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# Fabrication for Precision Mechanisms

By L. K. Gillespie

MASTER

Published March 1980

Final Report
G. R. Flebbe, Project Leader

Prepared for the United States Department of Energy
Under Contract Number DE-AC04-76-DP00613.

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FABRICATION FOR PRECISION MECHANISMS

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Miniature precision actuators, timers, and switches present a variety of manufacturing challenges due to part minuteness and the combination of miniaturization and precision. The study explored 25 manufacturing problem areas associated with these miniature mechanisms. Topics included small hole drilling and tapping, machinability of various materials used in miniature assemblies, press fit tolerances, swaging, fixturing and handling, and friction reduction. Plastics, ceramics, and metals were studied. Each of the 25 topics is summarized.

WM/srg



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SUMMARY

The fabrication of components and assemblies for miniature precision mechanisms provides a variety of exacting manufacturing challenges. Size alone makes many parts hard to pick up, handle, measure, and install. This same small size causes more distortion or bending during machining, assembly, and welding. Some parts even float on the cleaning and deburring solutions. Tools break easily in very small holes, and surface finishes play an important role in part operation.

Twenty-five manufacturing operations were studied to improve the precision of existing machining and assembly techniques. The study included the machining of metals and plastics using techniques new to the manufacture of miniature switches, timers, and actuators. Drilling, tapping, and press-fitting miniature features were evaluated. Fixturing and handling techniques, friction reduction, and the forming of ceramic parts were also studied.

Many of the new approaches from this study have been incorporated into existing processes and further refined. Detailed observations have been reported in 33 other Bendix reports and the highlights of those observations are summarized in this study.

# DISCUSSION

## SCOPE AND PURPOSE

This study was initiated to provide detailed machining and assembly data and concepts applicable to electromechanical mechanisms having extremely small, precision parts. The study included 25 specific development tasks covering the following areas:

- Machining new metals and plastics,
- Tapping ultraminiature threads,
- Press fitting miniature pins,
- Reducing dynamic friction on miniature parts,
- Fixturing and handling miniature parts, and
- Forming miniature ceramic parts.

These studies were specifically dedicated to defining the techniques required to successfully fabricate high precision, ultraminiature parts without breaking tools, distorting parts, or otherwise restraining production.

## PRIOR WORK

While Bendix has performed a number of related studies, at the time this study began only one was directly related to the unique problems of ultraminiature parts.[1] In that study, several approaches for producing slots less than 0.010 in. (254 $\mu$m) wide were studied, as were the problems associated with producing fillet radii smaller than 0.0003 in. (7.62 $\mu$m). A parallel study of deburring capabilities on miniature parts was also initiated at about the same time as this study.[2]

## ACTIVITY

### Small Parts Defined

Small parts create many problems in manufacturing by virtue of size alone. They are hard to pick up, handle, measure, and insert. Accurate surface finish results are often difficult to obtain. Their small size results in more distortion or bending during machining as well as increased potential for handling damage. If dropped on the floor, many of these parts are impossible to find and, if found, probably are discrepant. Small washers float in some cleaning solutions thus leaving some residue on one side. Taps fracture easily while producing threads smaller than 1.0 mm. Thin cutters deflect while milling thin slots thereby causing out-of-tolerance dimensions. Press fit pins bend, gall, or slip out of holes toleranced to normal press fit tolerances. In short, miniaturization of electromechanical parts significantly complicates manufacturing, particularly when performed on a job shop basis.

In 1970, designs of some electromechanical switches had shrunk such that units having up to 250 parts per cubic inch (16.4 $cm^3$) were being designed for fabrication. This development was initiated at that time because previous experience with some of the small parts indicated that a number of manufacturing problems occurred using the then state-of-the-art techniques. Since the basic problem was rooted in the smallness of parts rather than a manufacturing process alone, the study was designed as a broad base study to include machining, blanking, and assembly. In short, the study was devoted to solving a system-wide concern rather than a single problem. Twenty-five specific areas were studied. Many of these 25 areas of study have been previously reported in detail.[3-16] This report summarizes the findings made in each of the 25 studies.

The studies are presented in the order shown in Activity. In reviewing, it is obvious that many studies are similar or involve similar materials. The fabrication of polyimide plastic is included in at least four individual studies. Hole production occurs in four studies. Small slots were studied in two separate stages. Ballizing is studied from the standpoint of surface finish and in a separate study from the standpoint of accuracy of hole size.

This report is designed to summarize each study area as opposed to a general subject such as "holes." As a result, the report is written so that each study stands alone as a chapter in a handbook.

## Fine-Edge Blanking of Metals

When this study began, fine-edge blanking or fine blanking was just being introduced to American markets. At that time, there was little published information on process capabilities. This study was initiated to analyze capabilities and limitations related to precision miniature parts common to electromechanical mechanisms.

The study primarily indicated three things:

- Fine-edge blanking produces parts with less die break (Figure 1) and with superior edge finish than is attainable using conventional blanking processes.

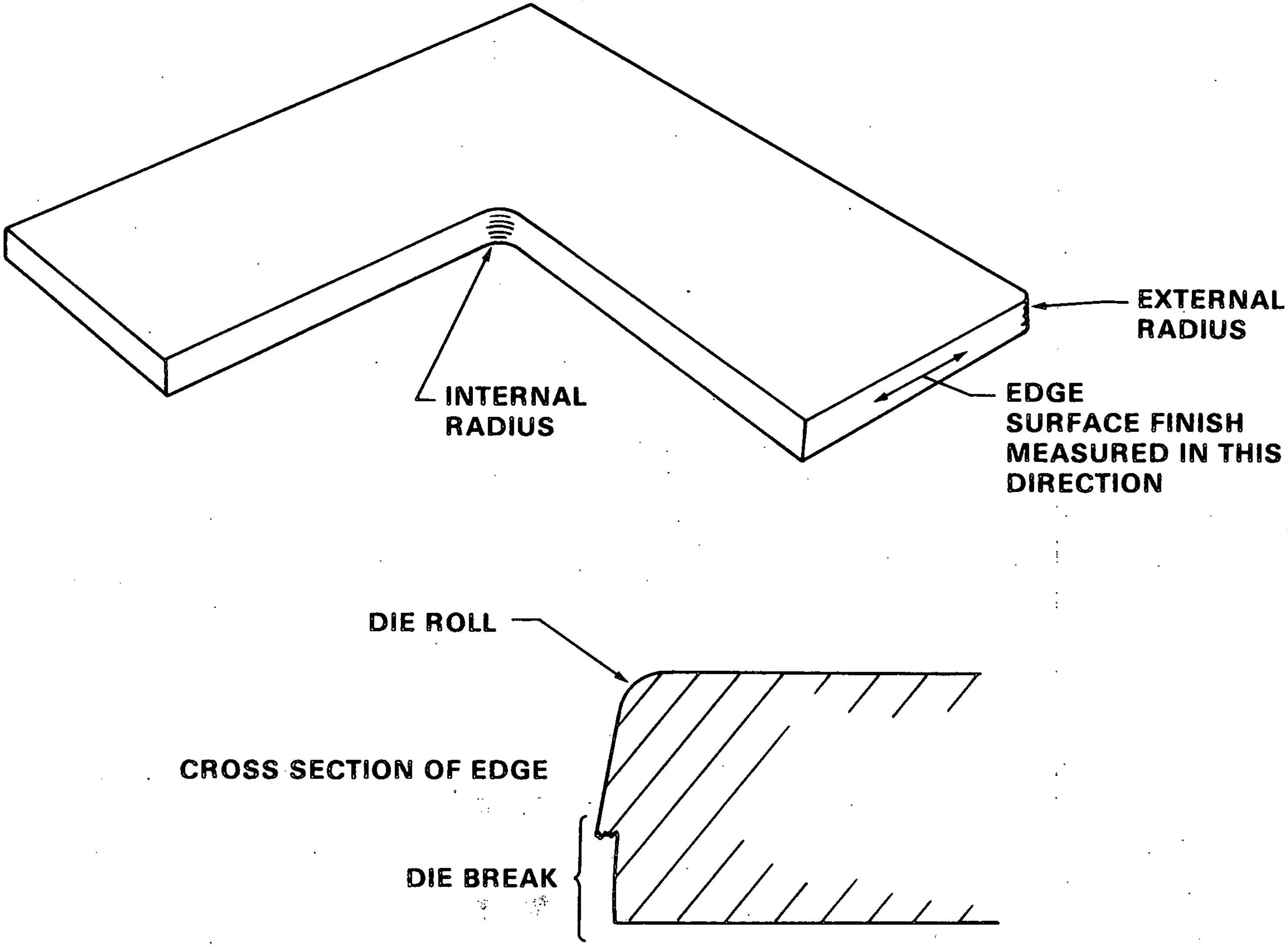


Figure 1. Limiting Features in Blanking Operations

- Fine-edge blanking can accommodate part designs with smaller inside and outside corner radii (Figure 1) than is attainable by using conventional blanking.

- Fine-edge blanking can maintain closer tolerances than conventional blanking.

Using 1020 mild steel as a basic material, the three most common effects of blanking are part edge finish, die roll, and corner radii. These were studied (Table 1) using tools designed and built by this country's leading fabricator of fine-edge blanking tools. As seen in Table 1, surface finishes by fine-edge blanking were better than by conventional dies.

Although 6061-T6 aluminum is not considered a good choice for fine blanking,[17] tests on the part shown in Figure 2 proved it to be acceptable and even better than 6061 in the TO condition.

The evaluation of parts of various materials and shapes revealed some limitations in the present fine-edge blanking press. The development and ultimate use of the blank and pierce die for the spur gear, Figure 2, required that counterpunch pressure be no more than 6 metric tons (6000 kg) to produce the part and maintain part thickness. The counterpunch pressure will coin the part if the part surface area is too small. The aluminum gear with a diameter of 0.5 in. (12 mm) (Figure 2) represented the smallest surface area which could be run without coining on the first fine-edge blanking press used at Bendix. A recently acquired smaller press allows counter pressures as low as 0.2 metric tons (20 kg) to be used, so surface areas 30 times smaller can be run without coining. Operating at the lower counter pressures helps reduce burr size on sharp cornered parts.

On the other hand, the maximum part periphery for a given material and thickness cannot require more than the 100 metric tons (100,000 kg) of ram pressure available on the machine for blanking. These limitations are listed in Table 2.

There is theoretically no lower limit of material thickness applicable to fine-edge blanking. However, due to narrowing tooling cost differentials, the process ceases to be competitive with conventional blanking from a cost or edge quality standpoint for material thicknesses below 0.010 in. (0.25 mm).

A typical burr produced by this process tends to be approximately 0.001 in. thick at its base and 0.002 in. high (25.4 by 50.8 μm). This is three to five times smaller than burrs produced by conventional dies.

Table 1. Basic Fine-Edge Blanking Capabilities on 1020 Steel

| Characteristic | Fine-Edge Blanking (μin.) (μm) | Conventional Blanking (μin.) (μm) |
|---|---|---|
| **Part Finish on Edges** | | |
| 0.020/0.060 in.* | 16-32 (0.63-1.25) | 32-63 (1.26-2.52) |
| 0.060/0.100 in. | 32-45 (1.26-1.77) | 63-90 (2.52-3.54) |
| 0.100/0.180 in. | 45-63 (1.77-2.52) | 90-125 (3.54-4.92) |
| **Die Roll** | | |
| Maximum die roll at extreme tip of 90-degree corner | 30 percent of thickness | 30 percent of thickness |
| **Inside and Outside Corner Radii** | | |
| Minimum feasible internal radius | 5 percent of material thickness | 20 percent of material thickness |
| Minimum feasible external radius | 10 percent of material thickness | 30 percent of material thickness |

*0.5/1.5, 1.5/2.5, 2.5/4.5 (mm)

Studies of hole repeatability by this process indicate that in annealed beryllium copper, holes 0.028 in. (0.71 mm) or larger are typically repeatable on location within ±0.0004 in. (0.01 mm). There appears to be some shifting of dimensions with each setup, however. At the present time, the best estimate for the amount of this shifting is 0.0001 to 0.0002 in. (2.5 to 5.1 μm). The repeatability of hole size has not been determined, although the process is being used to produce holes of the size mentioned having ±0.0002 in. (±5.1 μm) tolerances. In most cases, no subsequent operations are used to finish holes in which precision parts must rotate. The observed repeatabilities are closer than indicated by another recent separate study.[18]

The original stock in this study ranged in size from 0.0295 in. to 0.0345 in. (0.749 to 0.876 mm). As a result of coining during blanking, the thickness ranged from 0.0310 to 0.0330 in. (0.787 to 0.838 mm) which is a definite improvement in tolerance range.

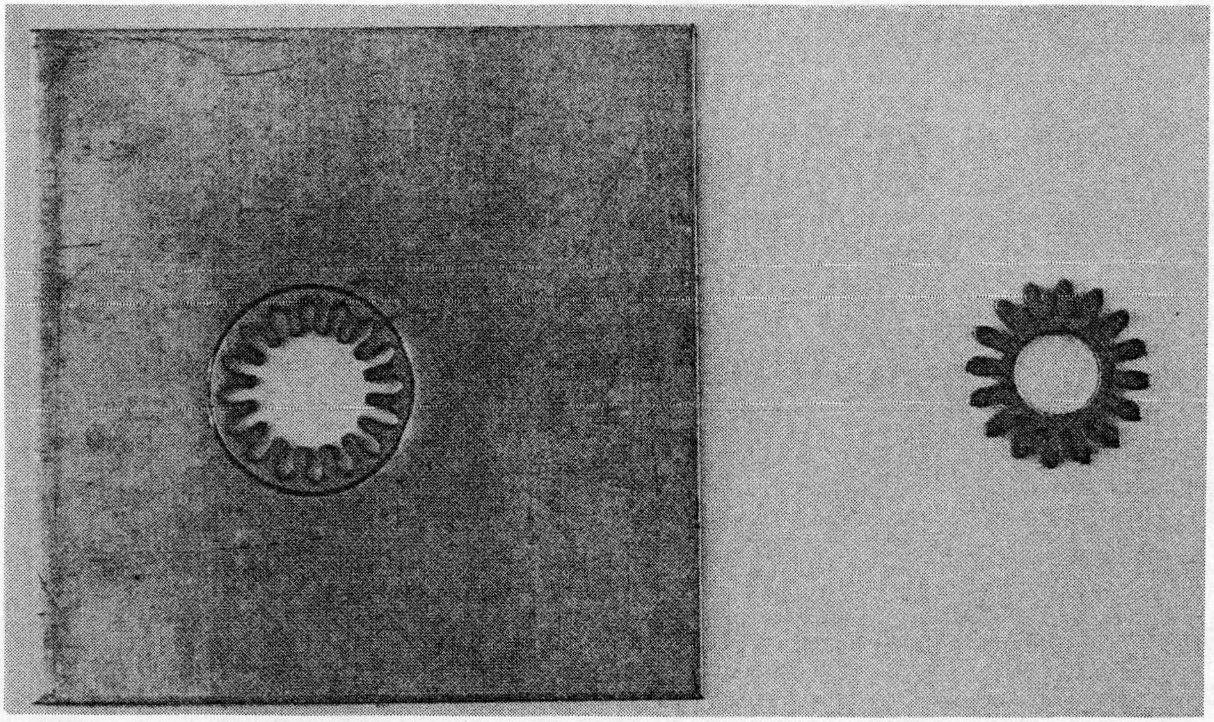

Figure 2. Spur Gear Blanked From 1/4-Hard Brass and 6061-T6 Aluminum

The ratio of length of die break to material thickness for a given material was found to be independent of thickness, within the range 0.030 to 0.125 in. (0.762 to 3.17 mm) thickness.

