the process planner. It is important that those involved in the machine tool industry of developing countries be aware of this beneficial difference in skills required.

Numerical control users who organize the part programming and planning activities separately, find that recent graduates of two-year colleges who major in mathematics, science, or mechanical technology make excellent programming personnel after a minimum of in-house training. Classroom training programs introduce the former students to the programming conventions. A three-week, 120-hour indoctrination session has been adequate to familiarize new personnel with the basic conventions of even the most complex languages. Some complex languages can be mastered in a one-week period; a few as quickly as one day.

On-the-job training activities follow the classroom session. While individual productivity is slight at the outset, most programmers are proficient within one to six months.

Transferring the Tape to the Shop

Transferring the proven tape to the machine operator is the third distinct operation of part programming. The desired qualifications of personnel who transfer the tape and communicate the processing instructions to the shop should be roughly equivalent to those of the personnel in planning. There is an important exception: liaison personnel require only a general knowledge of mathematics and computers.

The primary responsibility of the liaison personnel is to make sure that the machine operators thoroughly understand the operation plan. They explain the diagram and the operations sheet to the machinist, monitor the mounting of the fixture on the numerically controlled equipment, supervise the location of the workpiece in the fixture, and provide surveillance during the processing of the first piece. They also make notations of any corrections required in the manufacturing plan or the programmed tape. Once the first part is successfully produced by the tape, the liaison personnel advise the planning personnel of any problems or suggested changes for the tape or the process plan.

The skills required by the liaison personnel are usually present in the typical machine shop. Qualified machinists who have good communication abilities often make excellent liaison personnel after some introduction to the numerical control concepts.

The major considerations and topics to be covered in part-programming training programs are presented below:[6]

1. The programmer must be able to interpret the part drawing. From this drawing, the positioning and fixturing of the part on the machine tool is determined. The logical order of machining operations, together with appropriate cutting tools and their feeds and speeds are specified.
2. The programmer must be capable of determining proper machining feed and speed rates and the rotational speed of the workpiece or cutting tool—as influenced by the chip load, the durability of the machine tool, the work material,

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[6] For simplicity of illustration, the process-planning and part-programming activities are assumed to be performed by one person.

and the type of cutting tool. Many users of numerical control find that programmers with a few years of college quickly learn how to set proper machining rates from machinability charts and tables.

3. Programming requires the proficient use of shop mathematics, including basic arithmetic, algebra, plane and solid geometry, and trigonometry. The ability to use higher mathematics, including analytic geometry, calculus, vector analysis, etc., will improve the programmer's effectiveness.

4. A thorough understanding of all the numerical control principles inherent from process planning to finished part inspection is required. Of particular significance is the necessity for the programmer to understand thoroughly the capabilities and limitations of the machine tool and the numerical control system.

5. Where the computer is used to aid part-programming, knowledge of the following is also valuable.

   a. The conventions, capabilities and limitations of the part-programming language.

   b. Vocabulary and rules for completing the programming manuscript from which the tape or the computer-data cards can be punched.

   c. Interpretation of the computer print-out, including the diagnostic comments and the coded statements.

The art of part programming should not be taught as theory only. Acquiring the programming skill is like learning to ride a bicycle; the learning experience is considerably more effective if it includes actual practice.

With the proper structuring of part-programmer training, inexperienced personnel can be speedily taught to program tapes for numerically controlled machine tools. The tape will machine parts with higher precision and productivity standards than can be achieved by the most experienced conventional machinists. Mistakes can be expected from the relatively inexperienced programming personnel; however, the potentially good programmers quickly learn from their errors. Although extensive training is required to program 4- and 5-axis parts, some companies have successfully taught female secretaries with a good mathematics background to program the less complex parts.

Numerically Controlled Machine Tool Operator

It is not advisable initially to use unskilled machine operators for numerical control. Because the first piece of automated equipment attracts considerable attention from the work force, most new users assign highly qualified machinists to assure the maximum equipment performance. As experience grows, the skill reductions can be realized by replacing the skilled operators with semiskilled or even unskilled workers. The less qualified personnel have proven most successful where the programmed tapes have been completely verified before the operator uses them, and where the machine setup is not complex. An important side effect occurs from using inexperienced operators: these workers do not have a store of invalid information which may lead to poor machining practices—practices which result from misinterpreted experience rather than valid metallurgical and machinability theory.

Experiences gained from the training of operators for numerical control show that certain characteristics are desirable for a proficient operator. Such a worker must be able to:

1. Read and understand part drawings.
2. Verify that the geometry and dimensions of the cutting tool adhere to the manufacturing plan.
3. Load the cutting tools properly into the spindle or tool magazine.
4. Be alert to the development of a metal cutting problem.
5. Install the fixture accurately on the machine and the workpiece in the fixture.
6. Inspect the workpiece to determine if the operations conform to specifications.
7. Communicate the symptoms of a maintenance or programming problem to supervisory personnel.

Fortunately these seven characteristics can be acquired in days or weeks as contrasted to the one-to-four years required to qualify a machinist on conventional equipment. The complexity of the application again influences the required length of the training program. For experienced, but only semiskilled machinists, a 40-hour training program is usually adequate for even the most complex 5-axis equipment. Unskilled, inexperienced workers have been trained to operate a 3-axis drilling machine in less than eight hours. In the production of some small parts, female workers also have been quickly trained to operate numerically controlled drilling machines.

The major topics to be included in an operator's training program are:

1. A detailed introduction to the basic concepts of numerical control
2. Operational principles of the machine tool and its control system.
3. An overview of part programming.
4. Conventions used to code information on the tape
5. Procedures for starting and operating the machine—and the emergency steps to follow when a malfunction occurs.
6. Setup procedures including the coordination of the reference locations on the tape and on the machine tool.
7. Proper use of metrology instruments for part inspection.

Numerical Control Maintenance Personnel

Workers capable of repairing conventional machine tools which have some type of control apparatus can usually be trained to handle numerical control. Personnel capable of handling the mechanical and hydraulic malfunctions of conventional equipment require little additional skill to cope with these problems when they occur in numerically controlled equipment. A brief orientation program is usually all that is required.

The maintenance of the electronic control system, however, requires more specialized training. Maintenance personnel who service conventional electric wiring consisting of electromechanical relays and circuit breakers are often bewildered by problems in the photoelectric tape readers, the transistorized control logic, the power supplies or other solid-state circuits. Fortunately, the reliability of today's control systems is high enough that only a few workers must undergo the more specialized training to maintain them. It is also encouraging that the new control systems with integrated circuits are at least ten times more reliable than the quite reliable earlier controls. The mean time between failures is not only longer, but when a malfunction does occur, the faulty module is more easily identified and replaced.

It is imperative that the maintenance training program produce at least one maintenance worker who thoroughly understands the complete system operation of the machine tool and the control unit. Such a person must determine if a malfunction is caused by the hydraulic, servomechanism, or electronic subsystems. A worker qualified to perform such a complex task will often have had a few years of college and will be familiar with the basic operational and design principles of mechanical, hydraulic, and electronic devices. When the diagnosis has been correctly made, a maintenance technician then can be assigned to repair the equipment.

