ECONOMIC OPTIMIZATION TECHNIQUES
APPLICABLE TO PRECISION MINIATURE MACHINING

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ECONOMIC OPTIMIZATION TECHNIQUES APPLICABLE TO PRECISION
MINIATURE MACHINING

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Prepared by L. K. Gillespie, D/822, under PDO 6984735

Traditional techniques for optimizing the economics of fabricating precision miniature piece parts are not adequate when over 250 different fabrication processes are in use. Existing definitions of tool life are totally inadequate when they are applied to machining batch lots of precision miniature parts and this in turn affects machining economics. Eleven basic approaches to optimizing the economics of manufacturing precision miniature parts are described, including evaluating trade-offs between machining and deburring operations, using group technology, computer aided designs and direct numerical control, and implementing evolutionary optimization techniques. Several of the approaches described are in use at Bendix.

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CONTENTS

Section	Page
SUMMARY.	5
DISCUSSION	6
SCOPE AND PURPOSE.	6
PRIOR WORK	6
ACTIVITY	6
<u>Improving Fixturing, Handling, Assembly,</u> <u>and Cutting Tool Concepts.</u>	6
<u>Improving Processes.</u>	8
<u>Improvements Through Computer Aided Manufacturing. . .</u>	18
<u>Optimizing Function and Scheduling</u>	20
<u>Optimizing Metal Cutting Operations.</u>	21
ACCOMPLISHMENTS.	23
FUTURE WORK.	23
REFERENCES	25
DISTRIBUTION	27

ILLUSTRATIONS

Figure		Page
1	Approaches to Economic Optimization.	7
2	Typical Precision Miniature Components (P-90357).	9
3	Typical Precision Miniature Components--View 2 (P-92330)	10
4	Optimum Process With Single Dependent Variable	14
5	Example of One Independent Variable and Five Constraints	15
6	Example of Two Independent Variables and Five Constraints	16

SUMMARY

Traditional approaches to optimizing machining economics do not apply to the production of short run precision miniature parts. With the continuing need to accurately forecast and control costs, it is essential to economically optimize many operations. The economic optimization of fabrication techniques involves many approaches, some of which are already under study or in use at Bendix. The project represents an attempt to identify techniques specifically applicable to miniature piece parts.

Improving cutting tool life and geometry may help optimize machining economics on precision parts. Tool life is short when the criteria for life is the maintenance of ± 0.0001 inch ($\pm 2.54 \mu\text{m}$) tolerances on 0.002 inch (50.8 μm) nose radius tools. Such tools are required to produce 0.002 inch maximum fillet radii. On many precision parts, fabrication can best be optimized by improving fixturing, handling, and assembly techniques.

Computer routines are available which can be used on short run precision parts to determine the best feed and speed rates for a specific operation. These routines are used during the production cycle and essentially eliminate both scrap and the need for special test samples. However, in a few situations, optimizing single operations can result in higher total fabrication costs. Techniques are not yet available for the automatic selection of optimum machining sequences, such as fabrication of an entire part when several different types of operation are involved.

Group technology is one approach to optimizing groups of parts and operations. Direct numerical control provides some notable features, and computer aided tool design has been used to minimize design errors and tool tryout time.

DISCUSSION

SCOPE AND PURPOSE

The object of this study was to identify and define optimization techniques that can be beneficially applied to precision miniature machining.

PRIOR WORK

No previous work has been published at Bendix on this subject, although many process development reports have reported on the optimization of a specific situation.

ACTIVITY

The production of precision parts in small batch lots is one aspect of manufacturing that has not received much attention in literature devoted to the subject of minimizing overall costs. This study attempted to identify optimization techniques applicable specifically to precision *miniature* parts.

As indicated in Figure 1, several approaches exist for optimizing the economics of production, including techniques related to part design and function, part fabrication, and scheduling operations. Although this study was specifically concerned with the economics of fabrication, the other two facets are to some degree interlaced with those of fabrication, and for this reason, are briefly discussed later in this report.