The die break averages 30 to 50 percent of the material thickness on materials with high tensile strength in a hardened condition; while on materials with low tensile strength, such as 6061-0 aluminum, the die break is from 0 to 10 percent of the thickness. The capability of the material to flow into and through the die before shearing occurs determines the percentage of resultant die break.

A component common to many electromechanical switch assemblies is a complicated shape with an integral hub and flange. To eliminate numerous machining operations, a fine-edge blanking die was constructed to blank a finished shape from a pre-machined blank (Figure 3). The machining operations consisted of turning the hub with a flange and facing the blank stock to finish thickness on an automatic screw machine prior to blanking. This process produced an acceptable completed part after it was deburred. The combination of automatic screw machine blank preparation with fine-edge blanking results in the ability to hold close

Table 2. Part Design Limitations for Use on Bendix Fine Edge Presses With 0.02-in. (0.5 mm) Thick Stock

| Material | Minimum Part Surface Area (in.$^2$) | (cm$^2$) | Maximum Part Peripheral Length* (in.) | (m) |
|---|---|---|---|---|
| 6061-0 Aluminum | 0.07 | (0.43) | 796.0 | (20.2) |
| 6061-T6 Aluminum | 0.011 | (0.07) | 333.0 | (8.5) |
| 304 Stainless Steel | 0.006 | (0.04) | 141.0 | (3.6) |

*As material thickness increases, maximum peripheral length decreases proportionately.

tolerances with a minimum investment in labor for each part. This expansion of the fine-edge blanking process suggests that using dies to coin three-dimensional shapes may also be feasible on future parts. As a result of this study and the availability of a machine, Bendix Kansas City produces over 90 components by fine-edge blanking. Figures 4 and 5 are examples.

## Fine-Edge Blanking of Polyimide Plastic

In the initial study, a polyimide plastic with tensile strength of 12,500 psi (86.1 MPa), ultimate strength of 6,000 psi (41.3 MPa), and ultimate elongation of 7 percent was blanked on a 100 metric ton (100,000 kg) fine-edge press. A die designed for 0.032 in. (0.813 mm) thick brass was used on polyimide with a material thickness of 0.889 mm. Springback of the polyimide plastic caused the part to be 0.004 to 0.007 in. (101.6 to 177.8 $\mu$m) larger than brass parts blanked on this die. While only a few measurements were made, it appeared that a tolerance of ±0.002 in. (50.8 $\mu$m) could be maintained in this material.

The biggest disadvantage of this approach is the large amount of breakout which occurs in polyimide plastic. If part edges are functional rubbing surfaces, this process is not acceptable because the breakout effectively reduces contact area to 20 or 30 percent of the part thickness. It appears that the impingement ring on the die was at least partially responsible for the large amount of breakout. The elimination of this ring would probably improve edge quality somewhat.

Subsequent tests on molybdenum-disulphide-impregnated polyimide plastic resulted in similar results. As a result of these limitations, polyimide plastic parts are currently being machined rather than blanked.

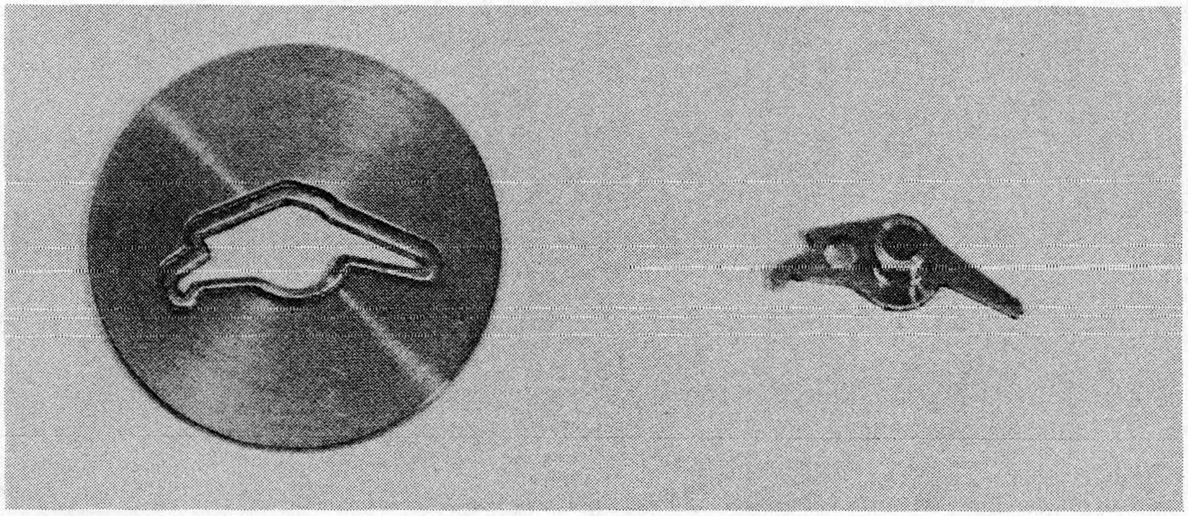

Figure 3. Drive Pawl From 304 Stainless Steel

## Molding Precision Miniature Parts

The objective of this activity was to develop injection and transfer molding procedures to produce small parts for miniature precision mechanisms, normally machined from metal. Molded components provide the miniature configurations, tolerances, and surface finishes at less cost by eliminating expensive contour milling and gear hobbing. In addition, lightweight plastic components reduce stress in high acceleration, mechanical shock, and vibration environments. The test parts used during development of the molding processes (Figure 6) are typical of metal components found in one development coded switch.

### Injection Molding Study

Two glass-filled polycarbonate materials were evaluated as potential injection molded materials. The first was a 10 percent milled glass-filled polycarbonate with 0.031 in. (0.79 mm) glass fibers. This proved more successful than a 10 to 12 percent short glass-filled material.

The first milled glass product was easier to mold because the cavity filled at a lower injection pressure. This resulted in better surface texture and material uniformity. Another molded part had a rough texture and numerous small cracks and voids.

For best material properties, it was essential that the raw polycarbonate be as dry as possible before molding. Moisture absorbed during molding made the part brittle and caused internal blowholes and surface depressions. To avoid these

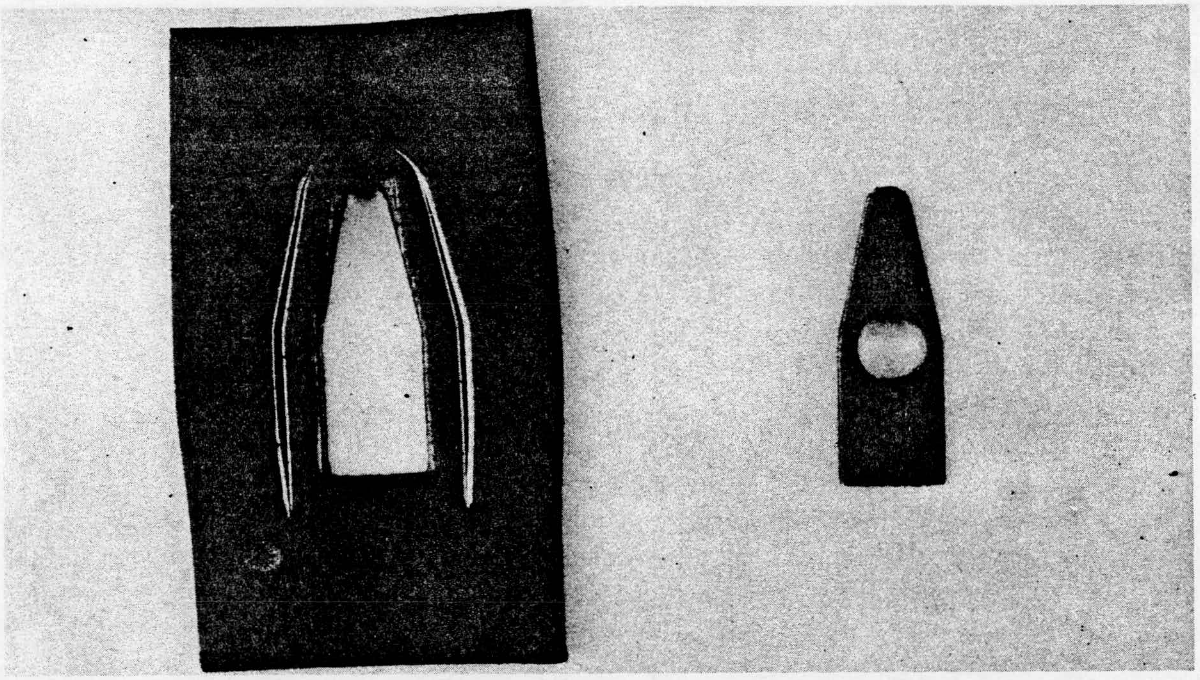

Figure 4. Pawl Blanked From Copper

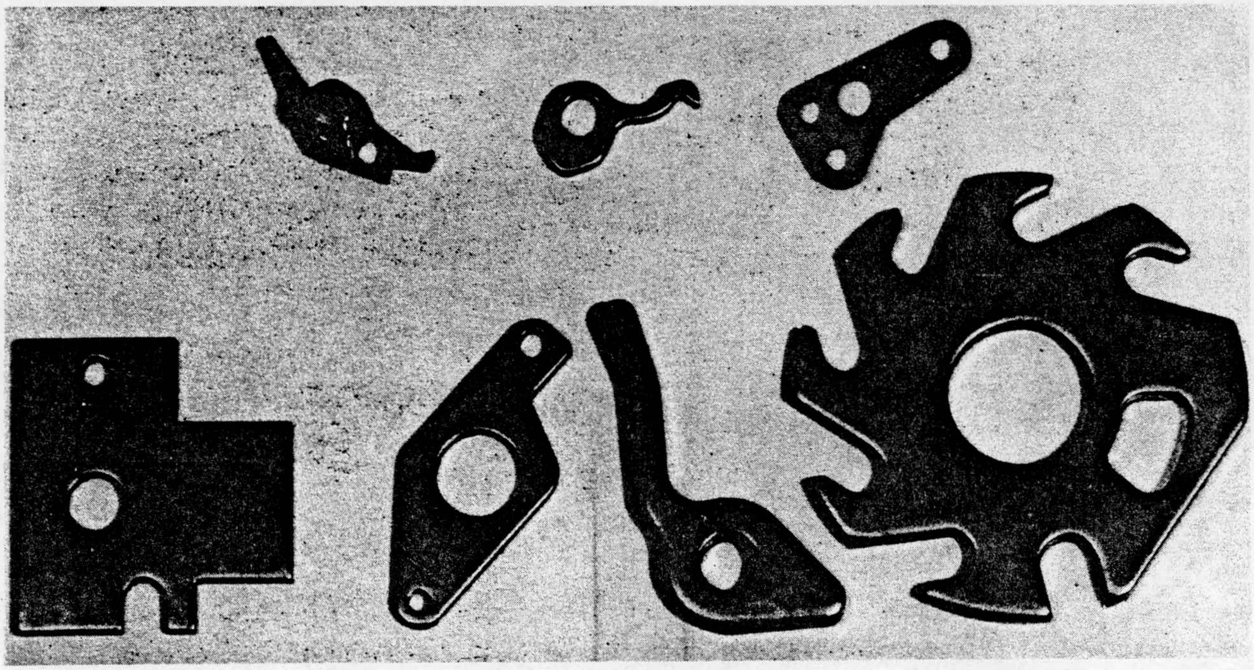

Figure 5. Switch Assembly Parts From Stainless Steel

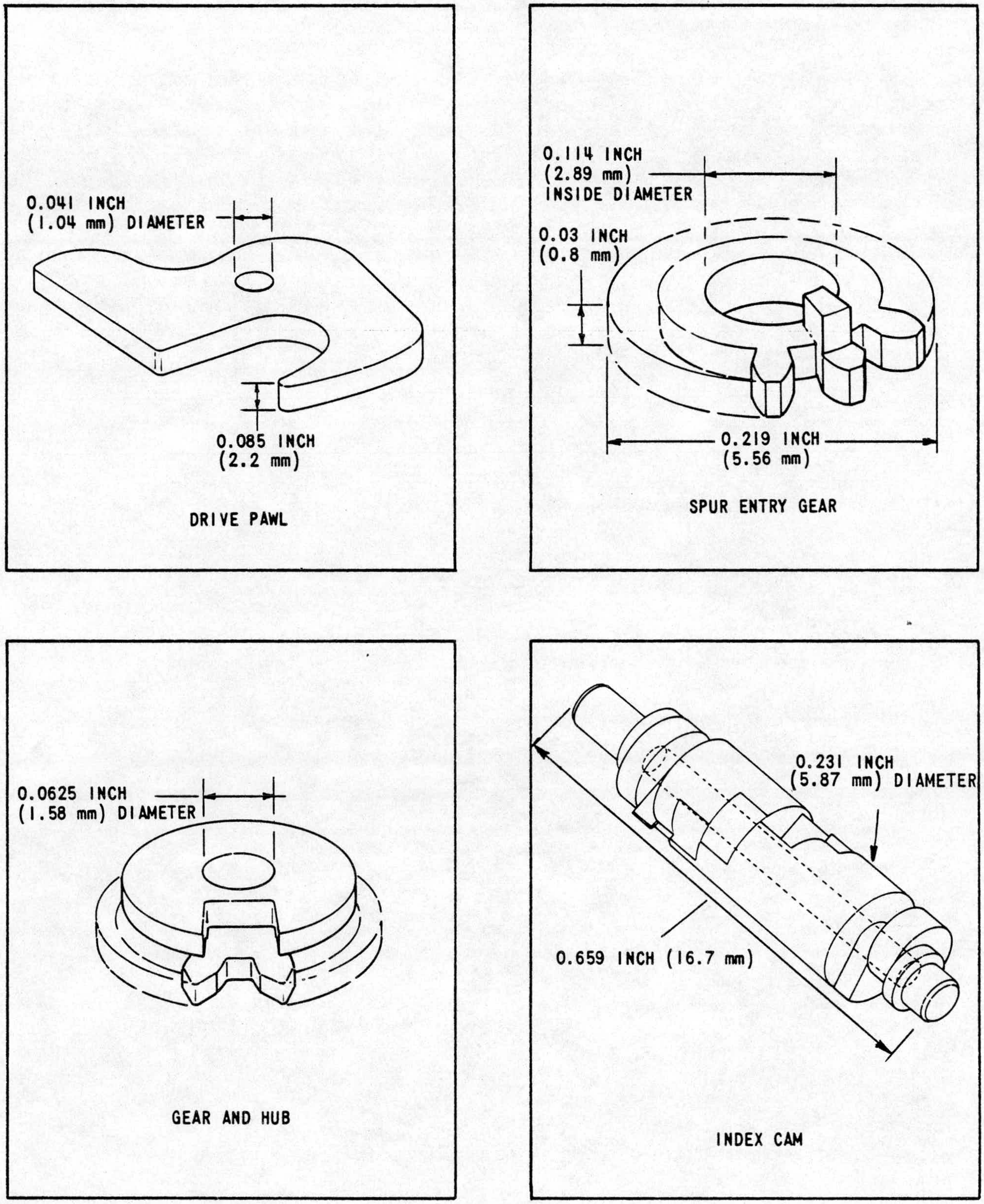


Figure 6. Four Molded Parts

conditions, the raw material was dried in a furnace at 250°F (121°C) for 4 hours immediately before use.