The topics shown below should be included in training programs for numerical control maintenance personnel:

1. A detailed introduction to the basic concepts of numerical control.
2. Conventions used to code information on the tape.
3. Capabilities of the machine tool and control system.

4. Binary number system.
5. Control system theory of design and operation.
6. Interpretation of electronic circuit drawings and schematics.
7. Step-by-step procedures for diagnosing a malfunction which is accompanied by specific symptoms.

The outline of a course for training electronic maintenance personnel used by a large numerical control user is shown below. The teaching staff for such a program may need to be recruited from a technical university in the developing country. Since only a few people will be required to undergo training at this level, it may be more efficient to send the trainees to the campus for the specially structured course.

TOPIC OUTLINE FOR
ELECTRONICS TRAINING PROGRAM

1. Screening Examination
2. Direct Current Theory
    - Magnetism
    - Current voltage, and resistance
    - Ohm's law for D.C.
    - Circuits - series, parallel, complex
    - Electromagnetism
    - Induced electromotive force
    - Inductance
    - Evaluation examination
3. Alternating Current Theory
    - A.C. theory
    - Inductance
    - Capacitance
    - Resonance and tuned circuits
    - Transformers
    - Evaluation examination

4. Tube Theory and Circuits

   - Electron emission and diodes
   - Basic triode action
   - Multigrid tubes
   - Amplifiers, power
   - Coupling methods
   - Wide-band amplifiers
   - Audio amplifiers
   - R.F. amplifiers
   - Oscillators
   - Evaluation examination

5. Transistor Theory and Circuits

   - Semiconductor fundamentals
   - Transistor fundamentals
   - Bias stabilization
   - Characteristic curves and charts
   - Audio amplifiers
   - Tuned amplifiers
   - Wind-band amplifiers
   - Oscillators
   - Measurements
   - Evaluation examination

6. Fundamentals of Binary Numbers and Logic

   - Binary system
   - Binary arithmetic
   - Boolean or logical algebra
   - "And" operation
   - "Or" operation
   - "Nor" operation
   - Inverters
   - Boolean equations
   - Evaluation examination

7. Logic Circuits and Applications

   - Fundamentals of pulse circuits
   - Multivibrators
   - Logic gates
   - Flip-flops
   - Counters
   - Delay lines
   - Typical application of logic functions
   - Evaluation examination

8. Integrated and Hybrid Circuits

9. Intermediate Systems and Servo-Loops

   - Feedback fundamentals
   - Resolvers
   - Synchros and servos
   - Applications

Detection
Command and error signal generation
Closed-loop system
Digital to analog conversion
Types of servo drives
Evaluation examination

10. Final Examination

For applications requiring complex equipment, at least two maintenance personnel should undergo the advanced electronics training. The duration of the training period for maintenance technicians will depend upon the skill levels of the trainee and the complexity of the equipment. One very effective training program used by a large aircraft manufacturer lasts 10 weeks or 400 hours. Trainees spend four hours each day in the classroom and four hours in laboratory work. Several companies thoroughly train one or two high-level personnel, e.g., college graduate engineers, who in turn train the maintenance technicians on the job.

Summary of Skill Shifts

Clearly, beneficial skill reductions are possible through the use of numerical control. Not surprisingly, however, these potential skill reductions require retraining to facilitate effective programming; as well, some upgrading of maintenance skills must take place. The realignment of skills has meant that more college trained personnel are attracted by the new opportunities available in the metalworking industry. The use of computers and numerical controls seems to awaken the interest of engineers in toolmaking. The resulting influx has lessened the shortage of scarce professional talent with mechanical skills, and as these new professionals have become proficient in their jobs, the number of machinists and tool or die finishers required for a given level of output has decreased.

The Use of Numerical Control in Toolmaking by Industries in Advanced Countries

Although many of the foregoing examples are from American applications, industries in several other countries—Germany, England, Scotland, Japan, Italy, and France—are also making significant advancements in the application of numerical control. Because of the relatively high wage rates in the United States, their industries are using numerical control for toolmaking to a greater extent than are similar industries in other countries.

It has been reported, however, that other countries, for instance, the Japanese shipbuilding and railway industries, utilize advanced integrated numerical control and computer-aided design techniques. In England, the British Pressed Steel Fisher Ltd. Company employes the joint use of computer-graphics and numerical control to design and machine tooling for automotive applications. Technical papers have also appeared by engineers of France's Renault Company which describe their development of advanced numerical toolmaking processes.[7]

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[7] For other applications see: "From Design Layout to Finished Product by Numerical Control," Machinery and

The Renault report describes the use of computers and numerical control for car body design and tooling.[8] Their initial applications dealt with prototypes, tooling fixtures, machine tool elements, and crankshaft balancing. Their application of numerical control for automotive stamping tools has been a recent development. Savings in time and money are cited as the principal benefits.

A recent report published by the research and development department of the British Pressed Steel Fisher Ltd. Company described some of its activities as follows:

> The work of the Numerical Engineering Section is to increase efficiency by the application of computer aids to design, and the introduction of numerically controlled machine tools into the company's toolrooms. Both of these activities use computers extensively and are linked by the need to express the engineering data numerically for manipulation in a computer.
>
> Templates, wooden models, and dies are being successfully machined under numerical control at Pressed Steel Fisher. Numerical control allows several machining operations at one setting and tools are completed more quickly as less time is spent waiting for the next operation and work-in-process is reduced. Before the control tape is

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<u>and Product Engineering</u>. I.T.B. Blackie—Ferranti Limited <u>Edinburgh, Scotland</u>. The Olivetti Company of Italy also recently announced their development of a numerical control program for making car body dies. The company reported that the system's main application is car body dies for the Italian bodymaker, Pininfarina.

[8] Pierre E. Bezier, "How Renault Uses Numerical Control for Car Body Design and Tooling," <u>Society of Automotive Engineers</u>, 1968.

> prepared, each detail of the machining operation is decided and optimum feeds and speeds are determined, resulting in much improved machine tool utilization. The model required for conventional milling is not required when numerical control is used and the elimination of the inaccuracies of this copy master has reduced hand finishing of the die surface.

The American automotive industry is also using numerical control for toolmaking to a great extent. This is attributable to two factors: first, American competition is forcing automotive manufacturers to cut the lead time of introducing new model cars; and second, the cost of jigs, fixtures, dies and molds has increased dramatically over the past several years with labor costs spiralling in the face of stagnating tool and die worker productivity. Ford, Chrysler, and General Motors have converted several large tracer controlled milling machines to numerical control; in some cases new numerically controlled machines have actually replaced the tracer machines.