There are at least ten basic approaches to optimizing fabrication economics (Figure 1). These involve tooling workpiece materials, computer aided manufacturing, and evolutionary changes initiated by production operators.

Improving Fixturing, Handling, Assembly, and Cutting Tool Concepts

In a companion report,¹ it was noted that the fixturing and handling of precision miniature parts consumes a significant portion of the total fabrication costs. As noted by one individual,²

The average workpiece in a batch-type production shop spends only 5 percent of its time in production machines and productive work is being done on the part only 30 percent of this actual time in the machines.

Figure 1. Approaches to Economic Optimization

Improving assembly techniques and tools is another aspect which was studied as a separate entity. This approach has also been reported on.³⁻⁶

While a number of cutting tool innovations have been introduced to industry within the past five years, few are applicable to the production of precision miniature components such as those shown in Figures 2 and 3. Many of these components have tolerances of ± 0.0002 inch ($5.08 \mu\text{m}$). Their shapes often dictate the use of sharp nosed tools (as opposed to commercial 0.030 inch (0.762 mm) nose radii. Such tools have extremely short lives because of the brittle tool nose.

While improving tool life often provides economic advantages, it provides little advantage when only low quantities of parts are involved. Furthermore, many of the cutting tool improvements have involved roughing cuts in which large amounts of material were removed. On miniature parts, the roughing cut, if it exists, is smaller than the finishing cut on a conventional large part. These tool improvements therefore offer little advantage for the small, short run part.⁷ The introduction of micrograin carbide material is one cutting tool advancement which has benefitted small screw machine parts.⁸ This material has increased the life of these tools 400 percent or more.

Optimizing any parameters which affect tool life requires a definition of how tool life is measured. Conventional descriptions of tool life refer to the number of minutes a tool can be used before a specific size wear land forms on the tool. The size of the end-of-life wear land differs for each type of machining operation and type of tool material. As indicated in another study still in process, wear land size is not a useful indicator with precision miniature parts. Surface finish, fillet radius, radial tool wear, and burr size are more realistic indicators of end-of-effective-tool-life for these types of parts.

Improving Processes

Optimization Through Feed and Speed Changes

This study emphasized the definition of techniques which could be used to do two things:

- Determine optimum cutting feeds and speeds, and
- Select the most economical alternative process.

Several approaches can be used to determine the optimum feeds and speeds for specific machining processes. These include informal cut and try, strictly analytical analysis, a black box approach, an analytical model treated as a black box, and the black box used to define the analytical model.

Figure 2. Typical Precision Miniature Components

The automotive industry has used most of these optimization approaches to improve production. While feed and speed improvement is the most common use for these techniques,⁹ they have also been used to optimize equipment replacement, lot sizes, reliability, and total machining sequences. These methods include both analytical and experimental approaches. In every case, however, the variables studied must be quantified and, with the exception of the cut and try method, a specific sequence of experimental steps must be followed. The following comments summarize the various optimization approaches.¹⁰

Informal Cut and Try Methods

Since machine tools were first developed, machine operators have varied speeds and feeds in an unstructured attempt to improve output. These cut and try techniques, combined with operator

Figure 3. Typical Precision Miniature Components--View 2

experience and intuition, have been responsible for a number of documented and undocumented improvements. There are four advantages to this approach:

- It incurs no noticeable additional testing costs;
- It requires no additional manpower, tools, material, or equipment;
- The operator is the individual most familiar with the operation and equipment and therefore he often has additional insight; and
- The operator can compensate for problems arising from spindle vibration, lead screw errors, and cutter deflection by simply by-passing conditions in which these effects occur.

This approach also has disadvantages.

- The operator cannot easily optimize the total operation since he does not have data on tool costs, setup costs, or overhead factors. Maximizing tool life generally will *not* minimize total costs.