A melt temperature of 515°F (268.3°C) provided optimum molding conditions. High temperatures caused excessive flash. Temperatures below this optimum would not allow material to fill the mold cavity. Pressures required for the parts shown in Figure 6 were 9450 psi (65.2 MPa) for all but the index cam which required 14,500 psi (100 MPa). Table 3 illustrates the repeatability of five dimensional characteristics of the part shown in Figure 6. As seen there, the standard deviation on dimensions was typically close to 0.0005 in. (12.7 $\mu$m) which implies that tolerances of ±0.0010 in. (±25.4 $\mu$m) can be held on most dimensions (95 percent probability) if the mean actual size is equal to the nominal drawing dimension.

Transfer Molding Study

In this study, 15 gear and hub parts (Figure 7) were molded from each of the following four materials to American Gear Manufacturer's Association (AGMA) Class 9 standards:

- A short glass fiber reinforced metadiallylphthalate;
- A short glass fiber reinforced heat resistant epoxy;
- A mineral and glass fiber reinforced high temperature epoxy, competitive with the above material; and
- An experimental polybutadiene formulation with thermal stability to 500°F (260°C) and good impact resistance.

The following six other thermoset materials were investigated for possible use but were determined to be unfeasible:

- A polyimide varnish;
- A filled polyimide compound;
- A glass reinforced diallyl phthalate;
- A short glass filled diallyl orthophthalate;
- A phenolic compound reinforced with woven chopped fiberglass squares; and
- A glass reinforced polyester compound.

These later materials were considered unsatisfactory, because the excessively high molding temperature required was not compatible with available equipment and because parts were too brittle.

Table 3. Repeatability of Gear and Hub Dimensions

| Characteristic Required | Lot 1 Results: Mean (in.) (μm) | Lot 1 Results: Standard Deviation (in.) (μm) | Lot 2 Results: Mean (in.) (μm) | Lot 2 Results: Standard Deviation (in.) (μm) |
|---|---|---|---|---|
| Gear Thickness of 0.020, +0.000, -0.001 in. (0.5 mm) | 0.02039 (517) | 0.00050 (12.7) | 0.01961 (488) | 0.00025 (6.3) |
| Cam Thickness of 0.020 ±0.001 in. (0.5 mm) | 0.0211 (536) | 0.00032 (8.1) | 0.02075 (527) | 0.00063 (16) |
| Part Thickness of 0.0700, ±0.0000, -0.0005 in. (1.7 mm) | 0.07168 (1.82) | 0.00049 (12.4) | 0.07237 (1.83) | 0.00051 (13) |
| Hole Diameter of 0.0625 to 0.0630 in. (1.58 to 1.6 mm) (gaged by attributes) | 100 percent accurate | | 72 percent accurate | |
| Gear Pitch Diameter | 0.2077 (5.275) | 0.00076 (19.3) | 0.2071 (5.260) | 0.00056 (14.3) |

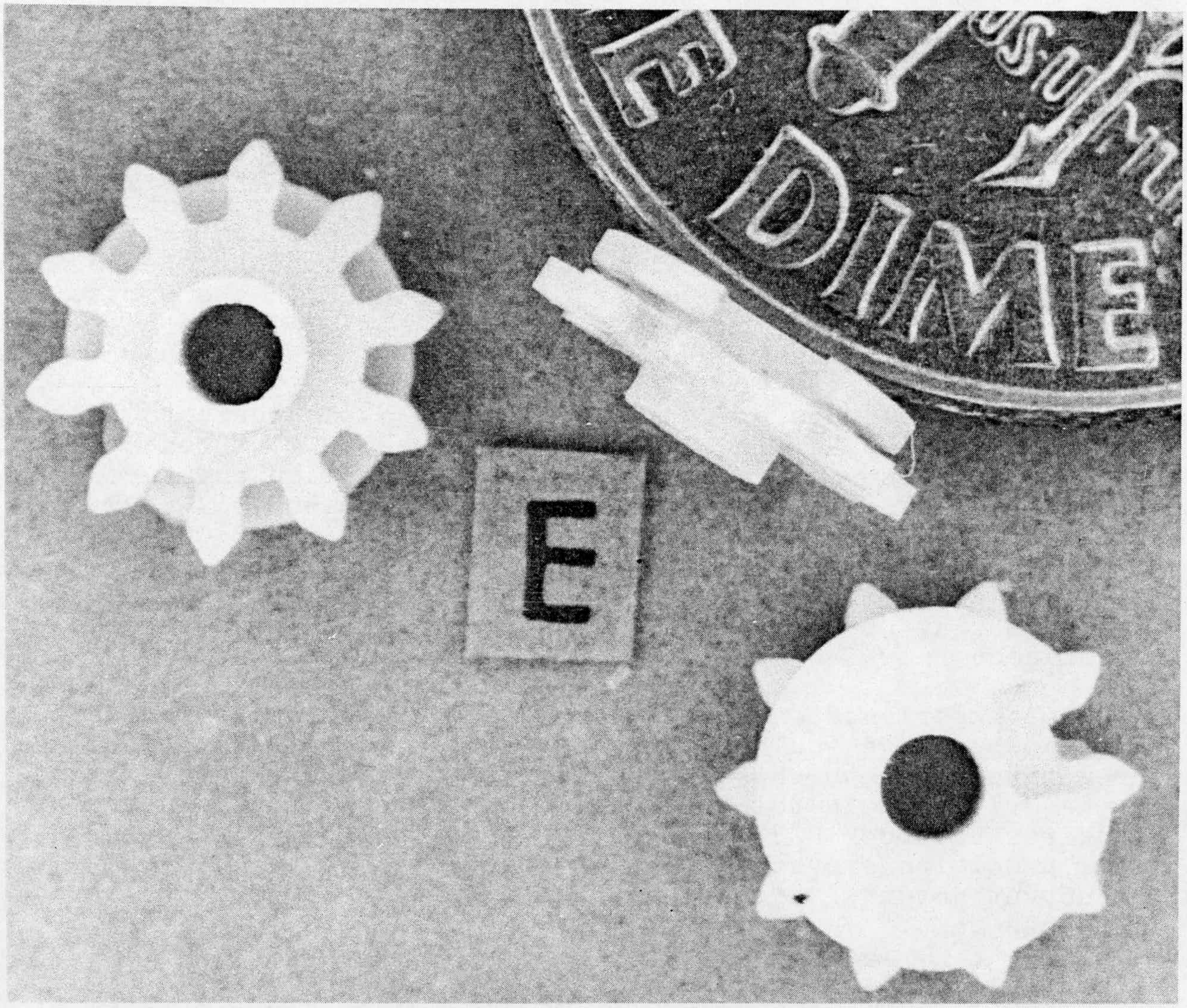


Figure 7. Dimensionally Repeatable Injection Molded Gear and Hub Assembly

This study explored the process requirements, tooling requirements, process repeatability, and flash removal characteristics of the material's studied. Only the first two of the four materials studied provided satisfactory parts. A statistical analysis of three lots of parts indicated that dimensional standard deviations ranged from 0.00013 to 0.00104 in. (3.2 to 26.4 $\mu$m). Typically, the standard deviation was 0.0005 in. (12.7 $\mu$m) or less. Thus, as in injection molding, it is possible to hold ±0.001 in. (25.4 $\mu$m) tolerances (95 percent probability level) if the actual part mean dimension is equal to the nominal drawing dimension. Those parameters with the greatest bearing on part dimensions are melt temperature, injection pressure, injection time, cooling time, and mold temperature. All of these are machine settings, except mold temperature. In injection molding, the mold temperature has a major impact on the dimensions of the final part, and elaborate systems have been developed to control it. However, the tooling used for this effort (coffin molds) did not lend itself to such controls. This is probably the reason that process repeatabilities were not better. For the parts studied, barrel tumbling in 60 to 280 mesh aluminum oxide or silicon carbide removed all flash, but larger particles of silicon carbide left obvious particles embedded in the parts.[5]

## Tapping Miniature Threads

The objective of this study was to develop a procedure to tap 0.6, 0.8, and 1.0 Unified National Miniature (UNM) threads in typical mechanism component materials. Both blind and through holes were made and studied in 7075-T6510 aluminum, 17-4 PH stainless steel, 303 Se stainless steel, and SAE K95100 high magnetic permeability steel. In addition to developing the ability to tap with these delicate tools, an effort was made to ensure that 0.003 in. (76.2 μm) positional tolerances were maintained.

In-house experience on conventional tapping equipment indicated that tap breakage would be a major problem, so a bench top lead screw tapper was purchased. Holes were drilled at both extremes of the drilled hole tolerance allowed by the National Bureau of Standards Handbook H28.[19] The taps used included high speed steel precision ground taps, high speed steel taps with the flute ground but not the threads, and custom made cold forming fluteless taps.

Thread quality was verified by the procedure outlined in Reference 18. Tapped holes were also sectioned to ensure that the taps did in fact follow the drilled hole.

The following observations were made during this study.

- Cold-drawn 303 Se stainless steel was the most difficult material to tap. Annealed material was somewhat better, but it was still borderline for the 0.6 UNM size.

- Photomicrographs indicated the taps maintained concentricity with the drilled hole. It should be noted that permitting the part to float ensures concentricity, but the flexibility of these small taps allows them to follow the drilled hole in the higher strength materials even when they are positioned with some eccentricity.

- The full tolerance range for the minor diameters can be used for tapping aluminum up to three diameters deep. (This was the deepest tested. It could probably be extended deeper.)

- The minor diameters of all the materials tested except aluminum are critical. The upper end of the tolerance band must be used. The allowable working tolerance band narrows as depth of thread increases. Recommended minor diameter limits for each size are shown in Table 4. This table is for use with cutting type taps only.

- Fluteless taps were not satisfactory. All attempts resulted in tap breakage.

- The taps with ground flutes but unground threads, though considerably less expensive, had a higher breakage incidence than the ground thread taps. The cutting taps with unground threads were satisfactory for aluminum.

- Countersinking the hole prior to tapping reduces deburring time and assists in positioning the holes under the spindle.

- A staging fixture is recommended to prevent the parts from rotating and still allow at least 0.005 in. (127.0 μm) for the part to center itself under the spindle. Large parts made from SAE K95100 were successfully tapped without a fixture, but the rapidity of locating parts under the spindle center and the simplicity of fixture design would normally justify its use. The base of the tapping machine has a tapped bolster plate for clamping fixtures.

## Producing an 8 μin. (0.2 μm) Surface Finish in Small Holes

Many miniature mechanisms require bearing and journal surfaces to have ultrasmooth surfaces to minimize friction. In several instances, these fine finishes must be produced inside 0.030 in. (0.75 mm) diameter or smaller holes. Although Bendix has produced many parts having holes in the 0.025 to 0.035 in. (0.64 to 0.89 mm) diameter size range, surface finish had not been monitored in these holes before this study began. On larger holes where finish has been monitored, 16 μin. (0.4 μm) finishes have been produced by reaming. Ball broaching has produced 4 μin. (0.1 μm) finishes on larger holes while sizing them within a 0.0002 in. (5.1 μm) tolerance. Gun drilling also has produced 4 μin. finishes in some materials, but the smallest gun drill producible is 0.078 in. (1.98 mm) in diameter.

The objective of this project was to determine if reaming and ball broaching could reliably produce 8 μin. (0.2 μm) surface finishes in 0.030 in. (0.75 mm) diameter holes and at the same time maintain a 0.0005 in. (12.7 μm) size tolerance in such materials as phosphor bronze, 7075 aluminum, and polyimide plastic.

Table 4. Recommended Limits of Drilled Hole Size as a Function of Drilled Hole Depth

| Thread Size (UNM) | Minimum (in.) | (mm) | Maximum (in.) | (mm) |
|---|---|---|---|---|
| 2/3 Diameter Drilled Hole Size | | | | |
| 0.60 | 0.0181 | (0.460) | 0.0190 | (0.483) |
| 0.80 | 0.0241 | (0.612) | 0.0252 | (0.640) |
| 1.00 | 0.0300 | (0.762) | 0.0314 | (0.798) |
| 2/3 to 1-2/3 Diameter Drilled Hole Size | | | | |
| 0.60 | 0.0187 | (0.475) | 0.0198 | (0.503) |
| 0.80 | 0.0248 | (0.630) | 0.0263 | (0.668) |
| 1.00 | 0.0309 | (0.785) | 0.0327 | (0.831) |
| 1-1/2 to 3 Diameter Drilled Hole Size | | | | |
| 0.60 | 0.0193 | (0.490) | 0.0198 | (0.503) |
| 0.80 | 0.0256 | (0.650) | 0.0263 | (0.668) |
| 1.00 | 0.0319 | (0.810) | 0.0327 | (0.831) |

The study concluded that surface finishes of 8 $\mu$in. (0.2 $\mu$m) can be produced in these small holes in both aluminum and phosphor bronze by reaming alone. In polyimide plastic, however, repeatable finishes below 16 $\mu$in. (0.4 $\mu$m) are not feasible. Finish in the two metals studied proved to be insensitive to variations in speed, amount of stock removed, and reamer geometry. Surface finish in the polyimide plastic is highly dependent upon reamer geometry, feedrate, and the setup used. Ball broaching the metals produced holes consistent in size within 0.0002 in. (5.1 $\mu$m), but the already fine finishes were not improved. Ball broaching did not improve hole finishes in polyimide plastic nor did it improve size consistency.

It was also noted that the stylus used to record surface finish left visible grooves in the polyimide plastic surfaces. This raises the question of how significant a quantitative reading is in this material. From a practical standpoint, if a 0.018 ounce (500 mg) load marks the part, then any feature rotating within the holes will also tend to mark or smooth the internal diameter.

Reaming Study

Eighty-four combinations of reamer geometry, feedrate, spindle speed, and workpiece material were evaluated in this study. The following listing illustrates the variables used. The test specimens were

| Variable | Values Used |
|---|---|
| Feedrate | 0.001 and 0.002 in./rev. (25.4 and 50.8 μm/rev.) |
| Speed | 1550 and 3000 rpm (162 and 3.14 rad/s) |
| Chip load | 0.002 and 0.004 in./side (50.8 and 101.6 μm/side) |
| Helix angle | |
| Left hand | 2 degrees and 10 degrees |
| Straight | 0 degree |
| Right hand | 2 degrees and 10 degrees |

hollow cylinders 0.062 in. (1.57 mm) in outer diameter and either 0.060 or 0.375 in. (1.5 or 9.5 mm) long. Initial pilot hole sizes were varied to accommodate reamer size and desired chip thickness (chip load). In all cases, the final holes were near 0.030 in. (0.75 mm). Three samples were produced for each condition tested.