The American Aerospace Industry, which leads in the ownership of numerically controlled equipment, has not used it as extensively for toolmaking because their machines have been profitably devoted to small-lot machining of product components. Just recently, however, several numerically controlled milling and boring machines of the Boeing Airplane Company were committed for several months to the machining of tooling for their soon-to-be-introduced 747 Jumbo Jet Transport. The success of this tooling program has precipitated plans to acquire numerically controlled equipment for their toolmaking departments, thereby freeing the existing equipment for the machining of component parts for the production of airplanes.

The business machine and electronic industries in the United States are also accelerating the introduction of numerical control. IBM has led in the utilization of numerical control in this industry, but the Control Data Corporation now has in operation a new machining division in Omaha, Nebraska, which uses numerically controlled equipment extensively. This division machines computer and other data processing equipment parts in low volume and produces tooling to the extent that capacity permits.

The growing application of numerical control throughout the industrialized countries indicates that a total manufacturing impact has affected the skills, costs, and quality in several related areas. Normally ancillary benefits, such as reduced inspection and assembly labor, far outweigh the significant machining advantages.

Those evaluating numerical control for tool and die industries in developing countries must recognize that toolmaking is being subsumed into an integrated computer-based design and manufacturing system. The computer-aided design techniques which produce mathematical definitions of parts and tools have been finding their way into advanced industries for several years. It is inevitable that these techniques will spread to the developing countries, thereby creating a beneficial shift in the skill requirements and in the type of equipment required to machine parts through the use of numerical definitions. If a developing country delays the implementation of the advanced techniques, it will be developing a tool and die industry having little chance of competing with the industrialized countries. Moreover, the quality of the products made from the inferior tooling characteristic of conventional techniques will likewise place the country at a competitive disadvantage.

II. ELECTRICAL DISCHARGE MACHINING IN TOOLMAKING

A demand for reducing lead time, together with the need to compensate for a shortage of skilled die and mold finishers but still improve dimensional accuracy, has forced tool and die shops to switch to electrical discharge machining (EDM). Recent technological advancements have greatly improved EDM metal removal rates and increased tool life. EDM has become very economical for producing holes and cavaties in dies and molds as well as for limited production runs of parts with complex shapes or unusual hardness. Reduction, and sometimes even the elimination, of many tool-finishing operations have resulted from these applications. Although EDM is not a cure-all toolmaking process, its present state of development, together with anticipated technological improvements make it a basic production technique for both developing and industrialized countries.

Since EDM equipment normally has a servomechanism, it is able to adapt to limited changes in the machining environment without human intervention.[9] Most EDM work can be accomplished, therefore without an operator; a semiskilled attendant who occasionally monitors the machine is sufficent. Often, one operator can monitor two or more machines.

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[9] The EDM servomechanism operates through a sensing circuitry which constantly monitors the voltage variations in the spark-gap and compares this voltage to a reference standard. The difference between the two voltages is the input signal which either regulates the servomechanism to control the distance and speed of the electrode movement or retracts the electrode, to prevent a short.

The ability to use a semiskilled worker for precision work contrasts sharply with the necessity to employ an experienced and skilled machine operator for a conventional milling or jig borer machine in traditional toolmaking operations.

Process Fundamentals

EDM shapes metal by a succession of controlled electrical discharges (arcs) from the electrode to the workpiece, which erode the metal. The electrode is wired to a generator which controls the power and frequency of the arc. Both the electrode and the workpiece are immersed in a flowing dielectric fluid—e.g., hydrocarbon oil—which increases the electrical potential in the gap and also carries away debris.

The electrode is advanced through the dielectric fluid to approximately 0.001 of an inch from the workpiece. The voltage across the gap builds until a high electrical field develops at the closest point. At about 70 volts, the dielectric fluid ionizes, giving way to the arc. The high energy of the arc vaporizes the surrounding dielectric fluid in an enlarging column, admitting an increase of current. As a result of the heat generated by the kinetic resistance in the arc, the temperatures on the surface of the tool and the workpiece rise above the melting point. A minute portion of each is liquefied and vaporized. When the current shuts off, the eroded metal cools and solidifies, and the dielectric fluid flowing into the gap flushes away the debris. This process is repeated at a consistent frequency affected by the durability of the metal being formed, the capacity of the dielectric fluid, and the surface finish requirements.

As the metal is removed, the size of the gap increases. This changing condition measured in terms of the voltage required to force the arc, is constantly applied to the servomechanism, which controls the tool's rate of penetration. If the gap between the electrode and the workpiece is too large, ionization will not occur; but if it is too small, there will either be a short or the electrode and the workpiece will weld themselves together.

METAL REMOVAL RATES

EDM metal removal rates are influenced by several factors including the capacity of the power supply, type of electrode material and the conductivity of the metal being cut. The peak metal removal rate of EDM was at first 15; later, 30; and later still, 100 inches an hour. On some of the EDM machines used in American automotive shops, dies as large as 6 by 10 feet are being machined at 100 cubic inches an hour. However, since surface finish deteriorates at higher metal removal rates, the machining rate is necessarily lower during the production of a very smooth surface. Although EDM can produce a surface finish as fine as 3-5 RMS, the practical use of EDM is usually limited to machining parts with a surface finish higher than 75-100 RMS. When a smoother finish is required, the workpiece is usually finished by hand relatively quickly with a 320-grit stone. In such an application, metal is removed economically at high machining amperages and the finishing cut is made at about 80 RMS; the finer finish is attained at slower metal removal rates and takes about three to five amperes of power.

ELECTRODE CONSIDERATIONS

Workpiece surface finishes, metal removal rates, and tool-wear ratios all influence the selection of electrode material. Yellow brass, carbon-graphite, copper, tungsten carbide, silver tungsten, and zinc alloys are materials which have been tried. Because electrode wear is directly related to melting temperatures, carbon-graphite which turns to a vapor at a temperature of 6300°F is a considerably better electrode material than brass or steel which have a melting temperature of 2800°.

In many early EDM die and mold applications, the electrode was produced by making a cavity in material such as wood or plaster, and spraying a thin layer of metal on the cavity's surface. This thin layer was reinforced with epoxy or a similar material; when the reinforced electrode was removed from the cavity it was ready for use. An improved electrode was needed, however, since electrodes with thin layers of metal wore out too quickly at high metal removal rates. A combination of zinc and tin sprayed on models also was tried, but high electrode wear rates and size limitations, together with the delays often experienced in waiting for models, complicated this experiment.

Finally, carbon-graphite material proved suitable for electrodes, and because of the newly found ability to use numerical definitions from product design operations, economical production of the carbon electrodes was readily achieved on numerically controlled machines. This procedure avoided time-consuming and costly model making delays and eliminated inaccuracies that had stemmed from the model making stage. The savings are still increasing as carbon electrode wear improves daily from the development of new application techniques, and the design advancements of high amperage, modularized power supplies. After exhaustive tests and thousands of applications, carbon-graphite has become the predominate electrode material for forging and stamping die work. The successful use of carbon-graphite and the "low-wear" EDM technique has created an extraordinary potential for the production of many dies and molds.