- The experience built up by the operator may bias his approach so much that potentially useful combinations may be ignored. The many new cutting material improvements, for example, allow one to machine under what were once impossible conditions. Many operators are still wary of the newer tooling materials and approaches.
- The operator may not be aware of the full range of cutting tools and machines which can be used.
- Operators may tend to override feed and speed instructions on parts sensitive to such changes. These changes can affect distortion and residual stresses. On ground parts residual stress effects may not be apparent for several months--until the parts begin cracking for unexplained reasons.

Analysis

A strictly analytical approach requires a series of equations which must interrelate available horsepower, feed, and speed. For precision miniature parts, these effects must be also related to dimensional size, surface finish, and time in cut. Tool wear must be defined in terms of all these parameters. Tool costs, setup costs, lot size, and overhead charges must also be defined.

To optimize a system, partial derivatives are taken of each of these equations with respect to the optimizing variable. The series of equations is then solved to determine the optimum feed and speed.

The advantage of such an approach is its universality. Once the equations are known, changes in labor costs, overhead, or tool costs can easily be programmed.

The disadvantage of such an approach is that each variable must be represented by a constant or an equation. This can involve the use of up to 20 equations, which is at best unwieldy. This analytical information is seldom available. Although several programs have been published which are adequate for high production, none that have been located are defined in terms of batch lot, small quantity, and precision parameters. While it is possible to prepare such equations, purely theoretical approaches often lead to misleading conclusions since they cannot easily take into account machine anomalies. Purely analytical equations predicting surface finish are grossly in error when finishes of less than 16 microinches ($0.4 \mu\text{m}$) are involved. Much of the information required to analytically relate surface finish, part dimensions, feeds, and speeds is not available at this time.

Black Box Approach

With the black box approach, a record is kept of each set of input conditions (feed and speed) and the resultant output (such as surface finish, dimensions, tool wear, and total cost). The differences between the first set of input and output conditions determine the next set of input conditions.

For example, if the objective is to maximize the number of parts drilled per dollar spent, drill life would be measured at one speed and feed for one type of drill. A different drill feed or speed would be used for the second test. The resultant costs, including tool change time, tool costs, and labor, would indicate which conditions to try next. The technique may require that conditions much different than the initial ones be used.

In general, this approach requires the presence of an engineer to determine test conditions and monitor results. It also ties up equipment and obviously requires some measureable amount of testing. The approach becomes more difficult as the number of variables increase.

Evolutionary Optimization (EVOP) and Evolutionary Optimization for Machining (EVOM) are two forms of this approach particularly applicable to manufacturing operations. These entirely experimental approaches rely on small changes to the machining conditions. For example, to optimize an NC end milling operation, the initial feedrate of 0.8 inches per minute (ipm) might be changed to 0.9 ipm in the second test. If life or accuracy improved, the next step might be 0.95 ipm. Once again, the technique requires a specific approach to selecting each set of conditions.

The advantage of this form of optimization is that it utilizes small increments of changes. Since a *small* change in a process will seldom cause gross errors or mass rejection, this technique is ideal for many production situations.

EVOP requires the involvement of an engineer, statistician, or other trained individual in addition to production operators. However, as pointed out by Box and Draper¹¹, the EVOP process can be used by production operators with only weekly direction by an engineer. In other words, EVOP and EVOM provide a scientific rationale for cut and try methods and can be incorporated as integral elements of the production cycle--with the machine operator making the simple calculations to determine the next set of machining conditions.

The disadvantage of EVOP and EVOM is that they are not well suited to short run or model shop applications. To utilize these optimization approaches when parts are produced in batches of 50 to 150 parts every two months requires alerting production controllers,

foremen, and engineers to the fact that a desired operation is ready to be optimized, as well as educating the machine operator in the procedures required.