An analysis of results of two different surface profilometers resulted in readings 2 to 4 μin. (0.05 to 0.10 μm) different on samples having a nominal roughness of 6 μin. (0.15 μm). Samples were cut in half to allow finish readings to be made axially in the holes. Deep holes in polyimide plastic tended to be rougher than shorter holes, apparently as a result of heat build-up and deflection of either the reamer or the test cylinder. Table 5 provides some comparative values of finish. While a difference in results was observed between reamer geometries, the differences were not large and there is some doubt as to whether they could be reproduced. Regression analyses were performed of all conditions used but are not reported here.

The tendency of polyimide plastic to move during cutting generates at least two problems. In turning, the specimen tends to climb the tool. In reaming, the high coefficient of expansion and the plastic deformation apparently were responsible for a 0.0002 in. (5.08 μm) diameter difference when the specimen was measured on a machine and allowed to sit for a day.

The poor surface finish (Table 5) in deep, reamed polyimide plastic holes may have been due to inadequate coolant. Occasionally swabbing coolant on the reamer is not an effective means of minimizing heat. A better method would be to force coolant through the spindle in such

Table 5. Surface Finish Results From Reaming and Ball Broaching

| Workpiece Material | Average Surface Finish (μin.) | (μm) | Standard Deviation of Finish (μin.) | (μm) |
|---|---|---|---|---|
| **Reamed Holes in Short Specimen** | | | | |
| Phosphor Bronze | 4.56 | 0.12 | 0.85 | 0.22 |
| 7075 Aluminum | 4.40 | 0.11 | 0.90 | 0.23 |
| Polyimide Plastic | 8.40 | 0.21 | 4.12 | 0.10 |
| **Reamed Holes in Deep Hole Specimen** | | | | |
| Phosphor Bronze | Not Studied | | | |
| 7075 Aluminum | Not Studied | | | |
| Vespel | 41.89 | 1.06 | 12.79 | 0.32 |
| **Ball Broached Holes** | | | | |
| Phosphor Bronze | 6.80 | 0.17 | 2.88 | 0.07 |
| 7075 Aluminum | 6.55 | 0.17 | 2.43 | 0.06 |
| Polyimide Plastic | 15.63 | 0.40 | 8.52 | 0.22 |

Readings are averages of four different geometries.

a way as to cool both the bore and the reamer and force the chips out the reamer flutes. The poor finish may also have resulted from a setup condition which produced runout in the drilled hole. The reamer, which guides on the drilled hole, may have been in a bind due to the runout; such binding may have affected the finish.

The manufacturer's literature indicates that surface finish may be improved by buffing or polishing with rotating cotton or muslin swabs. Cotton or muslin swabs which will fit in a 0.030 in. (0.75 mm) hole have not been located. However, polishing the holes with wooden lapping sticks did not noticeably affect the surface finish.

Although polyimide plastic exhibits a brittle fracture when suddenly bent or twisted, no chipping occurred in any of the specimens machined.

Boring and reaming 0.030 in. (0.75 mm) diameter holes on chucker lathes requires a careful setup and operation. Adjusting a 0.030 in. (0.75 mm) reamer with 1/2 in. flute length so that it is within 0.0001 or 0.0002 in. (2.5 to 5.1 μm) of spindle centerline is tedious. Attempting to float the reamer with standard floating holders does not work. The heavy holder bows the reamer much like the tip of a weighted fishing rod. Trying to maintain 0.001 in. (25.4. μm) concentricity between i.d. and o.d. on a 0.375 in. (9.52 mm) long piece of polyimide plastic is also a major undertaking.

Measured hole location runout varied from 0.005 in. (12.7 μm) to less than 0.001 in. (25.4 μm) for holes drilled through. This was minimized by drilling one-third of the way through from each end and then finishing with a longer fluted drill.

Ball Broaching Study

As shown in Table 5, forcing an oversize ball through aluminum and phosphor bronze produced surface finishes of 6 to 7 μin. (0.15 to 0.18 μm). This finish is reasonably independent of initial hole size. Final hole size varied 0.0002 in. (5.1 μm) and was independent of initial hole size. The standard deviation of finish was close to 2.5 μin. (0.06 μm). The finish of polyimide plastic did not improve when ball broaching was used.

General Conclusions

From the results of this test, it can be concluded that reaming aluminum and phosphor bronze can produce an 8 μin. (0.2 μm) finish in 0.030 in. (0.75 mm) diameter holes. Feedrates of 0.001 ipr (25.4 μm/rev.) or lower and spindle speeds of 3000 rpm (314 rad/s) or higher are required for optimum finishes. If the tolerance on hole diameter is less than 0.0005 in. (12.7 μm), ball broaching should be used to obtain size and finish in aluminum and phospher bronze. For aluminum, a ball 0.00025 in. (6.35 μm) larger than the desired hole size is used. For phosphor bronze, a ball 0.00035 in. (8.89 μm) larger than the desired hole size is used. Initial hole size can range from 0.0001 to 0.0004 in. (2.5 to 10.1 μm) below final hole size without affecting final size. A lower limit on initial size has not been established.

Surface finishes of 8 μin. (0.2 μm) can be produced by reaming polyimide plastic. However, the inherent variation in finish makes it impractical to meet such a requirement on a production basis by reaming or ball broaching. A 16 μin. (0.4 μm) finish can be reliably produced, but verification of this finish is very dependent upon the method used to measure the roughness. Measurements of surface finish on soft plastic materials may be meaningless when using equipment designed for metals.

For optimum finish in metals requiring short holes, a reamer with two right-hand 10 degree spiral flutes should be used with feedrates of 0.001 ipr (25.4 μm/rev.) or less. Finishes of 16 μin. polyimide plastic can be produced with a reamer having four straight flutes.

Ball broaching small holes in polyimide plastic does little to improve surface finish. Its effect on size is not predictable.

Milling Small Slots

In the past, producing very narrow slots to both close positional and width tolerances was a noticeable problem. The objective of this study was to develop a process for milling slots 0.005 to 0.006 in. (127.0 to 152.4 μm) wide by 0.55 in. (1.397 mm) deep in 7075-T6510 aluminum. Location and depth repeatability were to be held to ±0.001 in. (±25.4 μm) and ±0.002 in. (±50.8 μm), respectively.

Various speeds, feeds, and coolants were evaluated using the test sample shown in Figure 8. A small horizontal mill and a rise-and-fall milling machine were used for these tests. The test samples were held in a precision indexing head during slotting. The slitting saws used were 1.0 in. (25.4 mm) in diameter by 0.0055 in. (139.7 μm) wide with 20 teeth. The saws were made from solid carbide.

The horizontal milling machine provided the best control on slot dimensions, but this could easily have been because of differences in machine wear. Both machines had been used in production for many years.

Milling the small slots into the test samples did not require any special apparatus, such as special design holding devices or arbors for the mill. Standard spacers were used to clamp the saw and keep it rigid.

Using 7/8 in. (22.2 mm) diameter spacers to back up the 1 in. (25.4 μm) diameter cutter provided for a more rigid setup to start the cutter on a curved surface than the normally used smaller diameter spacers. The slot location was not affected by starting the cutter on the curved surface.

Slot location and depth repeatability were well within the tolerance range required.

The optimum feeds and speeds to prevent cutter breakage and outward lip deflection were 3.7 in./minute (1.56 mm/s) and 1850 rpm (194 rad/s). Under these conditions, the lip deflected outward 0.0002 to 0.0005 in. (5.1 to 12.7 μm). When speeds and feeds varied by 50 percent from these values, the lip deflection approached 0.002 in. (50.8 μm) and in one case was 0.0037 in. (94.0 μm). As a consequence, the slot width at the top of the slot was too wide by a similar amount. It should be noted that the lip is only 0.016 in. (0.41 mm) thick.

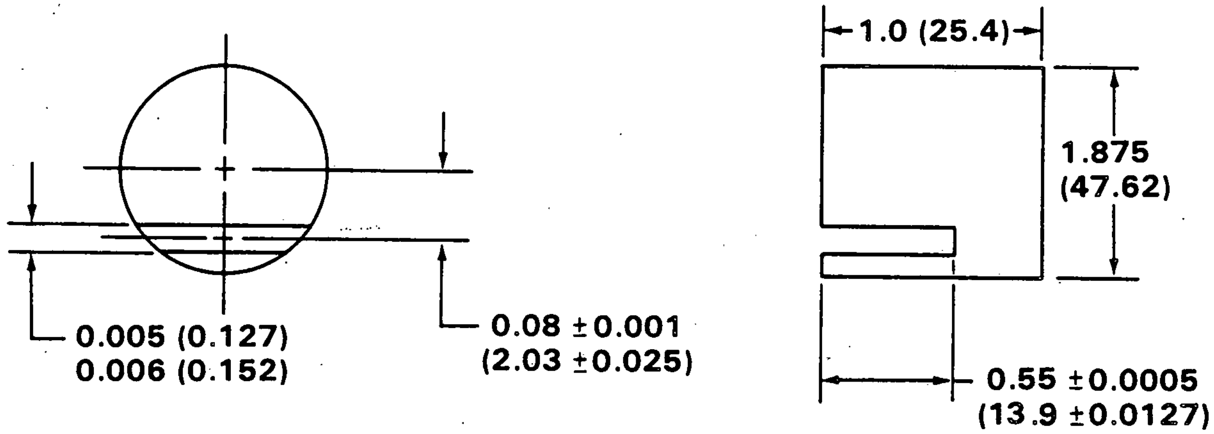


Figure 8. Milling Test Sample

Actual slot width was larger by 0.0005 to 0.0007 in. (12.7 to 17.8 μm) than the cutter width. This was due primarily to a small amount of cutter warpage and a small amount of runout in the arbor. At the bottom of the cut, the slot was only 0.0001 to 0.0002 in. (2.5 to 5.1 μm) wider than the cutter. In production situations, it would be imperative to have a cutter 0.0002 to 0.0005 in. (5.1 to 12.7 μm) thinner than the desired slot width in order to accommodate these setup inaccuracies.

Feedrates in excess of 5 in./minute (2.12 mm/s) resulted in frequent cutter breakage. The use of coolant had little effect on results in this material. Since the slitting saws have essentially square corners, fillet radii in the bottom of the slot were very small in the order of 0.001 in. (25.4 μm).

## Straddle Milling Thin Sections

As previously indicated, producing narrow slots and long thin flanges to tolerances of ±0.0005 in. (±12.7 μm) is a problem with many components. When straddle milling parts, the flange or web of remaining material will be torn off if it is too thin. When a side milling cutter cuts near the edge of a part, the outside flange tends to curl as illustrated in Figure 9. These tendencies to tear or bend are even more predominant when the workpiece is a low strength material such as aluminum.

This study was initiated to provide information on the distortion occurring in straddle milling. Specifically, this brief study sought answers to a number of questions:

- What size and locational accuracies can be maintained on miniature parts by straddle milling?

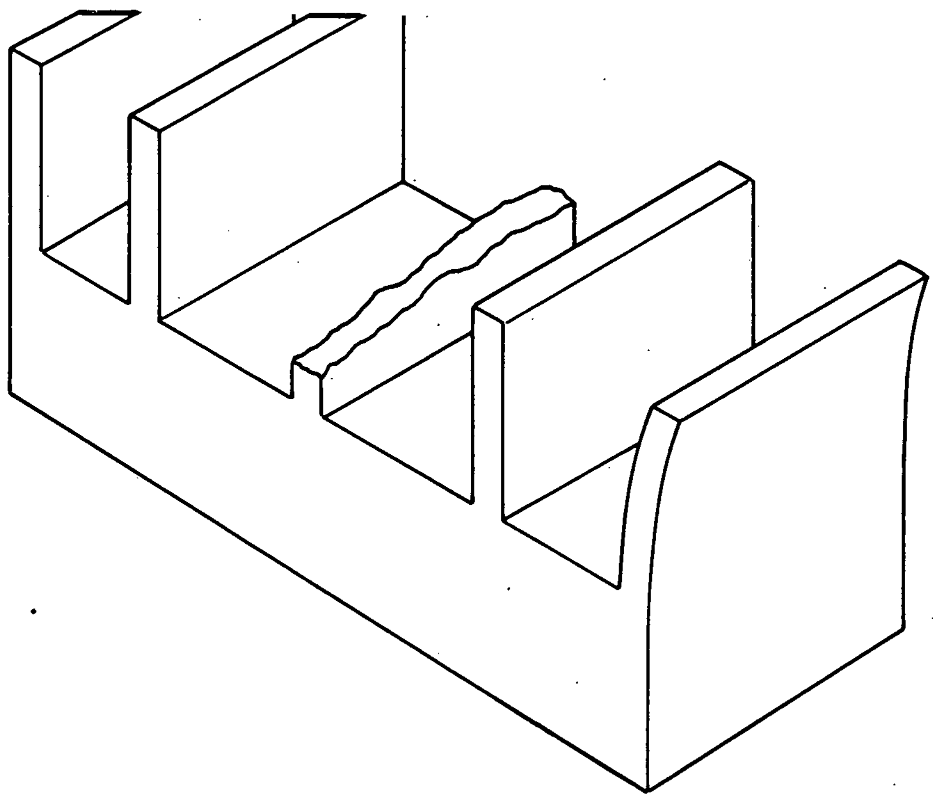

Figure 9. Torn and Bent Webs

- What distortion occurs and how can it be minimized?
- What cutter geometries, feeds, and speeds optimize production rate, but minimize distortion and overcut?
- What special techniques are required to hold 0.0003 in (7.6 μm) limit tolerance?
- What fixturing and backup is required?

While the previous study had explored the problems and repeatability of producing single 0.005 to 0.006 in. (127.0 to 152.4 μm) wide slots in components, no previous effort had been recorded on simultaneous milling of several slots (gang milling).

Test Results

A small horizontal mill was used to perform all tests. The 6061-T6 aluminum workpieces (Figure 10) were held in a small vise. Six hss slitting saws, each 0.048 in. (1.22 mm) wide by 3 in. (76.2 mm) in diameter were used. Slots were inspected on a 50X magnification comparator after the mills were run at a variety of speeds and feeds.