Although the EDM process removes material from both the part and the electrode, if the electrode material is selected properly and the power supply is appropriately designed, the removal of the material from the workpiece can be increased substantially over that of the electrode. It was recently discovered that by reversing the polarity of the electrode and the workpiece—by making the electrode the positive pole—the electrode wear could be greatly reduced and nearly eliminated. This new technique is appropriately referred to as "low-wear" EDM. Thus far, carbon-graphite has been the only electrode material to be used efficiently in these applications.

By reversing the polarity there can be a smaller gap and a higher temperature on the tool surface. These conditions allow metal expelled from the workpiece to adhere to the face of the electrode. The rate of transfer also can be controlled so that it is possible to compensate almost completely for electrode wear, thereby greatly lessening a previously serious economic restriction to higher metal removal rates.

So long as metal removal rates were low and electrode wear high, the many benefits which accrued through the use of EDM were offset by the economic penalties of high electrode costs. The "low-wear" electrode advancement, however, has opened the door for such benefits as simpler tool design, and has greatly reduced the need for die and mold finishing and benchwork labor. Because holes and cavities on certain applications can be entirely machined by EDM, expensive equipment, including jig borers, duplicator milling machines, and precision grinders are freed for other jobs.

SHAPING THE ELECTRODE

The electrode must be shaped to precise configurations to be imparted in the workpiece. When metallic electrode material, such as copper, brass, or some alloy, is used the electrode may be coined, sprayed or machined. Since carbon does not form readily, machining is the most popular method for shaping these electrodes. Carbon-graphite, however, is fragile and brittle, so caution must be exercised, particularly during machining of electrodes with thin elements.

A question commonly raised concerns the economic justification of the costs of preparing an electrode in the machining of one-of-a-kind dies or molds. Where considerations of economy take precedent over other factors, such as accuracy, or optimum utilization of scarce equipment and skills, each application must be analyzed separately to determine if EDM is the cheapest. The economic justification is more obvious where the country's product design techniques have progressed to the stage that mathematical definitions of the part configuration are generated as a by-product. Electrodes can then be quickly produced from mathematical definitions by numerically controlled machines.

The union of numerical control and EDM technologies has progressed rapidly in the United States and some other industrialized countries. The resulting benefits—large decreases in design-to-production time and a corresponding reduction in the number of required templates and patterns—are too great for developing countries to ignore. However, until they can acquire numerically controlled techniques, other methods, such as the conventional machining of electrodes, will have to suffice.

Even where conventional machining procedures are used, the costs of shaping the electrode still can be minimal.

Carbon-graphite not only can be machined much faster than metal, it also permits simpler tooling and more flexible machinability practices. Cutting tools can be less rigid, and more importantly, of a cheaper quality. Form tools can be used more liberally, permitting the machining of complex curves and contours with one pass of the cutter, with a minimum of adjustments to the machine. If any fixturing is required, it need not be durable or complex. Electrodes for some two-dimensional EDM work are shaped on simple jigsaw equipment.

EDM SURFACE FINISHES

In EDM any molten metal not flushed away resolidifies to form a hard crust on the workpiece. In heat-treatable metals this recast layer reaches near-maximum hardness during the EDM process; undesirable minute cracks sometimes develop during this process. A common procedure for avoiding these imperfections is to perform the finish machining operation at a high frequency and at a low amperage. The hardened crust which at first was thought to be a problem has actually proven to be beneficial. A die or a mold with a hardened EDM crust has better wear characteristics and produces many more parts before redressing is required. Furthermore, only a small amount of resurfacing is needed when it is necessary to recondition an EDM surface.

The friction characteristics of surfaces produced by EDM are also quite different from conventional finishes.

Tests conducted by the Cincinnati Milling Machine Company have demonstrated that while conventionally machined surfaces stick and slip with rapidly decreasing friction rates, EDM coefficients are linear and considerably lower in value. These tests have shown that an EDM finish reading of 45 microinches applied to stamping and hobbing dies can perform as well as a 15 microinch conventional finish.

EDM Applications

The union of numerical control and EDM for machining electrodes has proven especially profitable for complex mold and die manufacture. Delays are avoided as the mathematical information is used in the preparation of numerical control tapes to machine carbon electrodes. Accuracies have been improved and the amount of benchwork and hand finishing for tooling produced in this way has been greatly reduced. It is not uncommon for such tooling production techniques to require 40-60% less hand finishing.

Forging Dies

Prior to the practical use of carbon-graphite and the teaming up of numerical control and EDM, it was found that for EDM to be profitable in the manufacture of forging dies, at least three sets of dies were needed to amortize electrode costs. Copper, brass and zinc were the electrode materials used in the early applications, and because of high wear rates, three to six electrodes were often needed to produce a finished forging die cavity. Such an obstacle usually dictated that the rough machining be done on a conventional machine and the finishing by EDM. Now that the electrodes can be prepared by numerical control, and the "low-wear" technique is a reality, a set of forging dies can be economically produced entirely by EDM with one electrode. Of further importance is the common need to resink or redress forging dies two to five times during their service life; with "low-wear" EDM, the original carbon electrode can be quickly reinstalled on the EDM machine for resurfacing.

Recently, one automotive manufacturer electrically machined a small die for the hot forging of stabilizer bar eyes using the "low-wear" technique. A semiskilled machine operator successfully roughed and finished the die to 500 RMS with no measurable wear on the carbon electrode. Moreover, the die was put into production with no hand finishing whatsoever. The cost of producing the die by EDM was 50% less than the cost of the old method. When the die needed redressing, it was refinished by a semiskilled worker with the same electrode; once again no handwork was required and electrode wear was negligible; savings amounted to 75%.

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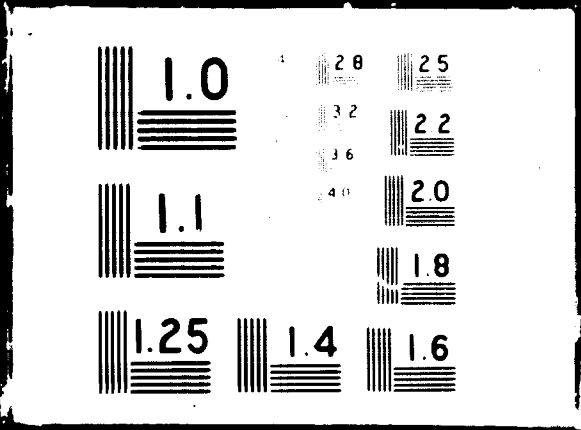

When EDM can be used it generally eliminates the need for hand finishing of forging dies. This produces a 25-50% reduction in the amount of benchwork required during die production, and a 40-75% reduction in resinking worn dies. When these reductions are related to the scarcity of the high level of skills required for conventional die finishing, the benefits to be gained by developing countries through the use of EDM become more obvious.

This new ability to easily and speedily redress a forging die has also produced important secondary effects— it has made stricter die maintenance practices feasible, thereby producing forged parts of higher quality with more uniform, closer tolerances. As well, the surfaces of forging dies produced by EDM will quickly glaze so that the craters form beneficial lubriation pockets, thereby reducing the sticking of parts in the die.