If tool life is the key parameter being monitored, 150 parts are to be made on a specific setup, and the life is greater than 150 parts, it would be impossible to make a single iteration in the process because of the low quantity of parts available. Even for minimal improvements it is desirable to be able to test four different combinations for each setup. If a specific operation were to be optimized on a specific part using four iterations per setup and six setups per year, roughly one year of production would be completed before something close to maximum optimization could be achieved and documented. For a multi-year run, however, or a group of look-alike parts, this could still result in significant savings. The key to improvement is having enough parts per setup to try several improvements.

When a production operator records his observations and selects the next set of speed-feed settings, he normally only optimizes the process with respect to a single variable (Figure 4). True optimization must involve several constraints (Figures 5 and 6). Despite this limitation, substantial improvements have been made by several companies using production operators to record and calculate the next setting using only simple optimization systems.

Analytical Model Treated as Black Box

Although the equations defining a system may be known, the number of equations or their form may make it inconvenient to derive strictly closed form analytical solutions. In these cases, analytical iteration may be used to solve the equations for least costs. The Newton-Raphson method of finding roots to equations is one such approach to finding solutions to a series of equations.

Using the Black Box Approach to Define the Analytical Model

In many instances, test data can be used to derive equations for the system. These equations can then be differentiated to obtain the optimum conditions. This response surface fitting has the added advantage of providing equations which can be used to predict results at any level, not just the optimum. Its disadvantage is that the results (and the equations) obtained are accurate only for the conditions tested.

Extrapolating the results to other conditions can lead to erroneous results. For example, if the feedrate surges on the machine from which the data was obtained, the derived equations will reflect an anomaly which will not actually occur on a better machine. Such anomalies can seriously bias the results.

Figure 4. Optimum Process With Single Dependent Variable

Each of the described approaches has been used to some extent in production or experimentation at Bendix Kansas City. The EVOP approach is the easiest to implement but its real advantage is in medium to long run applications. Continuous runs provide the operator with a feeling that something is actually being accomplished since he can see all the results as they develop. The time lag associated with intermittent runs results in knowledge gaps and consequent loss in interest by production operators.

The use of the black box and analytical approaches is best exemplified by a current Bendix study on molding heating and cooling.¹² In this study, which uses all of the analytical techniques described, an entire mold heating and cooling system is being optimized to improve the dimensional size and consistency of molded plastic parts.

Levels of Optimization

Optimization can be performed at several levels in the fabrication cycle. Typically, the feeds and speeds on a specific operation on

Figure 5. Example of One Independent Variable and Five Constraints

a specific part are optimized. The next level of optimization would be for the total machining approach. Another step would be to optimize the total machining-finishing-inspection of the part. Optimization of a family of similar parts, and of an entire plant represent even higher levels. Typically, an increase in the level of optimization involves considerably more complexity in the analysis.

In analyzing the appropriate level of optimization, it is important to note that optimizing one level in the sequence can *increase* the costs of the next higher level of optimization. For example, one can optimize the production rate for a special operation by increasing the feedrate and allowing tool wear to go beyond conventional limits. This can increase the cost of a subsequent deburring operation noticeably. In fact, it can increase the cost of the combined machining-deburring process beyond its 'nonoptimized' cost. The same is true of production rate. Increasing milling rates by 25 percent may not be an advantage if it slows deburring or the total machining-deburring output by 35 percent. In general, however, optimizing a specific operation will not degrade overall performance.

Figure 6. Example of Two Independent Variables and Five Constraints

When an engineer selects a fabrication sequence, he consciously and intuitively compares the following factors to select the total process as well as individual processes:

- Equipment tolerance capability,
- Available feeds and speeds,
- Ease of setup and tool change,
- Quantity of parts made per setup,
- Equipment loading (availability),
- Tooling costs,
- Size and configuration of parts, and
- Horsepower available.

With roughly 270 production processes¹³, and a wide variety of equipment available within each process, it is obvious that true optimization is not likely to result from a mental process only. Even though a particular part might utilize only 10 of the 50 different types of equipment found within a precision miniature machining area, it is difficult to categorically state that an optimum fabrication sequence has been achieved.