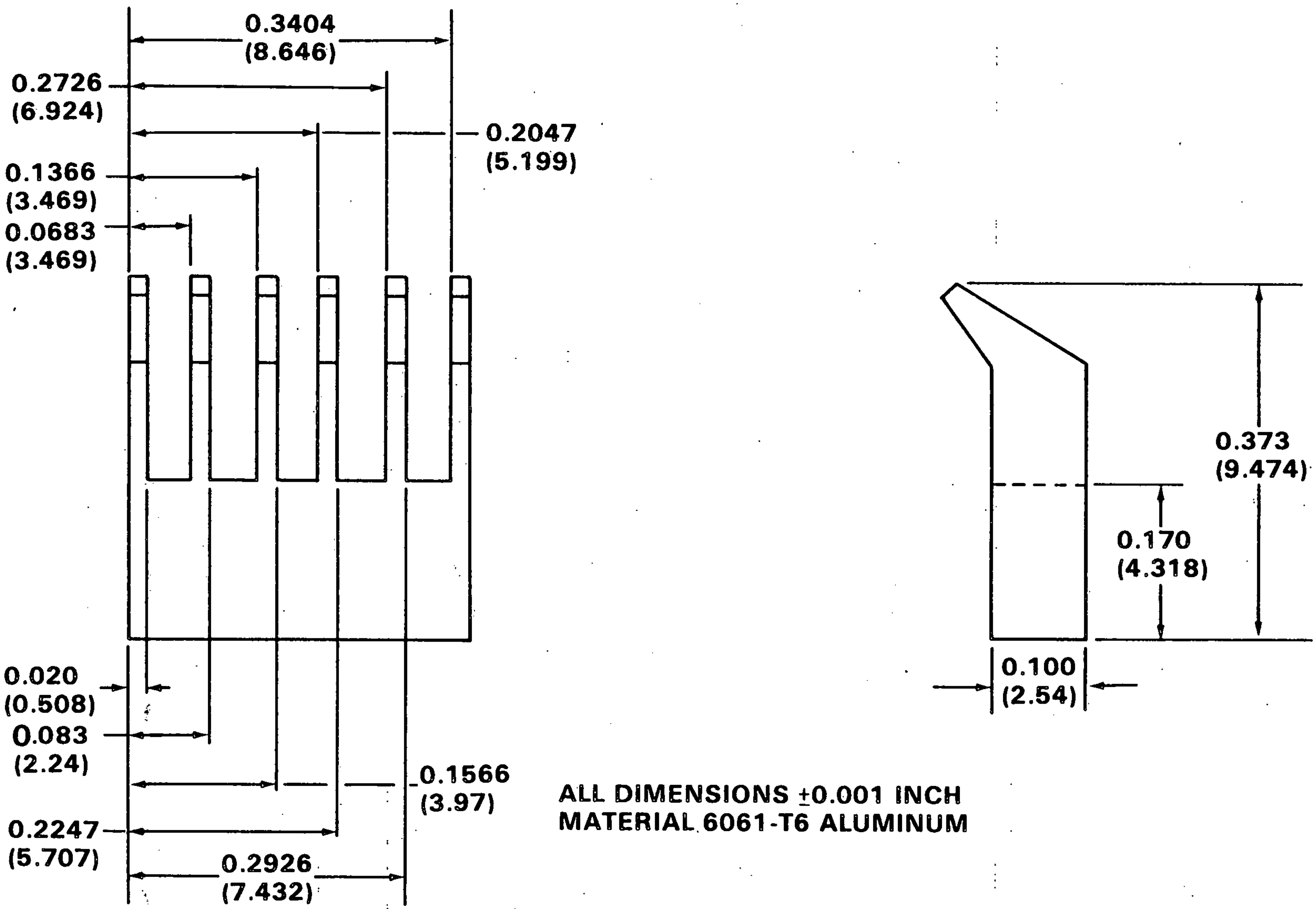


Figure 10. Workpiece Configuration

The width repeatability of the initial parts was a not very good 0.001 to 0.003 in. (25 to 76 μm). Saw alignment and rigidity created most of this problem. The standard shop spacers, used to provide the necessary spacing, proved to be the major culprit. The usual technique of building up spacers by placing two or three together to provide the necessary width allows some spacer flexing to occur. The dish-shaped sides of the cutters accentuate movement of the spacers. The spacers, as a result of continuous shop use, frequently do not have parallel faces, and the faces may not be perpendicular to the arbor hole. For precision, repeatable slots such as illustrated in Figure 10, spacers must be parallel within 0.0002 in. (5.1 μm) Total Indicator Reading (TIR).

Cutters were eventually shimmed to produce slots located within ±0.001 in. (±25.4 μm). Slot sizes could be held within ±0.0005 in. (±12.7 μm) in aluminum. Within the range 0.001 to 0.005 ipr (25.4 to 127.0 μm/rev.) and 220 to 880 rpm, speeds and feeds did not materially affect results.

No tearing of the 0.020 in. (0.5 mm) wide flanges occurred, and no special piece part fixturing or workpiece backup was required. Conventional milling was used, although climb milling was considered.

Subsequent work on 303 Se, 17-4 PH stainless steel, 6061-T6 and 7075-T6 aluminum, and half-hard beryllium copper using the specimen shown in Figure 11 indicated that a 0.010 in. (0.25 mm) thick flange is the typical lower limit possible using conventional side cutting mills. Some tearing occurs, probably as a result of tool dulling; flange straightness varies as much as 0.005 in. (127 μm). Recent work on 17-4 PH stainless steel indicates that the "master cut" tooth form on solid carbide cutters minimizes flange deflections. In this test, 0.062 in. wide by 3.5 in. diameter (1.57 by 88.9 mm) high speed steel cutters having 30 teeth were used. Feedrate and speed were 0.22 in./minute (0.09 mm/s) and 220 rpm (23 rad/s), respectively.

## Conclusions

This study indicated that the single most important factor in slot location and flange consistency is cutter alignment. Precision spacers should be used rather than typical shop spacers. For the conditions studied, ±0.001 in. (±25.4 μm) locations and ±0.0005 in. (±12.7 μm) widths can be held in aluminum. (Flange length-to-width ratios were 10:1.) Tearing of flanges does not occur unless flange widths are in the order of 0.010 in. (0.25 mm) wide. Standard cutters can be used. Parallel rather than relieved faces should be used to minimize setup time. "Master cut" cutters appear to produce less flange distortion than standard cutters. No special fixturing or backing is required.

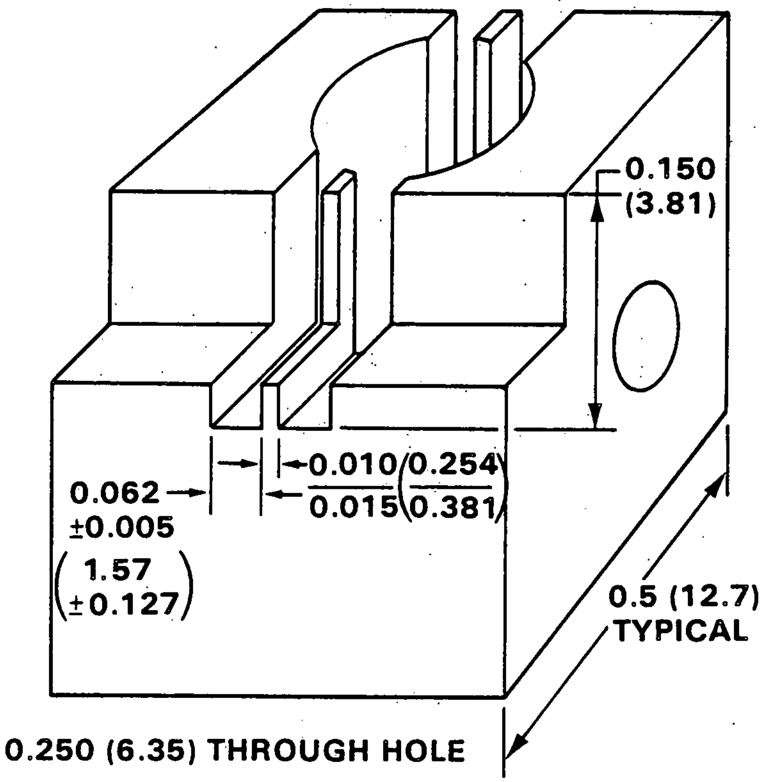


Figure 11. Slotting Specimen 2

The technique required to produce slots with 0.0003 in. (7.6 μm) limit tolerances was not determined. It appears highly doubtful that such tolerances can be maintained by milling, on the types of cuts studied.

## Broaching Miniature D-Shaped Holes

When D-shaped holes are required for shaft alignment or driving purposes, they are usually produced by broaching. Since the broach cross section is not symmetrical, the cutting forces push the tool toward the flat edge. This represents a problem on small parts which have precision location tolerances such as 0.0005 in. (12.7 μm) concentricity.

This study was initiated to find how three different broach designs affected size repeatability, cycle time, and concentricity. Data on the breakdown of the sharp broach corners was also desired since 0.003 in. (76.2 μm) maximum fillet radii is a print requirement on many of the recent generations of miniature mechanisms.

Previous experience on 0.125 in. (3.175 mm) diameter holes in 303 Se stainless steel indicated that at least 0.002 in. (50.8 μm) total tolerance was required on part size and concentricity, and that four different broaches would be required to produce each hole.

## Test Results

The results of this study indicate that 0.0005 in. (12.7 μm) concentricity is not feasible when broaching D-shaped holes of the indicated size.

Fillet radii of 0.003 in. (76.2 μm) maximum are possible in aluminum workpieces. Hole dimensions can be held to +0.0005 -0.0000 in. (+12.7 -0.0 μm) tolerances; the effect of tool wear, however, was not explored. The controlling factor in producing more concentric holes appears to be chip clearance. The required chip clearances weaken the tool below usable limits.

## Test Approach

All of the tests were directed at 0.0935 +0.0005 -0.0000 in. (2.3876/2.3749 μm) diameter holes (0.0762 +0.0005 -0.0000 in. (1.9482/1.9355 μm) D dimension) as shown in Figure 12. The workpieces were made from 7075-T6510 aluminum.

The initial approach was to obtain three different sets of broaches and evaluate the effect of their design on size repeatability, cycle time, and concentricity. The first set of broaches would be a typical design utilizing four broaches and a starting hole concentric to the desired finished hole. As indicated in Figure 13, this design removes a uniform amount of stock from the starting hole except in the area of the flat. The tendency for the finished hole to move in the direction of the flat is apparent from the geometry involved. The second set of broaches would utilize the same basic design but would utilize different chip clearances, tooth pitches, and material removed for each broach (three broaches instead of four).

The third set of tools would be designed around the geometry shown in Figure 14, which should provide more uniformly-distributed cutting forces with a net improvement in concentricity of the D-hole to the outside contour. If this approach were successful, it would eliminate one or more subsequent turning operations to make the o.d. concentric to the D-hole.

Unfortunately, none of the six broach manufacturers contacted were willing to make such small precision broaches. By shortening the length of the test specimen to 0.125 in. (3.175 mm), Bendix tool engineers were able to design and build sets of three and four broaches for the "starting hole concentric to finished hole condition." The pilot hole size was 0.056 in. (1.42 mm).

Table 6 summarizes the inspection results of 18 parts broached with the set of four tools. Concentricity was measured by recording the total indicator reading of the outside diameter measured with respect to a D-shaped pin in the hole. This reading was divided by two to give a concentricity reading. The initial pilot holes were concentri to the outside diameter within 0.00005 in. (1.3 μm) in most cases.