Stamping Dies

Stamping dies ranging in size from small intricate shapes to large complex body tooling for cars and trucks are being produced by EDM with marked savings of machine operator and die finishing labor. In some applications both the punch and the die are produced by EDM. More often one element is machined on a conventional mill; after suitable preparation this die element serves as the electrode for electrically machining the opposite member of the die set. When this technique is used the punch is usually tipped with carbon-graphite. The electrode material is attached to the ends of the punch after the heat-treatment and before the finish grinding operation. After installation on the EDM equipment, the punch-electrode is gradually lowered into the opposite half of the die set, and the EDM process etches a perfect clearance between the two die members. Little or no hand fitting of the two die members is required.

Where mathematical definitions of the die are available from the design activity, numerically controlled machines are used to produce the electrodes, and both the punch and the die are produced by EDM. The Ford Motor Company has achieved remarkable results with one electrode—without models—thereby taking full advantage of both numerical control and EDM.

A hood outer panel was one of the first tools Ford selected for this method. The process was initiated with the aid of mathematical information from design activities. Styrofoam patterns for castings and the electrodes were then numerically machined. The cusps left on the carbon were only 0.001 inch high, so little hand finishing was required. Moreover, where precise finishing was necessary—around character lines, for instance—the carbon was so soft that the handwork presented little difficulty. As an indication of how rapidly the "low-wear" technology has progressed, after machining the draw, trim, and flange dies on EDM equipment with reverse polarity, the electrode had worn so little that the very small unremoved cusp lines could still be seen on its face.

Savings of labor also result in the fitting of stamping dies by EDM. Semiskilled workers can be used since punches electrically machine their own clearances. Die set openings produced in this manner are precise duplicates of the punch configuration. The most popular technique for this application involves the mounting of carbon strips on the punch with a thermosetting adhesive. The carbon is then finished or routed to conform precisely to the die's configuration by means of a small portable grinder mounted on a portage layout machine. A cutting tool is guided along the die's edge by a round "pilot" attached to the end of the tool. To support the carbon and protect it from accidental breakage or dislocation, plastobond epoxy is packed behind it. The completely carboned die is then ready for mating to its opposite half by EDM.

A higher quality and better performing stamping die is produced by EDM. A perfectly uniform die clearance is one reason for the improvement, and the EDM surface provides for excellent distribution and retention of the lubricant. Improved punch-die uniformity permits a longer production run without causing burrs, pinches, tears, or fractures in the product, which occur all too often on hand fitted dies.

Surface tests conducted by the Cincinnatti Milling

Machine Company demonstrated that EDM surfaces have better lubricant retaining properties than any other type of finish. Because the finish is a series of peaks and craters, the stamped part is formed with less force as it picks up the oil contained in the craters.

Owing to both the advantages of improved surface and uniform clearance, stamping dies produced on EDM can produce more parts between grindings of the die set. One automotive manufacturer has noted a 25% improvement in the life of dies made with EDM. The use of EDM also has the advantage of requiring less die sectionalizing in construction. As a result, fewer die elements and less assembly and hand fitting labor are needed.

Molds

The production of molds by EDM has also grown in importance, but not as rapidly as has the manufacture of forging and stamping dies. Because of the relatively smooth surface finish requirements for molds, current EDM metal removal rates must be restrained at the expense of economy during the finish machining. As developments in the power supply and breakthroughs like the reversed polarity technique continue to be made, more efficient metal removal rates for surface finishes of low ratings will be achieved; then EDM will be even more effective for molds.

Despite the problems faced in using EDM efficiently for very smooth surfaces, it still cuts the amount of hand finishing work required on molds. Less handwork is needed for cavity surfaces and parting lines alike. The latter can be simply matched with EDM by using one mold half as the anode and the other as the cathode. The benefits of this technique are especially impressive when irregular parting lines are encountered in the mold. Since the surfaces must nest perfectly if leakage is to be prevented during service, it is necessary to match and "seat" the mold elements along the parting lines very precisely. When conventional techniques are used, this mating operation requires extreme skill and long hours; with EDM the matching has commonly been achieved in 20-25% of the time needed with the old method. As was true for the finishing of forging and stamping dies by EDM, there is also a significant reduction in the level of skills required.

Molds designed for EDM production often require fewer inserts which take hours to design and produce. This advantage becomes especially noteworthy when one considers that even with molds produced conventionally by highly skilled workers it is nearly impossible to prevent inserts from leaving impressions in the product after the mold has been in service for a while. One-piece designs are more often feasible since thin members and complex shapes can be successfully machined from a solid material without stress.

Molds needing improved heat dissipation capabilities, or facing serious corrosive problems caused by some plastic materials require the use of the more exotic materials such as beryllium-copper and beryllium-nickel. Since EDM is insensitive to metal hardness, the designer is free to specify extra hard metals for improved performance without suffering cost penalties in the mold production phase.

Although most molds demand a highly polished surface, in some applications a stippled finish is desirable or acceptable. For instance some inner plastic parts for appliances or cars can have a semi-rough finish. As in the production of forging dies, molds to be used to produce a part with a stippled surface will require virtually no hand finishing.

Other Applications

Successful EDM applications are growing so rapidly that a detailed listing of all of them is impractical. Some of the more important applications, however, which appear to have immediate relevance for developing countries are summarized below:

> Wire-drawing dies: Because of the relatively hard materials used in these dies they can be surprisingly difficult to produce and even more challenging to maintain effectively. EDM simplifies these problems somewhat by replacing conventional grinding and honing operations by the use of an electrode which is produced with relative ease on a lathe. After slight modification

this same electrode may be usable for salvaging worn wire-drawing dies by electrically machining the die opening to a larger size. Moreover, with EDM carbide material may be used if greater durability and productivity is needed from the dies.

Extrusion dies: Since complicated shapes can be readily imparted in the workpiece by the electrode and the spark, extrusion dies which often contain complex patterns are good candidates for EDM. These dies can be electrically machined after heat-treatment, thereby avoiding a common problem in the conventional production of extrusion dies.

Burr-free parts: Since EDM results in burr-free parts, the process can be used to avoid burrs when such a characteristic would have a detrimental effect or create an untenable economic penalty, EDM is seldom competitive with machining processes having high metal removal rates in production lot sizes; however, where secondary grinding or deburring operations can be eliminated by using EDM, it may prove economical to use only the electrical process.

Applicability of EDM to Developing Countries

All manufacturing processes have physical and economic limitations, and EDM is no exception. EDM is not a universally applicable process; however, with careful application it can produce a superior die or mold and greatly lessen the volume and level of skills required.

Today in many American tool and die shops EDM is standard equipment for applications ranging from forging, blanking, piercing, and trimming, to cold-heading, injection molding, and extrusion dies. Because of the graphite and the "low-wear" machining advancements, the use of EDM in the United States tool and die industry is expected to double the 1965 level by 1970 and triple it by 1975. As EDM is used more extensively, the optimum techniques in toolmaking applications will become more apparent as will the more profitable combinations of power supplies, electrode and workpiece materials, and surface finishes.