No operational technique has yet been reported which would allow an individual to use design and cost information to scientifically select and verify optimum machining conditions for all the operations required to produce a part. As previously indicated, it is currently possible to do this for individual operations. The major limitation at this time is that essentially no data is available regarding the impact of one process on another. Data is just now being compiled on the impact of machining conditions on deburring costs.¹⁴ On precision parts, data is particularly significant, since not every process can maintain ± 0.0001 inch ($\pm 2.54 \mu\text{m}$) tolerances or 8 microinch ($0.2 \mu\text{m}$) finishes. A recent Bendix guide, however, offers some significant tolerance, size and cost related information for various quantities of parts produced by approximately 150 process piece part shape combinations.¹⁵⁻¹⁶

Group technology is one approach to optimization on a broad scale being pursued in a separate study.¹⁷ As indicated in Figure 1, group technology is a method of improving schedules in addition to optimizing fabrication techniques. Group technology may be used to encourage more uniform piece part design which in turn would optimize part function.

As indicated recently by Houtzeel and Schilperoot¹⁸, group technology actually encompasses several aspects of production and optimization of fabrication may not be the most significant benefit. According to Houtzeel and Schilperoot, the production aspects benefitting from group technology include these:

- Drawing retrieval,
- Operation and machine routings,
- Standardization of materials and shop operation,
- Optimization of product mix,
- Analysis of operations,
- Shop layout based on work cells, and
- Investment analysis for machine tools.

On short run precision miniature parts the standardization resulting from group technology offers distinct savings on setup and tooling costs. In addition, it promises to provide more accurate tool cost forecast and to shorten production flow times. To some extent, it will also minimize the amount of effort required to convert piece part drawings to fabrication instructions.

Improvements Through Computer Aided Manufacturing

Computer aided manufacturing (CAM) is another multi-faceted approach to optimizing manufacturing economics. This field includes the calculation of optimum settings for a single operation, the automatic selection of sequences of operation, the computer control of equipment, and computerized production management.

Computerized Selection of Fabrication Economics

The calculation of machining economics is a relatively simple but tedious process. As an example, Field's equation for calculating the cutting speed which minimizes machining cost¹⁹ on NC equipment, has 33 terms involving reciprocals, multipliers and exponents. Different equations are required for each type of process and for the type of optimization desired. A process can be optimized to result in minimum cost, maximum profit, or maximum production. The computer is an obvious asset in such calculations.

A large number of computer programs have been written for calculating metal cutting economics and for selecting optimum cutting conditions. Three such programs have been obtained by Bendix. The first of these, titled *Production Optimization Method (POM)*, calculates optimum feeds and speeds for turning operations.²⁰ It requires input data on tool life, speeds, and feeds available on the lathe, maximum and minimum depths of cut, initial and final workpiece dimensions, setup times, production and tool costs per minute or piece, horsepower available, and unit horsepower for the material to be cut. After calculating optimum conditions, the user implements these conditions and monitors tool life. This new information is then also fed into the computer which then recalculates optimum conditions. This EVOP cycle is repeated until significant improvements fail to occur.

The *Performance Index Method (PIM)* requires data similar but less extensive than that of *POM*²⁰. Test data input, however, is simpler than that of *POM* in that only machining time, number of pieces produced per unit time, and the number of tool changes made during the test are required. Optimum conditions are then calculated from this information. Because of its generality, it can be used for any of the basic machining operations such as drilling, milling, tapping, grinding, or turning.

NCECO, developed by the Air Force Machinability Data Center²¹, evaluates optimum machining conditions for turning, end milling, face milling, drilling, reaming, and tapping. Different equations are used for NC and conventional machines. This program also utilizes the basic input data of cost, length of cut, non-cutting tool approach lengths, tool life, number of parts to be machined, resharpening and setup time, and so on. Like the other programs, it optimizes with respect to maximum production or minimum costs. This program, however, is not an interactive program such as *PIM* and *POM*. It assumes sufficient test data is available to make decisions.