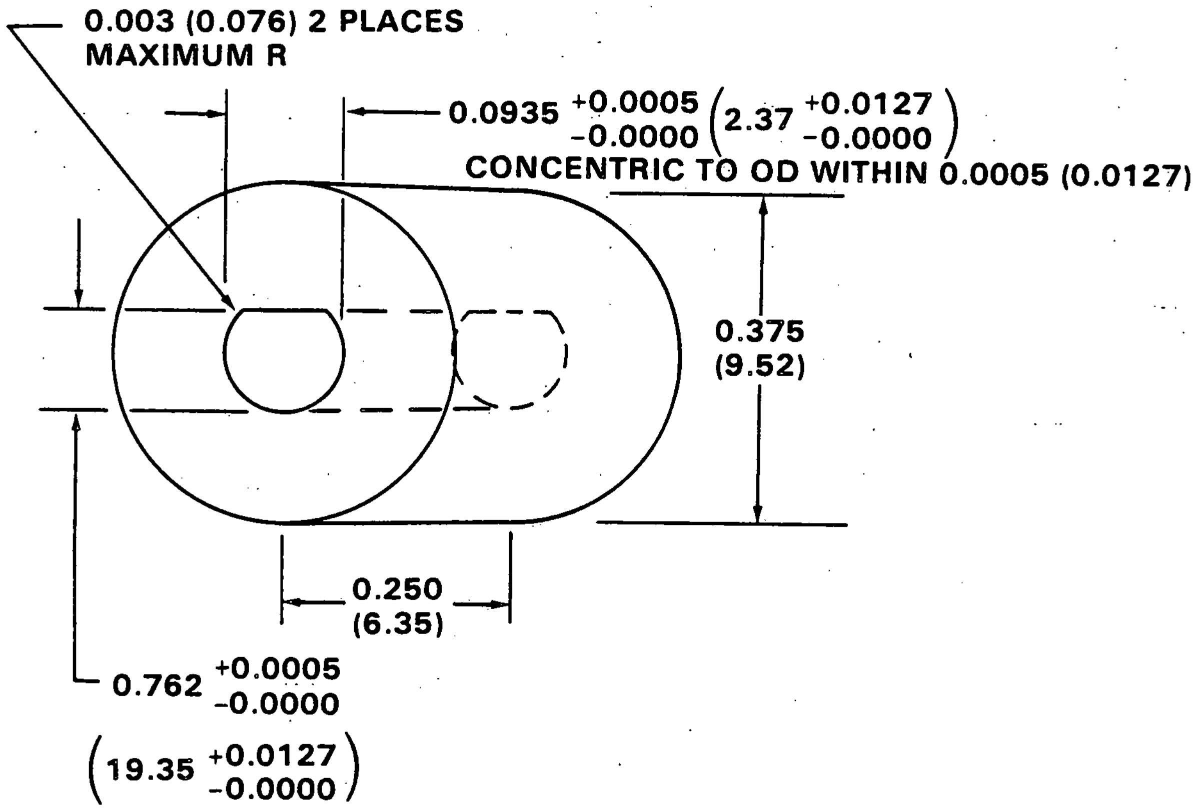


Figure 12. Desired Final Shape of Test Specimen

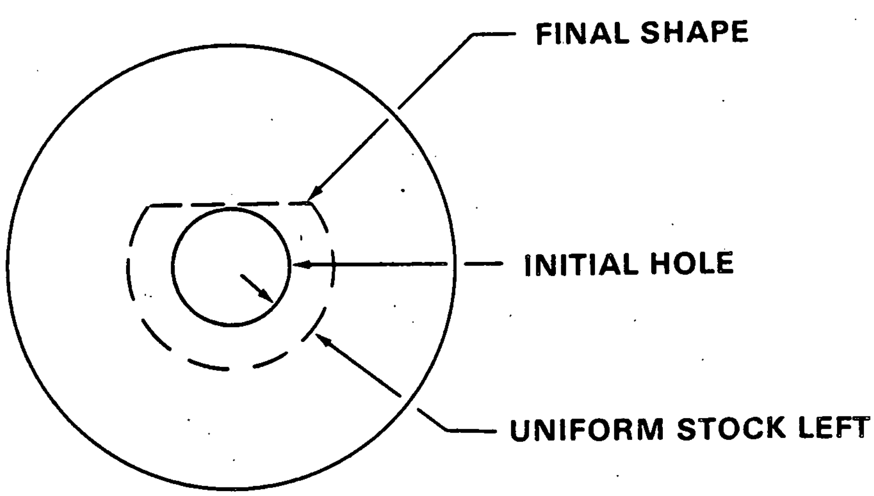


Figure 13. Relationship of Initial Hole and Final Hole Typical Broach

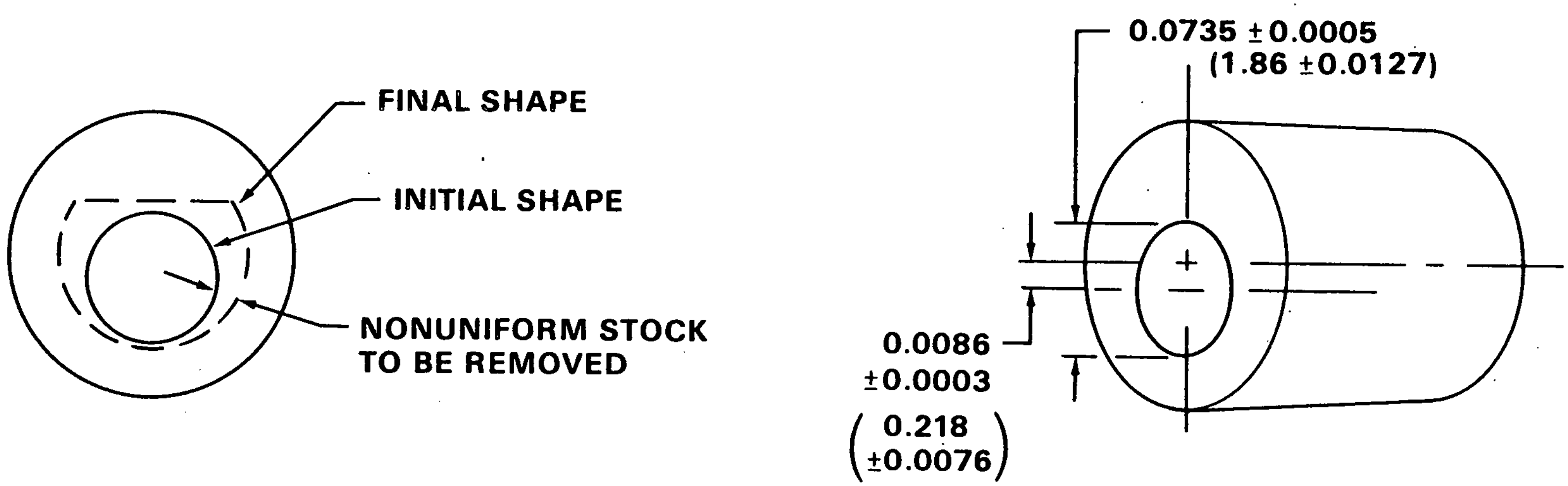


Figure 14. Approach for Uniformly-Distributed Cutting Forces

In all cases, the D-hole mislocation was in the direction of the flat. Corner breakdown was small. After 40 parts were broached with the four broach set, the corner radii were 0.003 in. (76.2 μm).

The concentricity of these parts fell short of the desired 0.0005 in. (12.7 μm) maximum concentricity. Also, since the three broach set was designed for an on-centerline pilot hole, there appeared to be little advantage in using it to improve concentricity. Broaches for the off-center pilot hole were not made because not enough chip clearance could be provided at the corners of the broach. As shown in Figure 14, much more material must be removed by the corners than by any other portion.

Although the concentricity was worse than the desired 0.0005 in. (12.7 μm), these tools performed well. Because of the amount of material that must be removed, however, these tools would probably not work well on 0.250 in. (6.35 mm) long parts. The short-run practice of broaching part way, backing out and clearing the chips, then continuing is not desirable in a precision production situation, because the interrupted cut must influence location and finish and it doubles the cycle time. Drawings of the required tools indicate that the initial tools would have length to diameter ratios of 40:1, an obviously weak tool when precision locations are involved.

It should be noted that for proper tool guidance the minimum thickness for broaching should be greater than three times the tooth pitch (0.150 in. or 3.81 mm for these conditions). Some parts, however, can be stacked so that minimum thickness limits are not a problem.

Additional Observations

In addition to the previous observations, it was noted that the finish produced varies from 16 to 32 μin. (0.41 to 0.82 μm), and a corner radii of 0.003 in. (76.2 μm) maximum radius can be maintained for at least 40 parts. The concentricity cannot be held to less than 0.002 in. (50.8 μm) for the conditions studied. Major broach suppliers are not willing to produce such small broaches for precision applications. The limiting factor in the use of these small broaches is the chip clearance. Chip load per tooth must be in the order of 0.001 to 0.002 in. (25.4 to 50.8 μm), and chip volume is directly proportional to part length, thus long parts must have more chip storage space. Since the sum of two times the radial clearance plus the core diameter of the tool is a constant, large clearances necessitate near zero core diameters.

The concept of an off center pilot hole with corresponding broaches appears to have two major disadvantages.

- Adequate chip clearance at the corners cannot be provided.

Table 6. Range of Measured Results on D-Shaped Holes

| Measurements | Range | Average |
|---|---|---|
| D Dimension | | |
| (in.) | 0.0763 to 0.0766 | 0.0765 |
| (mm) | (1.938 to 1.946) | (1.943) |
| Diameter | | |
| (in.) | 0.935 to 0.938 | 0.0936 |
| (mm) | (2.375 to 2.383) | (2.377) |
| Corner Radius | | |
| (in.) | 0.002 | 0.002 |
| (mm) | (50.8) | (50.8) |
| Concentricity | | |
| (in.) | 0.0010 to 0.0025 | 0.0017 |
| (mm) | (25.4 to 63.5) | (43.2) |

- Most of the tool wear will occur at the corners. This is less desirable than adding a second operation to machine the outside diameter concentric to the D-hole.

Hobbing Ratchet Wheels

Precision ratchet wheels on miniature mechanisms are typically produced by milling individual teeth or by blanking and shaving. While hobbing can be used, published literature was devoid of comments on geometrical limitations. To meet the increased requirements for precision ratchet wheels, this study was initiated to determine the advantages and limitations of hobbing.

Basic Limitations

Three important requirements must be met before a part can be produced by hobbing. The first and most important requirement is the spacing and number of teeth. Teeth must be evenly spaced, a whole number of teeth must exist and all must be present on the ratchet wheel. The second requirement is the shape of the teeth. Although curved tooth surfaces are a possibility, all ratchet wheels studied have straight tooth surfaces, except for fillet radii or tooth crest flats or radii (Figure 15). The third consideration for hobbing is the number and size of teeth and is dependent upon the capacity of the hobbing machine to be used.

Figure 16 shows the three basic types of ratchet teeth investigated. All three can be used for detenting and indexing functions. Type 1 is the most common form in general use and was the one chosen for

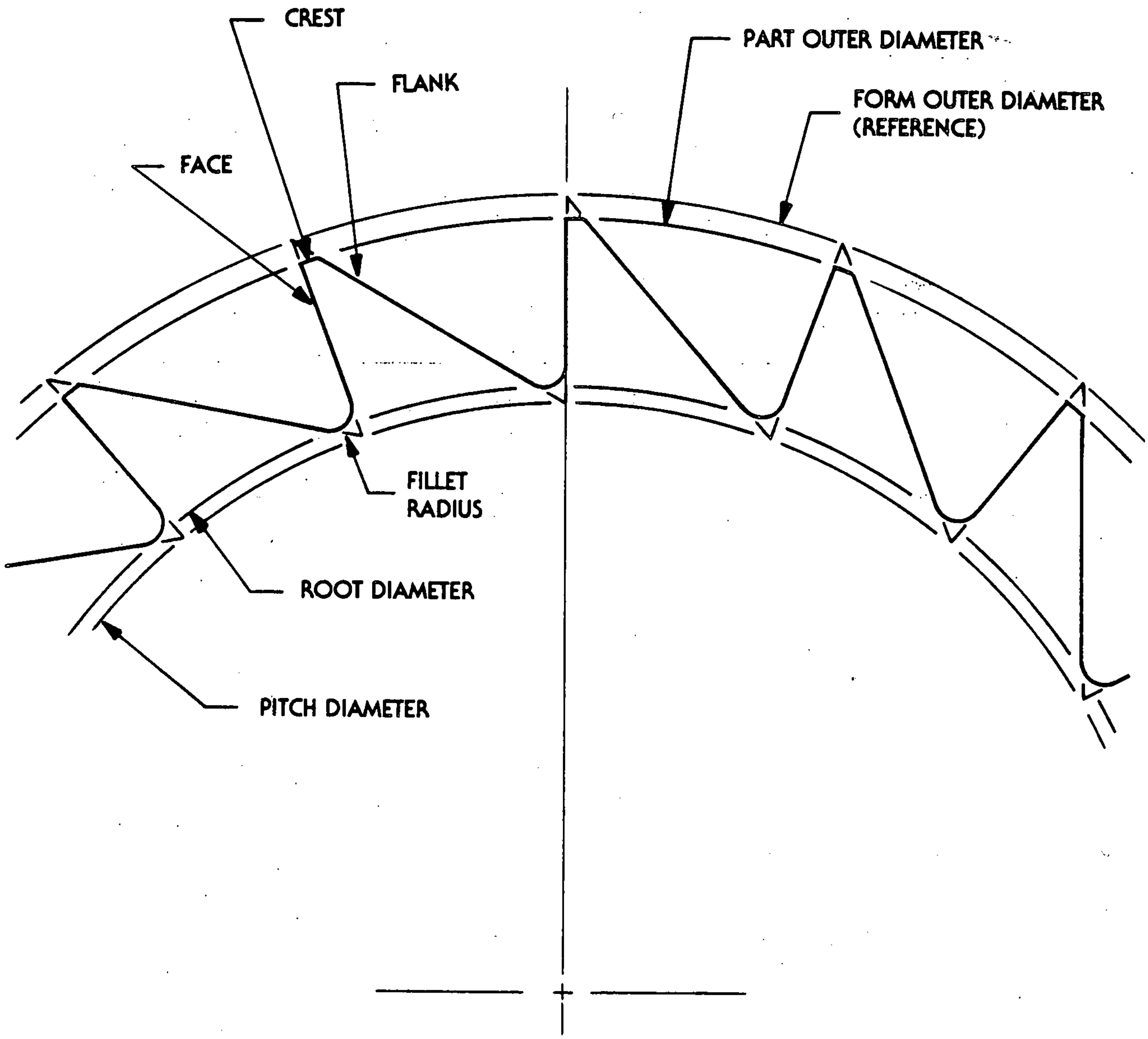


Figure 15. Ratchet Wheel Nomenclature

study in this report. In its extreme form of $\theta = \phi/2$, Type 2 is used as an escape wheel in timing mechanisms. Type 3 must be considered carefully if hobbing is to be used, because when recessing is too severe, hobbing is not possible.

Three different materials were machined: polyimide plastic, 6061-T6 aluminum, and beryllium copper. A variety of feeds and speeds were used. The only significant deviation from the desired nominal tooth form was with polyimide plastic. The difference

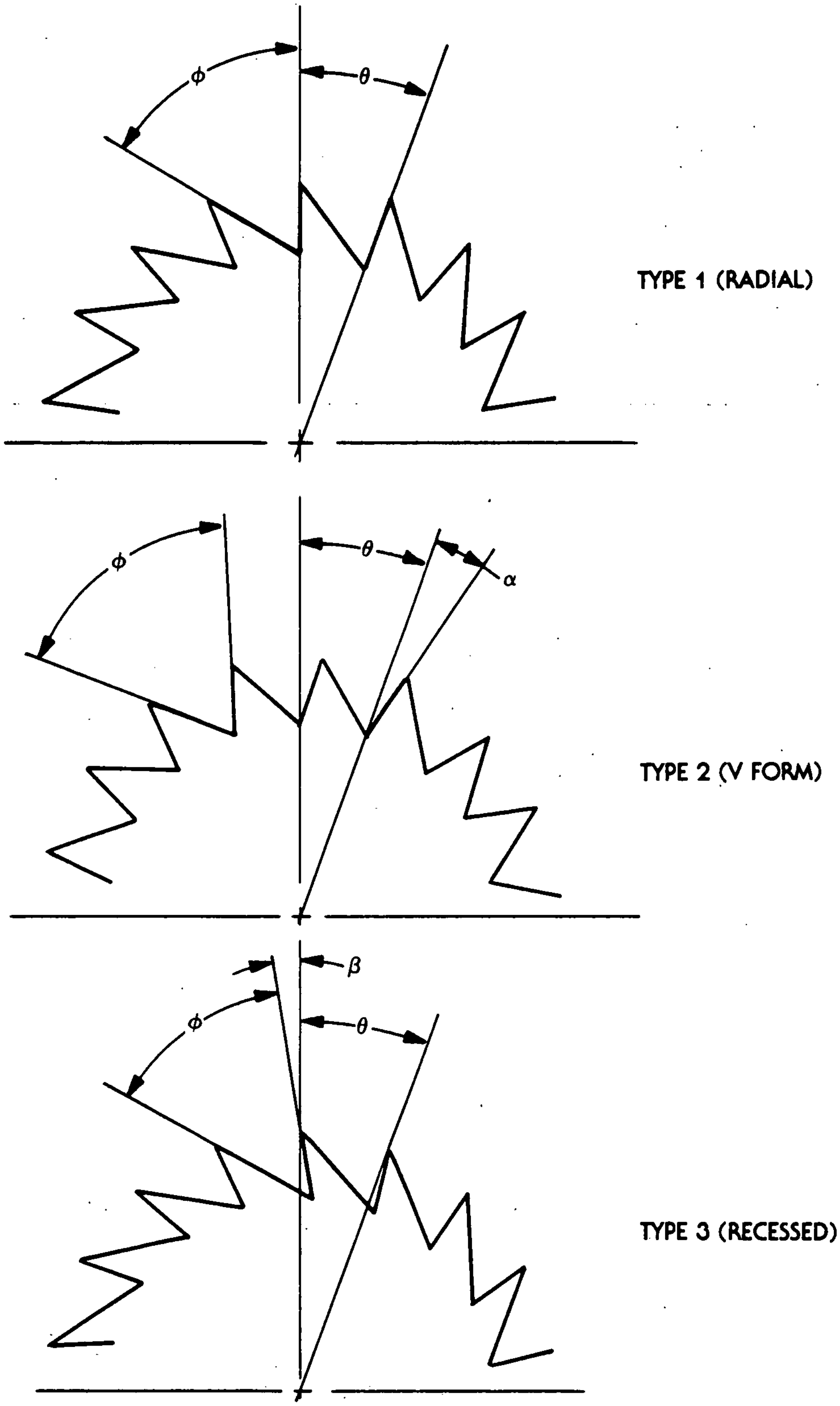


Figure 16. Ratchet Wheel Types

was apparently caused by part deflection, but was still within the 0.002 in. (50.8 μm) wide contour band selected as the test tolerance.

When at all possible, teeth to be used for indexing or detenting should be evenly-spaced and continuous. If it is necessary to have ratchet segments, they should be designed with the nontoothed portion lower than the root diameter of the ratchet form. In this way, unwanted teeth can be cut away in secondary machining operations. When this is not possible, a second part could be screwed, riveted, or welded to the side of the ratchet wheel to block out unwanted teeth. When none of these possibilities exist, it will be necessary to use some manufacturing method other than hobbing.

Fillet radii should be specified when defining ratchet tooth configuration. The radius should not be a part of the contour band unless absolutely necessary. A radius of about 0.004 in. (101.6 μm) was the most common radius on the size parts investigated and should result in reasonable tool life from hobs. Different sizes of fillet radii can be investigated as necessary.