The important benefits achieved thus far with rather limited knowledge of the varied EDM techniques and applications will be insignificant compared to those achievable as more research and development takes place. As the technology progresses EDM will create as many favorable shifts in the skill requirements for tool and die industries as are developing from the application of numerical control and computer-aided design.

III. ELECTROCHEMICAL MACHINING IN TOOLMAKING

The use of EDM in toolmaking will continue to increase as electrode wear improves and metal removal rates further increase. When current EDM capabilities create serious economic penalties, and conventional processes prove physically or economically unfeasible, electrochemical machining may be a solution.

Electrochemical machining, (ECM), though only a few years old, has already produced labor savings and quality improvements similar to those achieved through EDM. In addition, ECM can achieve considerably higher removal rates with practically no electrode wear. The successful applications of this process include production of parts without burrs or mechanical stresses, the deburring of conventionally machined parts, and the production of forging dies where more than one-of-a-kind are involved. Metal removal rates in forging die applications have been as high as 200 cubic inches an hour—considerably above EDM's present maximum of 100 cubic inches an hour.

ECM, with its higher equipment and electrode costs, is sometimes difficult to justify for one-of-a-kind toolmaking applications. On the other hand, EDM electrode preparation is relatively simple and is therefore more likely to be economical in the machining of one-of-a-kind dies or molds. Of particular significance to developing countries however, is ECM's versatility. In one operation ECM can perform the mechanical equivalent of several operations and eleiminate the need for turning, planing, milling, grinding, and drilling—all at one setting on one machine by one operator.

FUNDAMENTALS OF ELECTROCHEMICAL MACHINING

ECM is basically similar to Electrical Discharge Machining, yet the process details differ greatly. Essentially, ECM reverses the electroplating process. A chemical reaction dissolves metal from a workpiece into an electrolyte solution. Direct current passes through the electrolyte between the negative electrode tool and the positive workpiece. The resulting action creates an electrolytic cell that causes metal removal to take place ahead of the electroide as it advances toward the workpiece. Since the electrolyte flows to the front end of the electrode into the machining gap between the tool and the workpiece and flows out around the outer part of the electrode, insulation is required outside of the electrode to prevent machining action on the sides of the tool.

The basic elements of the ECM process are:

(1) An electrode which must be a conductor of electricity.

(2) A workpiece which also must be conductive.

(3) An electrolyte solution.

(4) A current source.

Electrode

Since it affects the other elements in the electrolyte cell, the most important element in the ECM process is the electrode or the tool. The electrode also has certain fundamental characteristics which are important to the successful application of the process:

(1) It is an electrical conductor.
(2) It is chemically inert to the reaction.
(3) It must be strong and rigid.
(4) It is negatively charged.
(5) Its shape determines the shape machined in the part.
(6) It has low electrical resistance.

The accuracy of ECM depends upon the precision of the electrode. The configuration and precision of the electrode, however, are only two of the many aspects of concern; another is the surface finish. The roughness or smoothness of the electrode also affects the surface of the machined part. As in EDM, the ECM electrode preparation requires skillful processing, and can be a costly procedure in some applications. More skill is required to produce an ECM electrode than an EDM electrode since it must properly conduct the electrolyte solution—sometimes at a demanding pressure—and have adequate insulation to ward off the undesirable machining action that may occur when the ECM tool interfaces the electrolyte and the workpiece.

Once prepared, however, the ECM electrode can machine thousands of parts. The insignificant abrasion caused by the electrolyte passing over the electrode is the only wear on the ECM tool. No single material is best for all applications; brass, stainless steel, and copper have all been used successfully for ECM electrodes.

Electrolyte

For the machining of ferrous metals, sodium chloride in water is the most common electrolyte used. It has good electrical conductivity, is nontoxic, reasonably safe, and is widely available at a reasonable cost. Although, sodium chloride, like most electrolytes, is corrosive, this limitation can be controlled with proper precautions. Sodium nitrate and, occasionally, sulfuric or hydrochloric acid have also been used as electrolytes. The following are essential characteristics of the ECM electrolyte:

(1) It is a strongly ionized concentrated solution.

(2) It has high specific conductance.

(3) It operates under 40 to 150 psi pressure.

(4) It operates from 100-140°F.

(5) It removes chemical reaction products from the machining zone.

The electrolyte also removes the heat generated in the ECM process. Nearly all the energy used in deplating and pumping the solution is transferred into the electrolyte— a 10,000 amp machining operation at 18 volts can generate up to 800 BTU's per hour. Since the performance of the electrolyte is affected by variations in temperature, an electrolyte cooling system often is necessary.

Electrolyte resistivity is also influenced by the presence of impurities. The sludge impurities added to the electrolyte as it carries debris from the gap must be removed from the electrolyte to maintain the proper concentration. Metal oxides or hydroxides of about 1.0 micron in size are the usual products of the metal removal process. Four methods have been used to filter these minute impurities from the electrolyte.

(1) The run-and-dump method—the electrolyte is used until it is too dirty to be effective; it is then discarded.

(2) Centrifugal separation.

(3) Sedimentation through a settling tank.

(4) The use of a clarifier.

The centrifugal separation technique has been the most commonly used method to remove the sludge. In one popular centrifugal system, a sump pump moves the contaminated electrolyte from one container into a centrifuge where it is clarified. The clean electrolyte is then drained into a storage reservoir and is subsequently passed back to the machining gap through the electrode. Many of the newer centrifuges use a self-cleaning metallic filter. The centrifuge, which must be made of stainless steel, can be quite expensive.

The run-and-dump method is still utilized in smaller operations. In large operations, where the ECM equipment must be shut down during the dump process, this method usually proves uneconomical and filtering instrumentation is installed. Where the sedimentation method is used, settling tanks may be as large as swimming pools. The large volume of electrolyte required for such a system creates an effective heat sink which helps to control the electrolyte temperature.

The clarifier, an accelerated settling system, is about twice the size of a comparable centrifuge and only half as costly.

Today, the filtration problem is not as serious an obstacle to operate ECM equipment as it was at first. Nevertheless, some of the cleaning equipment can be quite costly. That EDM can be used without a filtration device is another reason why EDM is more popular for toolmaking.

Electrical Current Source

The power source for electrochemical machining is the same type of DC power supply that is used for electroplating. It provides from 6-24 volts in current capacities of 500 to 10,000 amps. Its response must be rapid to prevent damage to the electrode.