The major limitation of *POM* and *NCECO* is that an analytical expression of tool life is required. As previously indicated, such information is not now available when the criteria for life are defined by such constraints as 8 or 16 microinch (0.2 to 0.4 μm) maximum surface finish, 0.002 inch (50.8 μm) fillet radius, ± 0.0001 inch (2.54 μm) tolerances, minimum cutting force (to prevent part deflection or damage), or minimum burr size. Rather than a single equation for life, these criteria common to precision miniature parts result in a series of constraint or bounding equations. *PIM* is the only known program not affected by the format of the tool life equation(s). It is not as precise a program in terms of including all pertinent machining costs as *NCECO*, however. In most commercial situations, the difference in degree of optimization precision would not be noticeable, particularly in instances where cutting costs are small in proportion to total fabrication costs.

Selection of Machining Operations

As previously indicated, the automatic selection of the total sequence of manufacturing steps required is a desirable goal. To a very limited extent this has been implemented using computers. A recent article by Keating,²² for example, indicates that an International Harvester plant utilizes a computer to decide from hole tolerances whether to drill only or to drill and ream. Their program also generates an accurate time study and a process sheet listing feeds, speeds, tools, and production rates.

Barash²³ describes a Purdue University program for optimizing lathe operations involving up to 20 tools working at the same time or sequentially in the same setup. Unlike other programs, this one includes all lathe operations (such as facing, turning, and drilling). Among the functions performed by the computer are these:

- It checks the compatibility of tool motion for the particular machine. In other words, it will confirm whether the machine tool can drive the tools the way the planning engineer specifies.

- It checks all possible combinations for the formation of feasible groups of simultaneously working tools.
- It computes feeds and speeds for each feasible group of tools based on the minimum cost of minimum production time considering deterministic tool life relationships.
- It prints out the cost and production time for each feasible group.
- It computes feeds and speeds for each feasible group based on the minimum cost or minimum production time, considering tool life to be probabilistic in character.

While this approach still involves only a single setup, it does involve several tools and types of operations.

Despite the lack of techniques and programs, a recent Delphi-type forecast²⁴ indicates that by 1980 a computer software system for full automation and optimization of all steps in part manufacturing will be developed and in wide use.

Computer Control and Related Facets

The Bendix effort on direct numerical control²⁵ is another project which will improve the economics of precision miniature part manufacture. In this effort, the optimization occurs by the minimization of machine downtime for NC tape changes, costs for resetup, and the minimization of nonproductive cutting time. The potential also exists for marrying programs for calculating optimum speeds and feeds with DNC, although no such effort is currently in progress. Guidelines have been issued for determining when existing NC tapes can be economically optimized by Bendix DNC equipment.

The recent introduction of commercial NC screw machines will also help optimize the production of short run precision miniature parts. This equipment eliminates the cost of screw machine cams and minimizes the tooling and setup costs associated with inevitable workpiece redesigns. It also minimizes flow times in such instances, since new tooling is not required.

Optimizing Function and Scheduling

As previously indicated, economic optimization also embraces workpiece function and scheduling. While no effort was devoted in this study to these two subjects, it is significant to note that other efforts are benefitting these areas directly and indirectly benefitting fabrication. The Bendix *Work In Progress* System (WIP) is one such effort. This computerized system prints out a daily listing of parts by priority which are to be machined by a given process.

While *Computer Aided Design (CAD)* is being used to develop piece part configurations, it also has been used to design tooling for production. Shaper cutters for producing gear teeth, ratchet teeth, and symmetrical contours are now being designed and inspected by a Bendix developed computer program.²⁶ Screw machine cams are also currently being commercially designed by computer which results in faster delivery and more accurate cams.²⁷

The Sandia developed Tramper program, designed to verify the functionality of machined hole patterns, is another function related aspect of economic optimization. In the past, many hole patterns have been defined in respect to a single set of data. The functional requirement, however, was that the parts which would be out of locational tolerance by conventional tolerancing and inspection techniques be accurately located in relation to all other holes in the pattern. The Tramper program now provides a technique for determining how accurately holes are located with respect to each other. This helps minimize the problems associated with deciding functionality and helps optimize production from the standpoint of providing better information on capabilities.