The crest configuration of the tooth should be formed by the o.d. of the part. Crest radii or flats other than the o.d. of the part must be generated by a topping hob or in secondary machining operations. When topping hobs are used, adjustments in the hobbing process are very limited, resulting in the necessity of closer hob size control and shorter tool life. Secondary machining operations are expensive and should be avoided.

Cost comparisons of blanking and shaving, fine-edge blanking, index milling, and hobbing have shown that not only is it practical to hob ratchet wheels, it is desirable from an economic standpoint.[20] The relatively low tooling cost compared to dies, and the high production rate compared to milling, make hobbing a process that must be considered when designing ratchet wheels or defining manufacturing processes for producing them.

A layout method of determining if a shape is adaptable to hobbing has been developed.[20] Examples are given which demonstrate graphically the limitations of the various shapes of ratchet wheels that can be hobbed and the shape of the cutter required to produce them. Also, similar results for using gear-shaper cutters for ratchet wheel production have been reported.[21,24]

## Concentric Opposed Hubs, Centers, and Bores

The trend toward miniaturization of mechanical mechanisms has created increasing demands for extremely close tolerances and concentricities on machined parts. Typical miniature mechanisms require a concentricity of one-half the sum of the size tolerance on the two closest toleranced diameters. Many of these parts have 0.0002 in. (5.1 μm) size tolerance and 0.0002 in. (5.1 μm) total indicator reading (TIR) concentricity.

This study was initiated to determine the tolerance capabilities and relative costs of producing concentric hubs, bores, and centers located in opposite ends of miniature parts.

Approach

Five processes were investigated to produce miniature parts with 0.0001 to 0.0003 in. (2.5 to 7.6 μm) TIR concentricity requirements and to determine the costs related to each process (Table 7). Two of the processes studied were performed on precision tool room chucker lathes, but differed in the types of holding devices used. The third process used a manual jig bore machine while the two remaining processes were performed on an automatic screw machine (ASM) and a four-spindle boring machine, respectively.

The test sample (Figure 17) was designed to simulate miniature parts such as those used in miniature assemblies, but it was made large enough that it could be fixtured and handled reasonably well. The parts shown in Figures 18 and 19 were used to evaluate the fourth process (ASM).

The first part was designed to minimize distortion thereby increasing the reliability of the process and inspection repeatability studies. The part was produced from 303 Se stainless steel bars and has opposed hubs, centers, and bores which necessitate a minimum of two separate operations to complete.[28]

General Observations

Process 1 (precision chucker) is capable of holding 0.0003 in. (7.6 μm) TIR concentricity when machining opposed hubs, bores, and centers in two separate operations.

Process 1 is capable of holding 0.0002 in. (5.1 μm) TIR concentricity between a single turned outside diameter and a respective center or bore while holding the bar stock with a collet.

Process 1 is capable of holding 0.0001 in. (2.5 μm) TIR concentricity between a single turned outside diameter and a respective center or bore while holding the part with an air chuck.

Process 1 and Process 4 (screw machine) are the most economical processes.

Processes 1, 2, and 4 (lathe processes) required much less deburr time as compared to Process 2 (jig bore) and Process 5 (four spindle boring machine).

Process 2 (precision chucker) is capable of holding 0.00015 in. (3.8 μm) TIR concentricity between a single turned outside diameter and a respective center or bore only.

Table 7. Table of Processes Studied

---

Process 1 (precision chucker)
Primary operation (Bar stock/collet)
1. Face
2. Turn 0.100 in. diameter (2.54 mm)
3. Turn short 0.060 in. diameter (1.52 mm)
4. Center drill
5. Drill
6. Bore
7. Cutoff

Secondary operation (air chuck)
1. Face
2. Turn long 0.060 in. diameter
3. Center drill
4. Drill
5. Bore

Process 2 (precision chucker)
Centerless grind bars to 0.100 in. diameter (2.54 mm)
Cut bars into piece part blanks

Primary operation (ground blanks/air chuck)
1. Face
2. Turn short 0.060 in. diameter
3. Center drill
4. Drill
5. Bore

Secondary operation (air chuck)
1. Turn long 0.060 in. diameter
2. Center drill
3. Drill
4. Bore

Process 3 (jig bore)
Centerless grind bars to 0.100 in. diameter
Cut bars into piece part blanks
Face blanks to length

Primary operation (ground blanks/air chuck)
1. Turn short 0.060 in. diameter
2. Center drill
3. Drill
4. Bore

Secondary operation (air chuck)
1. Turn long 0.060 in. diameter
2. Center drill
3. Drill
4. Bore

Table 7 Continued. Table of Processes Studied

---

Process 4 (Automatic screw machine)

Centerless grind 36-inch (0.9 m) long bars to 0.093 in. (2.36 mm) diameter.

Screw machine operation

1. Rough turn front diameters
2. Finish turn front 0.0263 diameter (0.66 mm)
3. Finish turn front 0.0407 diameter (1.03 mm)
4. Rough turn back diameters
5. Finish turn back 0.0407 diameter
6. Finish turn back 0.0263 diameter (0.668 mm)
7. Cutoff

Centerless grind 36-inch long bars to 0.2311 in. (5.87 mm) diameter.

Screw machine operation

1. Center drill
2. Drill
3. Ream
4. Turn 0.0932 diameter (2.36 mm)
5. Turn middle diameter
6. Cutoff

Process 5 (4-spindle, boring machine)

Piece parts were machined square on all sides and rough drilled prior to boring operation.

Boring operation

1. Finish bore large diameter on right side
2. Finish bore small diameter on right side
3. Finish bore large diameter on left side
4. Finish bore small diameter on left side

---

Process 3 (jig bore), as applied in this endeavor, is not capable of holding 0.0003 in. (7.6 μm) TIR concentricity. This process resulted in both excessive machine and deburr times with no apparent gain in tolerance capability. Machining time for the jig boring operations was approximately three times greater than the lathe time for Process 1.

Process 4 (screw machine) is capable of holding 0.0001 in. (2.5 μm) TIR concentricity between opposed turned diameters and a respective centerless gound diameter.

Process 5 (four spindle boring machine) is not capable of repeating positional location closer than 0.0011 in. (27.9 μm).

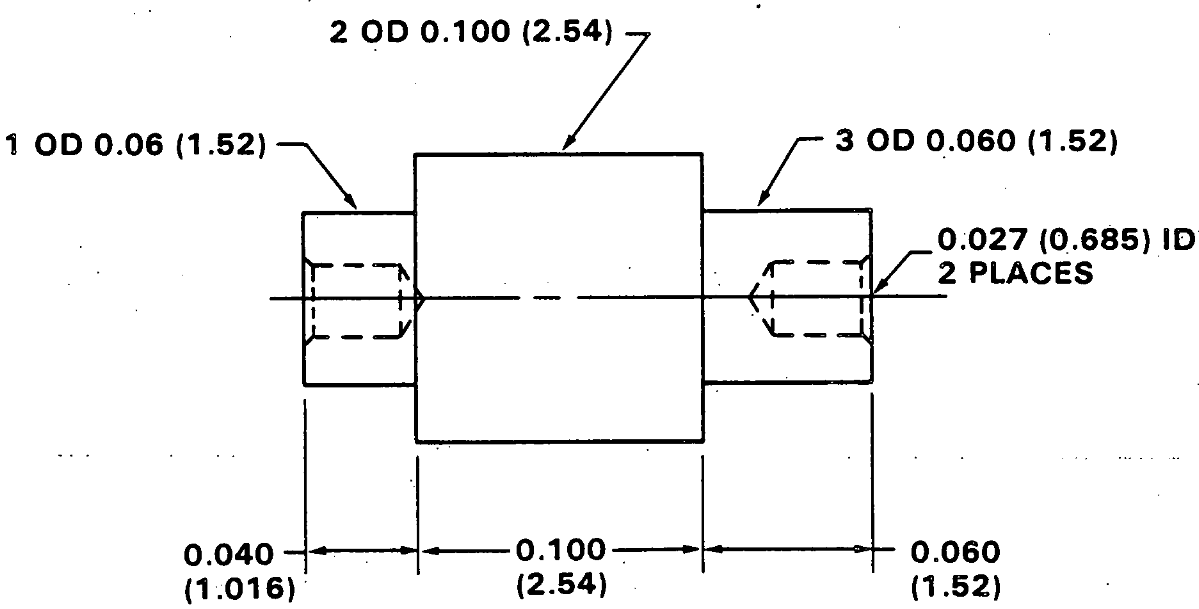


Figure 17. Test Sample Designed to Simulate Miniature Parts

The removal of burrs is extremely important in holding 0.0003 in. (7.6 μm) TIR concentricity tolerances.

Ballizing Small Holes

Ballizing (ball broaching) is a fast, low cost method of sizing round holes to less than 0.0005 in. (12.7 μm) tolerance and at the same time imparting a fine surface finish. It consists of pressing a slightly oversize precision ball through the unfinished hole. Hole tolerances of 0.0002 in. (5.1 μm) have been maintained in some metals by this process.

The objective of this study was to determine the capabilities and limitations of ballizing holes 0.010 to 0.050 in. (0.55 to 1.25 mm) in diameter to a size tolerance of ±0.0001 inch (±2.5 μm). Although Bendix has produced many holes in the 0.010- 0.050-inch (0.25 to 1.25 mm) diameter range, total tolerances of 0.0002 in. (5.1 μm) were not normally held.

Test Approach

Three different hole sizes were ballized in this investigation (Table 8). The test specimens were drilled and reamed cylinders having an initial hole size variation of 0.0005 in. (12.7 μm). A 0.03125 in. chrome alloy steel ball was pushed into the holes in the first series of tests by hand feeding on a drill press. Hole sizes were checked with wires sized to the nearest 0.0001 in. (2.5 μm). The 0.2412 in. (6.13 mm) hole was ballized using the

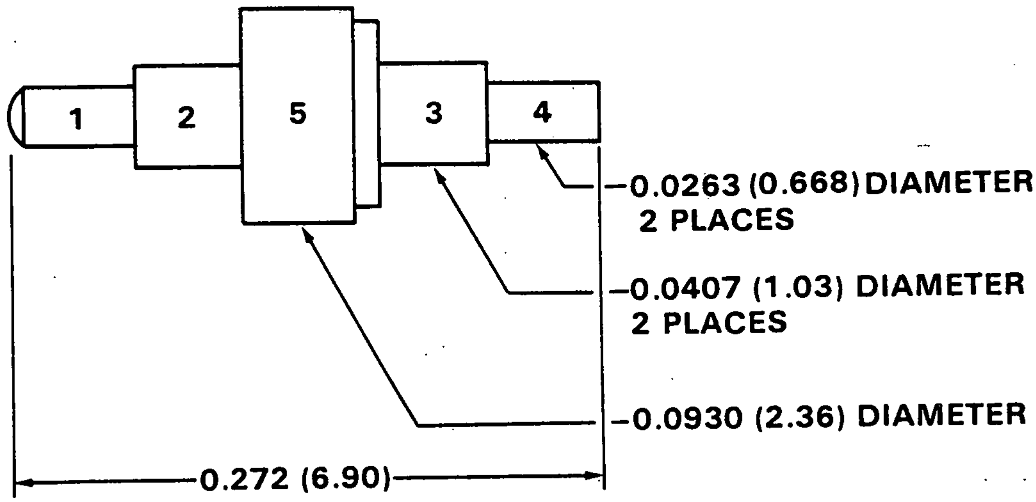


Figure 18. Part Used to Evaluate Fourth Process

tool shown in Figure 20. A new type of reamer, evaluated on 0.0469 in. (1.191 mm) diameter holes, proved to be far more accurate than the ballized holes. The standard deviation for the reamed hole was half the standard deviation experienced with the ballizing operations. The reamer does cut material and probably also burnishes.

A major problem experienced in working with small holes is inspecting for size. This problem must be solved before miniature holes can be manufactured to 0.0001 in. (2.5 μm) tolerances. Tests run on the reamed holes showed a 0.0001 in. (2.5 μm) nominal variation from one inspector to another and a 0.00005 in. (1.27 μm) variation between different types of inspection equipment with the same inspector.

This study also revealed that size changes of 0.0001 in. (2.5 μm) occur when the part is removed from the collet used to hold it for ballizing.

While ballizing did maintain the hole size variation desired, some experimentation is required to obtain the ball size required to produce a specific nominal size hole. Ballizing is very fast and is tolerant of variations in initial hole size. Hand feeding is not a desirable production technique, however, because it can cause ripples in the hole. A recent publication indicates that high velocity is required for consistent hole quality.[25] While the reamers produced better holes, they can require considerably more production time, greater care in initial size selection, and higher tool costs.

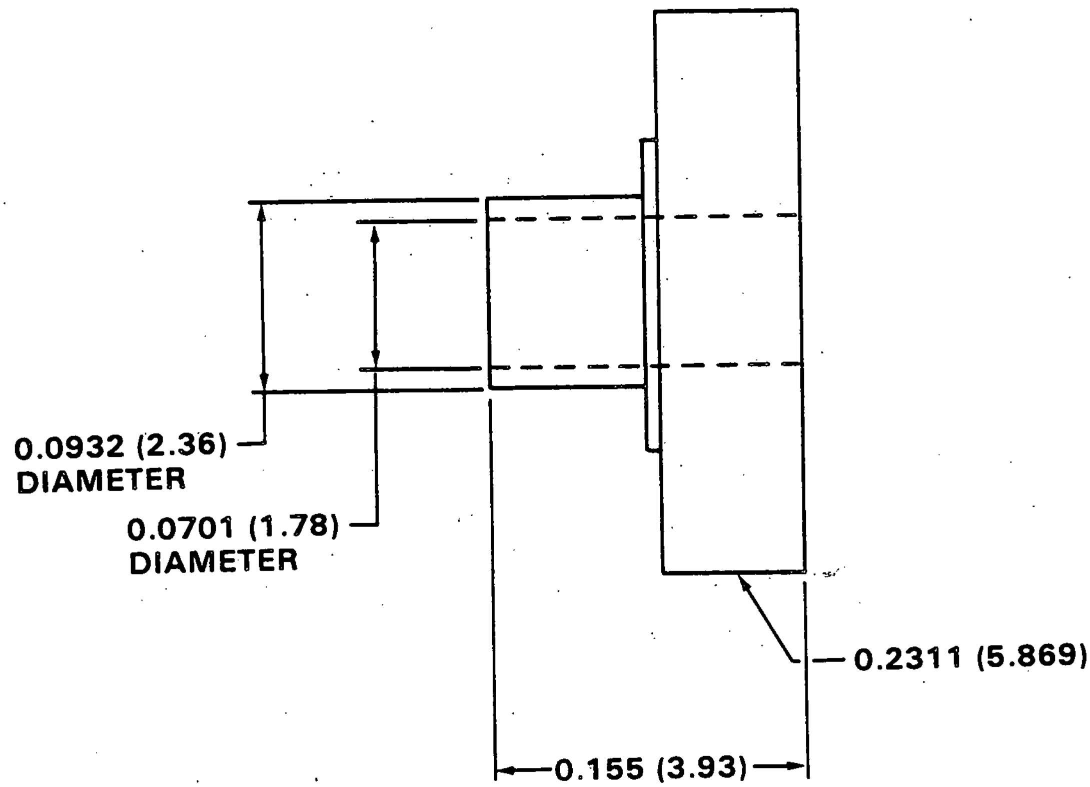


Figure 19. Part Used to Evaluate Fourth Process

## Drilling Miniature Holes

Precision miniature electromechanical mechanisms typically require a number of precision miniature holes for rotating shafts and press-fit pins. Because of the tolerances required, the hole depth, and the materials involved, conventional drilling approaches must be utilized. These approaches are tedious and require great care to prevent drill breakage and assure high quality holes.