Workpiece

The workpiece must be a positively charged electrical conductor. The current density of the workpiece material will influence ECM's effectiveness. For example, to remove 1/10 cubic inch of metal per minute, it requires 1100 amps per square inch for iron or steel and 1490 amps per square inch for titanium.[10]

As in EDM, the workpiece hardness does not affect the process characteristics; furthermore, and in contrast to EDM, the metallurgical characteristics of the workpiece remain unchanged by the process. ECM, therefore, does not cause many undesirable surface effects that can occur from the mechanical or thermal shock inherent in some conventional machining or grinding operations. ECM surfaces usually have better wear, friction, and corrosion characteristics than mechanically finished surfaces. Very little hand finishing is required since surfaces on the order of 30 to 60 microinches can be achieved. Finishes as low as five to ten microinches have been reported.

Other material properties such as the grain size also affect the surface finish. The use of ECM on course grained structures such as cast iron produce a rough surface finish, while use on a fine grained structure, for example, heat-treated steel, results in a much smoother finish.

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[10] The metal removal rate is directly proportional to the total current passing through the tool and electrolyte to the workpiece. The rate at which metal is removed from the workpiece is a function of Faraday's law, which states that for each Faraday of electricity (96,500 coulombs) that passes through the electrolyte, one gram equivalent weight of matter is liberated from the anode.

THE ROLE OF ECM AND EDM

The developmental status of present EDM and ECM technologies shows that although EDM's metal removal rate is lower than ECM's, the added operational cost of using ECM for the production of one-of-a-kind tools and dies is often difficult to justify. At the present state of development EDM is comparatively useful for the manufacture of one-of-a-kind items while ECM is more effective where the lot sizes are larger. ECM has been effectively applied to four types of machining operations: round and square through-holes, blind holes, cavity sinking, and planning. ECM is most commonly used to machine precision parts in small-lot sizes—especially those of the complex shape or of unusual hardness.

The need to develop a small-batch machining capability in a tool and die industry is demonstrated by the American industry where approximately 25% of the output is in very small batches of precision machined parts. ECM produces more and more of these precision parts for customers who dislike tooling-up for such small runs. Tool and die shops with ECM equipment are ideally prepared to provide such vital support to metalworking industries.

Even though one-of-a-kind tool and die manufacture is extensive, ECM is expected to be popular in the future because the need for complex machining in small batches in some metalworking industries is even greater. The potential value of ECM in low-volume machining is indicated by the expectation that by 1970, ECM will be used in the United States to a greater extent than EDM.

The demand for support machining services is believed to be present in most industries in developing countries—expecially where mass markets are absent. It is often difficult for manufacturers with limited markets to justify the costs of preparing tooling for their small-to-medium lot sizes. These manufacturers need reliable support from the domestic tool and die industry. Manufacturing processes such as ECM, that are readily tooled-up for a small batch of precision parts, may be the key to supplying the needed support.

Skill Impact

ECM provides labor savings and skill reductions similar to those achieved through EDM. ECM, however, is a more complex process, and the skills required to implement it are considerably greater than those for EDM. ECM introduces scientific phenomena, which are new and quite unfamiliar to the typical metalworking environment. The effective application of ECM requires an extensive knowledge not only to electrochemical principles, but the full comprehension of their relationship to conventional metalworking concepts and practices. Even in industrialized countries, it is difficult to find engineers possessing the necessary combination of scientific education and training in both electrochemical and metalworking disciplines.

The introduction of ECM into a developing country can be hastened by making ECM equipment available at a university or a research institute. Educators in American universities have observed that engineering students naturally become inquisitive and involved in a new or unique piece of equipment. Students soon master the operation of the equipment and attempt to apply it to practical problems; later they are often attracted to the industry which can use the equipment in its activities.

A resurgence of interest in the United States' metalworking industries by graduate engineers has occurred because of the excitement in becoming involved in the development and application of new technologies such as ECM and EDM, numerical control and computers. As this infusion of professional talent grows, metalworking operations become less dependent upon the skills of machinists and toolmakers.

IV. IMPLEMENTING THE NEW TECHNOLOGIES

The benefits from using numerical control, EDM, and ECM in toolmaking and small batch machining can substantially enhance the capability of a developing country's metalworking industry. Higher precision standards and reduced skill requirements are attainable, however, only be a planned industrail development program to inspire the necessary changes. Incentives are required to motivate small shop managers to invest the capital for the necessary training and expensive new equipment.

Several methods should be used to encourage technological change in a tool and die industry. Some incentives can be indirect, such as the granting of low-cost loans and tax concessions. More direct inducements will also be needed, such as the government's organizing toolmaking companies to exploit the capabilities of the new technologies. Depending upon the political and economic conditions in the developing country, combinations of these incentives will be required.

OBSTACLES FROM SMALL COMPANIES

The barriers which restrain technological change in a developing country's metalworking industry cannot be overestimated; they are not, however, insurmountable. The technological lag which characterizes many developing countries is frequently explained by the erroneous logic that industrial companies are too small to utilize advanced techniques. The results of the 1967 UNIDO survey of one developing country disclosed that although the country involved in the study lacked very large companies, there was actually no marked difference in size between the typical tool and die shop in the developing country and its American counterpart, if the effects of one- and two-man shops were eliminated.[11] In that country at any rate the lack of technological progress in toolmaking should not be attributed solely to the small size of the companies.

While several factors dissuade the adaptation of new technology in developing countries one of the most critical is the lack of technological differentiation between large companies and the one- and two-man shops. Because there is little difference in the quality and delivery capabilities of the largest and smallest companies, too many of the small shops survive by barely providing a living wage for their one or two employees. The low prices of these marginal shops depress profits throughout the industry and prevent the larger companies from modernizing, a vital necessity for efficient manufacturing, better quality, and the eventual lowering of prices. As long as toolmaking profits are

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[11] The median size of tool and die shops among the 850 American firms in the State of Michigan is 15 employees, compared to 11 workers for 16 similar firms visited during the UNIDO survey. Of the plants in the U.S. tool and die industry, 80.7% have less than 20 workers and 60% of these 5,800 shops have less than 10 workers.

depressed by the unrealistic price levels, the use of inefficient equipment, which requires excessive time and benchwork to produce quality tooling, will prevail.

Although profits which are affected both by the prevailing price levels and the economy of operation strongly influence the long-term developments by which production methods change, the change is quite slow if left to evolve at a natural pace, years, perhaps decades, will be required to achieve the desired industrial improvement. During such an evolution, the substantial benefits of numerical control, EDM, and ECM will remain largely untapped. Direct government action is, therefore, needed to accelerate the necessary evolution.

For a developmental program to upgrade a toolmaking industry, it must concentrate on improving the technological capability of the larger firms and the more promising small companies. As modernization progresses the ability of a few firms to deliver faster and at closer tolerances should upgrade the competitive standards throughout the industry and cause a badly needed shake-out of the marginal firms.

It is impossible to substantially upgrade a metalworking industry by letting industrial development policies be determined by the reactions, limitations, and capabilities of the inefficient small companies. Such companies are incapable of assimilating the professionally trained personnel and advanced techniques required to cause an essential improvement in toolmaking and precision machining operations. The shaky foundations upon which the small inefficient companies exist make it illogical to plan an industrial development program which has as its main goal the injection of new technology into metalworking companies. To upgrade a tool and die industry through the adaptation of new technology a developmental program must be structured to build upon the strengths of the most efficient companies.