Optimizing Metal Cutting Operations

As indicated earlier, the objective of this study was to identify and define optimization techniques that can be beneficially applied to the machining of precision miniature parts. Before implementing any of these techniques, several steps must be taken.

The first step is to decide whether a process should be optimized to

- Maximum profit,
- Minimum cost, or
- Maximum productivity (maximum number of parts per shift).

This decision is not as simple as first might appear because in a large company accounting data may not be available in the detail or form required to optimize profit.

The second step, which presents some of the same fiscal questions as the first, is to determine how the results are to be used. The overhead rates may vary by intended use of the results. In comparing the economics of one process versus another, for example, one overhead factor may be used. In determining actual cost savings resulting from making a change, a different overhead factor may be used. In a small company, an even different factor would be used to determine sales dollars. In a similar vein, one has to decide if equipment with high capital costs is to have the same cost of use rate as that of less expensive manual equipment.

The third step is to obtain accurate cost and time data for such items as these:

- Purchase cost of tool,
- Cost of inserts,
- Grinding wheel resharpener cost,
- Labor and overhead cost on tool grinder,
- Labor and overhead cost of machine,
- Resharpener time,
- Number of resharpenings (or indexes) per tool,
- Time to rebrake tool,
- Time to reset tool,
- Time to load and unload tool, and
- Lathe setup time.

Again, obtaining such data may be difficult since accounting departments may not break down costs in this manner.

The fourth and most difficult step is to determine how tool life is to be defined. The factors which must be considered on precision miniature parts are the maximum allowable:

- Surface finish,
- Fillet radius,
- Dimensional change,
- Burr thickness,
- Burr height,
- Taper,
- Cutting forces, and
- Wear land size.

The data from these four steps will then allow one to use the *PIM* computer routine to calculate optimum machining conditions

for a single operation. While *PIM* is the easiest program to use, either *POM* or *NCECO* should also be used at the completion of optimization to provide more exact costs. As indicated earlier, *NCECO*, in particular, includes a number of cost elements ignored in other programs. If an analytical expression for tool life can be obtained in the form of the Taylor equation (below) then *POM* or *NCECO* can be used rather than *PIM*.

$$VT^n f^\alpha d^\beta = C$$

where:

V = Cutting velocity,

T = Tool life in minutes,

f = Feedrate,

d = Depth of cut, and

c, n, α , and β are constants.

Unfortunately, as noted by Field¹⁹, this equation is not valid for milling, drilling, tapping, and reaming of aerospace and many other materials.

One other factor of note in *PIM* and *POM* is that a value of unit power must be given as input data. This factor is a function of feedrate at low feeds and handbook values which generally ignore this can be low by a factor of 3.0 in strain hardening materials.

It is possible to use the three computer programs to compare the economics of alternative processes. To do so, one has to manually run *PIM* or *POM* for each process, then manually compare results. *NCECO* does not require rerunning for each process, but it does require manual comparison of the printed economics of each process.

ACCOMPLISHMENTS

Economic optimization techniques applicable to short run precision miniature parts have been identified. Some of these techniques are currently in use at Bendix.

FUTURE WORK

No future work is planned at this time on optimizing the speeds and feeds on specific machining operations. Related projects

involving defining machinability for cuts in precision miniature parts, optimizing cutting tool angles, defining trade-offs between machining and deburring costs, implementing group technology concepts, using computer aided design techniques, and direct numerical control are currently in work or nearing completion. The implementation of such programs as *PIM*, *POM*, and *NCECO* appears to be a viable technique that should be considered for some operations.

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