The one- and two-man shops, however, should not be ignored. Developmental programs to improve the arts and crafts of the skilled and semiskilled workers in these plants should be continued. These efforts should, however, be construed as an investment in personnel development, rather than as an industrial development effort. This conclusion is based on the findings of the 1967 UNIDO survey; the smallest companies observed simply lacked the managerial ability to successfully cope with the business and production challenges inherent in a larger or technologically advanced operation. For many developing countries, the prospects are bright for intensively developing the existing larger companies or for establishing entirely new and modern, large companies.

Although tools and dies are a critical requirement of a metalworking economy, the total amount of tooling needed represents less than 1% of a nation's gross national product. Because all the tooling needed can be produced by a relatively small number of large efficient companies, intensive governmental action can be readily applied to produce the necessary industrial development. Depending upon the political or economical environment, the program of incentives designed to speed the development among existing companies should include:

1. Granting governmental insured low-interest, or no-interest loans to make it possible for qualified companies to acquire the advanced equipment.
2. Liberalizing the rules for computing the depreciation expenses of advanced equipment so that a company will realize an accelerated tax write-off for such equipment. Cash flow will thereby be speeded up.
3. Allowing companies which acquire advanced equipment to deduct 10-20% of the equipment cost from their taxes in the year of the purchase. Such an investment tax credit would be in addition to the accelerated depreciation write-off. The investment tax credit could be used to help provide the down payment for the new equipment.
4. Purchase by the government of a large group of advanced equipment to be consigned to qualified tool and die plants for use on

governmental work. A small use charge could be arranged for the equipment when it is employed on non-governmental jobs. This technique was utilized by the United States Government and is an important reason why that nation leads in the profitable use of numerical control.

These relatively indirect incentives will not by themselves sufficiently accelerate the adaptation of the new technologies. More direct measures, such as government establishment of a few relatively large modern tool and die companies will be needed.

When the developing country is characterized by an economy relatively free from government intervention and control, projecting the government into the toolmaking industry can create problems. Private entrepreneurs' objections to governmental competition can sometimes be minimized by establishing new toolmaking companies which are jointly financed by governmental and private capital. The newly established company can be operated under profit objectives by a management team appointed by the board of directors. Such a procedure was successfully utilized by the developing country involved in the 1967 UNIDO study and the technique appeared to create only a nominal amount of criticism from the companies which were forced to compete with the new company.

The criticism from private companies will be extensive if some of the indirect incentives described earlier are not made available to the old established toolmaking shops. A typical comment voiced by managers of the private firms in the 1967 UNIDO study provides an example of the criticism—they felt that the government should have made available to established companies a part of the capital it was spending to set up new companies. In certain companies it was evident that these private managers indeed could have put new capital to good use, simultaneously helping the government to achieve its industrial development objectives.

By establishing a few new large toolmaking companies and granting low interest rates and tax concessions to the established private firms, all sectors of the metalworking economy will be motivated; moreover, they will be able to participate in the important process of introducing numerical control, EDM, and ECM technologies.

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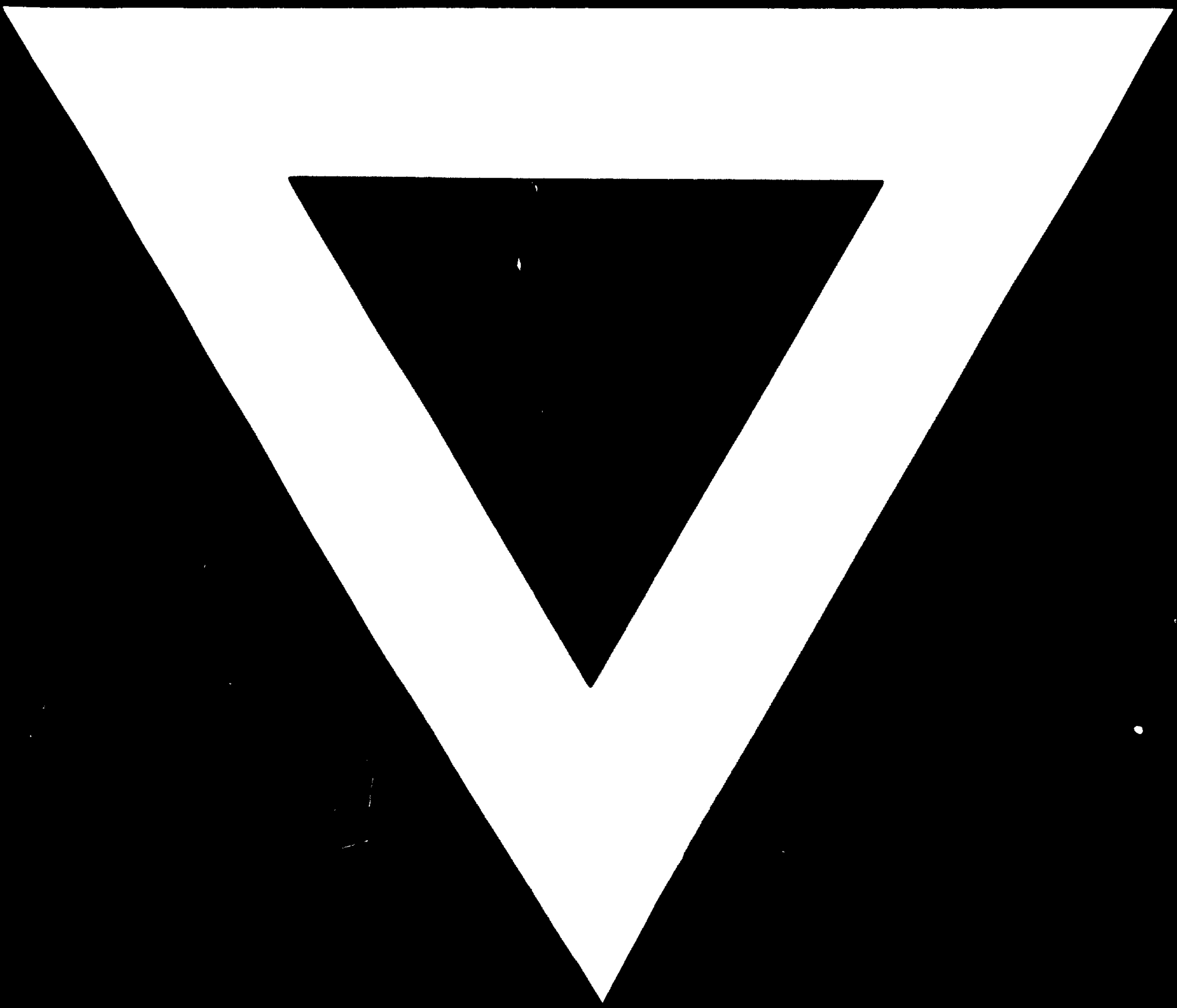

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