The objective of this study was to determine which drilling variables and tool geometries result in minimum hole mislocation and maximum hole-size consistency. Specifically, the study evaluated the effects of several types of drilling machines and tooling and the effects of drill geometry, feeds, and speeds.

### Study Phases

This study was performed in three phases. The first phase utilized a single machine to evaluate the basic capabilities of eight different drill geometries. In this phase, only one hole was produced in each specimen.

Table 8. Conditions Studied in Ballizing

| Hole Diameter (in.) | Hole Diameter (mm) | Workpiece Material | Specimen Size: Outside Diameter (in.) | Specimen Size: Outside Diameter (mm) | Specimen Size: Thickness (in.) | Specimen Size: Thickness (mm) | Results: Size Maintained (in.) | Results: Size Maintained (μm) | Results: Surface Finish Range (μin.) |
|---|---|---|---|---|---|---|---|---|---|
| 0.0312 | (0.792) | 17-4 PH (H-900 Cond.) | 0.200 | (5.08) | 0.130 | (3.30) | ±0.0001 | (±2.5) | 2/27 |
| 0.0312 | (0.792) | 304L Stainless Steel | 0.200 | (5.08) | 0.130 | (3.30) | ±0.0002 | (±2.5) | 2/27 |
| 0.0312 | (0.792) | SAE K95100* | 0.200 | (5.08) | 0.130 | (3.30) | ±0.0001 | (±2.5) | 3/12 |
| 0.0469 | (1.191) | 304L Stainless Steel | 0.205 | (5.21) | 0.026 | (0.66) | ±0.0001 | (±2.5) | -- |
| 0.2412 | (6.126) | SAE K95100 | 0.489 | (12.42) | 0.185 | (4.699) | ±0.0001 | (±2.5) | 10/26 |

*SAE K95100 is a high magnetic permeability steel containing 49 percent iron, 49 percent cobalt, and 2 percent vanadium.

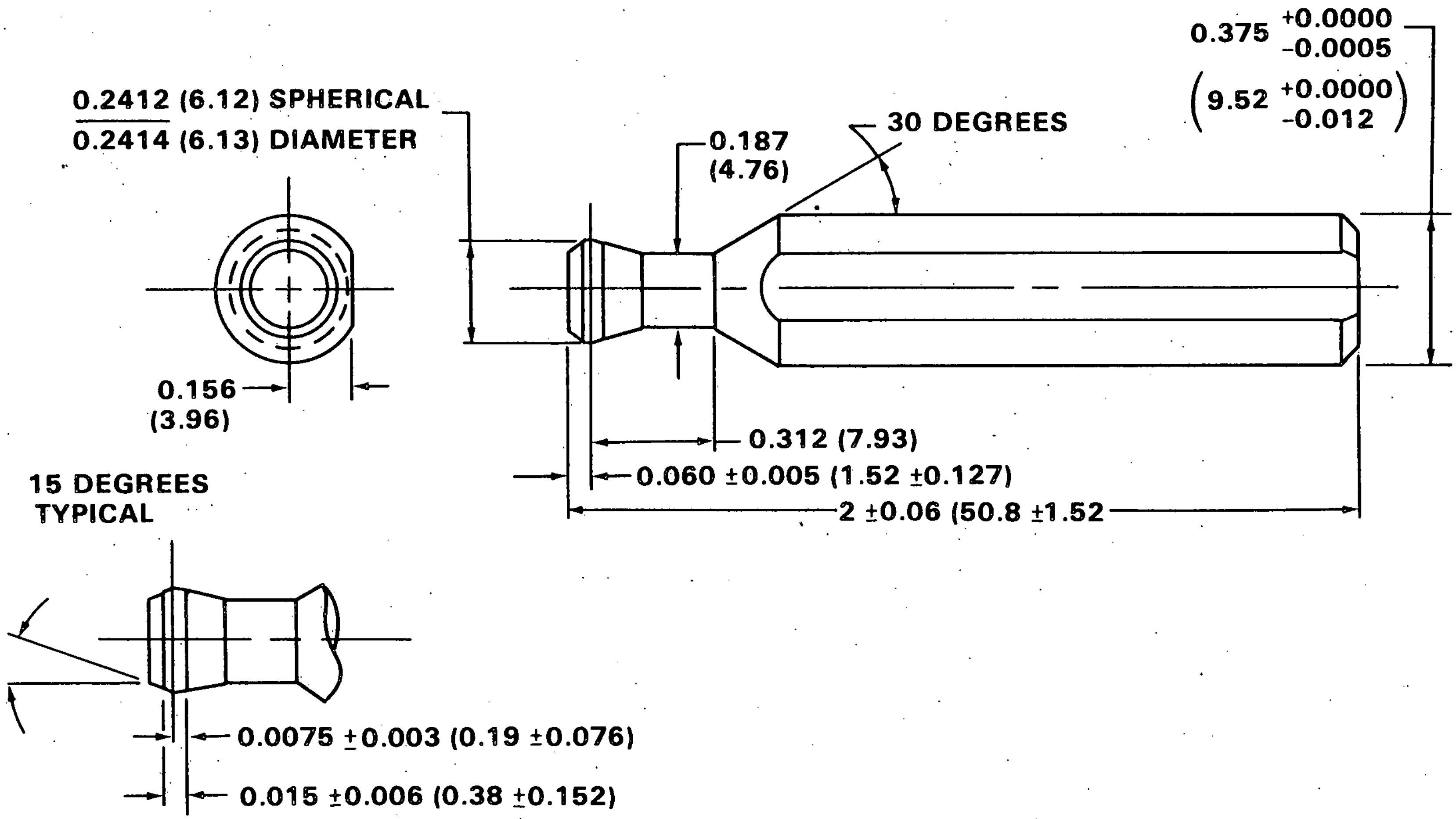


Figure 20. Ballizing Tool

In the second phase, analytical and empirical analyses were made of drill rigidity and its effect on hole location and size consistency. Typical drilling torques and thrusts were also evaluated and compared to hole location and size trends.

In the third phase, patterns of holes were drilled with the more successful drills from the first phase. These patterns were then evaluated by computer techniques to determine the optimum positional locations that could be expected with the equipment used.

The results of this study in 303 Se stainless steel and half-hard brass are summarized in the following observations for 0.026 inch-diameter (0.66 mm) drills.

- When centerdrilling was not used, printed circuit board drills, spriral-flute pivot drills, and bore-size drills produced distinctly more consistent hole size and location than the other drills studied.

- Feedrate did not influence hole location except for some drills in brass workpieces.

- Centerdrilling, as a general rule, dramatically improved hole locations when chisel-point drills were used but had no effect when printed circuit board drills were used.

- There was little difference in the locational accuracy of the new Burgmaster drilling machine and the N/C jig borer.

- Boring holes did not improve hole location.

- When drilling was performed without prior or subsequent operations, the holes tended to be 6 μm larger than the drill in stainless steel. Reaming reduced this oversizing effect to near zero in some tests.

- Of all the conditions studied, half resulted in hole patterns positioned within 31 μm. Under the best conditions, a diametral positional tolerance of 11.20 μm was maintained.

- Of all the conditions studied, half resulted in a repeatability ($\sigma$) of hole size of 31 μm. Under the best conditions, a size repeatability ($\sigma$) of 9.60 μm was maintained.

- The most repeatable drill, when both size and location had to be maintained, was the printed circuit board drill.

- The tool itself is the least expensive of all the factors which contribute to drilling cost. Setup time is typically the most expensive factor when producing precision holes in small lot sizes.

- A chip clearing (pecking) operation may influence hole location unless centerdrilling is used.

- Spindle speed did not affect hole size or location.

- Some combinations of feedrate, technique, and drill geometry were distinctly better or worse than others. (The best combination of feedrate and drilling technique may be different for each drill.)

The feedrates used ranged from 0.097 to 0.487 μin./rev. (0.0025 to 0.0125 μm/rev.), and the spindle speeds ranged from 2200 to 6800 rpm (230 to 712 rad/s).

Table 9 and Figure 21 indicate the apparent most economical drilling techniques and relative costs as a function of hole tolerances. More detailed information on these results is reported elsewhere.[6-8]

## Profile Milling

When producing small slots, pockets, and contoured shapes on small parts, several small depth-of-cut passes are usually made. In the past, more than one pass has been needed because the small end mills either deflected beyond the allowable tolerance or they broke in single-pass cuts. This study indicated that lateral deflection (the component most affecting tolerance) can be prevented if suitable cutting conditions are chosen.

This project determined those conditions which allow single-pass profiling with miniature end mills. In addition to strictly edge profiling, the more critical condition of milling non-linear slots or channels was also pursued.

More specifically, this development established those combinations of feedrate, and axial and radial depths-of-cut, that have no lateral deflection. Profile cuts and blind slots 0.020 to 0.060 in. (0.51 to 1.525 mm) wide with 0.0005 in. (12.7 μm) width tolerances were produced using miniature end mills. Preliminary data for this study was obtained from two earlier Bendix studies. A complete report on this study has also been published.[9]

### Cutting Forces

The thrust of this project was to identify the machining conditions which put no lateral force on an end mill. These conditions could, in one pass, produce a workpiece almost as precise as the machine tool that made it. As evident later, the deflection of a small end mill can be many times greater than the positioning repeatability of the machine tool.

Table 9. Drilling Technique Apparently Most Economical

| Positional Tolerance (μm)** | Drilling Technique* | | | |
|---|---|---|---|---|
| | Centerdrill, Drill, Ream | Drill, Ream | Centerdrill, Drill | Drill Only |
| ±2.5 Hole Size Tolerance | | | | |
| 25 Location Tol. | X | | | |
| 50 Location Tol. | X | | | |
| 75 Location Tol. | | X | | |
| 125 Location Tol. | | X | | |
| ±7.6 Hole Size Tolerance | | | | |
| 25 Location Tol. | X | | | |
| 50 Location Tol. | X | | | |
| 75 Location Tol. | | X | | |
| 125 Location Tol. | | X | | |
| ±12.7 Hole Size Tolerance | | | | |
| 25 Location Tol. | X | | | |
| 50 Location Tol. | X | | | |
| 75 Location Tol. | | | | X |
| 125 Location Tol. | | | | X |
| ±25.4 Hole Size Tolerance | | | | |
| 25 Location Tol. | X | | | |
| 50 Location Tol. | | | | X |
| 75 Location Tol. | | | | X |
| 125 Location Tol. | | | | X |

*Assumes 0.65 mm through hole in 1.825-mm thick stock having a flat starting surface. These recommendations do not take into account any differences which might occur in deburring times because smaller burrs result from one approach. The use of chisel-point drills requires centerdrilling.

**1 in. equals 25.4 mm.

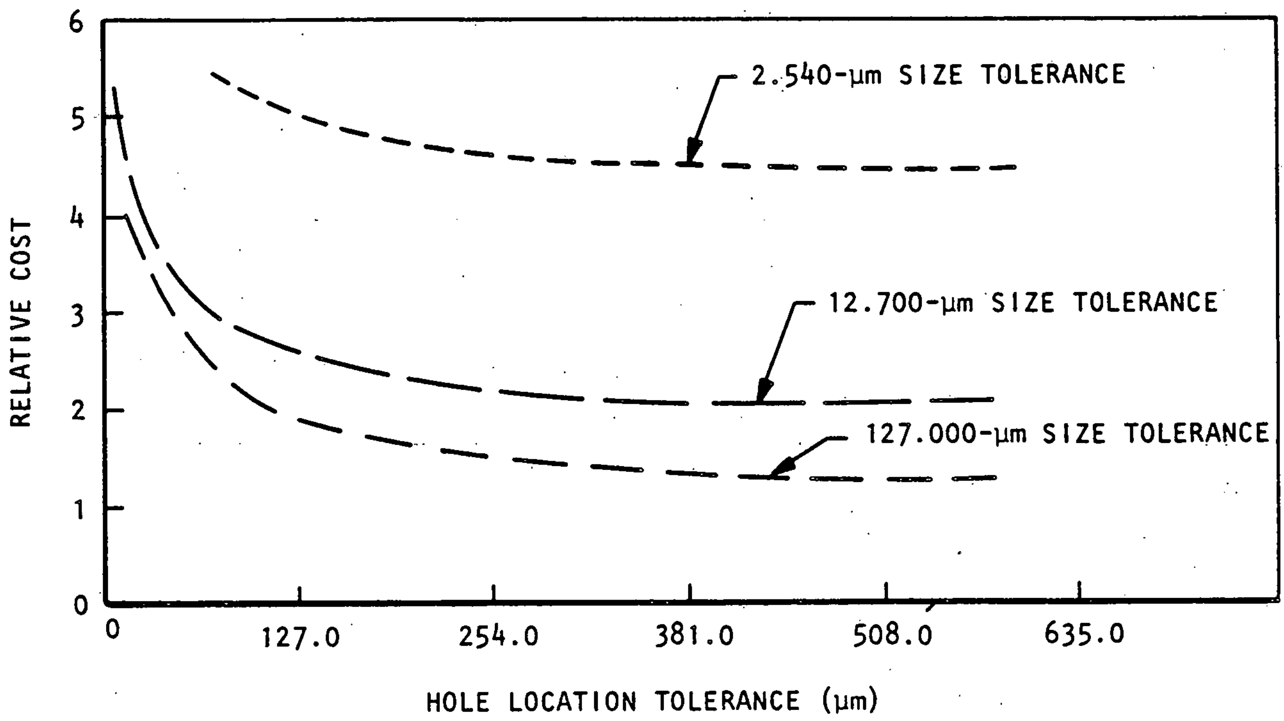


Figure 21. Estimate of Tolerance Influences on Costs

The little-known phenomenon of zero lateral thrust is illustrated in Figure 22 for one set of conditions. As indicated by the arrows, the magnitude and direction of the total force on the cutter varies considerably with the type of cut and the radial depth of cut. This view, which looks down on the cutter, shows that on a 0.025 in. (0.635 mm) diameter cutter, a 0.010 in. (0.254 mm) radial depth of cut (conventional cut) produces almost no lateral force. At the opposite extreme, a 0.020 in. (0.50 mm) radial depth of cut (climb cut) produces almost no longitudinal force. The trends shown in Figure 22 are typical of all end mills in all metals. In all cases studied, the minimum side force was produced with a radial depth of cut of 40 percent of the cutter diameter.

Brass, aluminum, 303 Se stainless steel, and 17-4 PH stainless steel specimens were used in this study (Figure 23). Most tests were straight-line cuts 1 in. (25.4 mm) long.

In addition to finding zero side load conditions, an equation was desired which would predict cutter deflection under any condition. This secondary objective was only partially attained; an accurate force-predicting equation could not be found which covered all machining conditions.

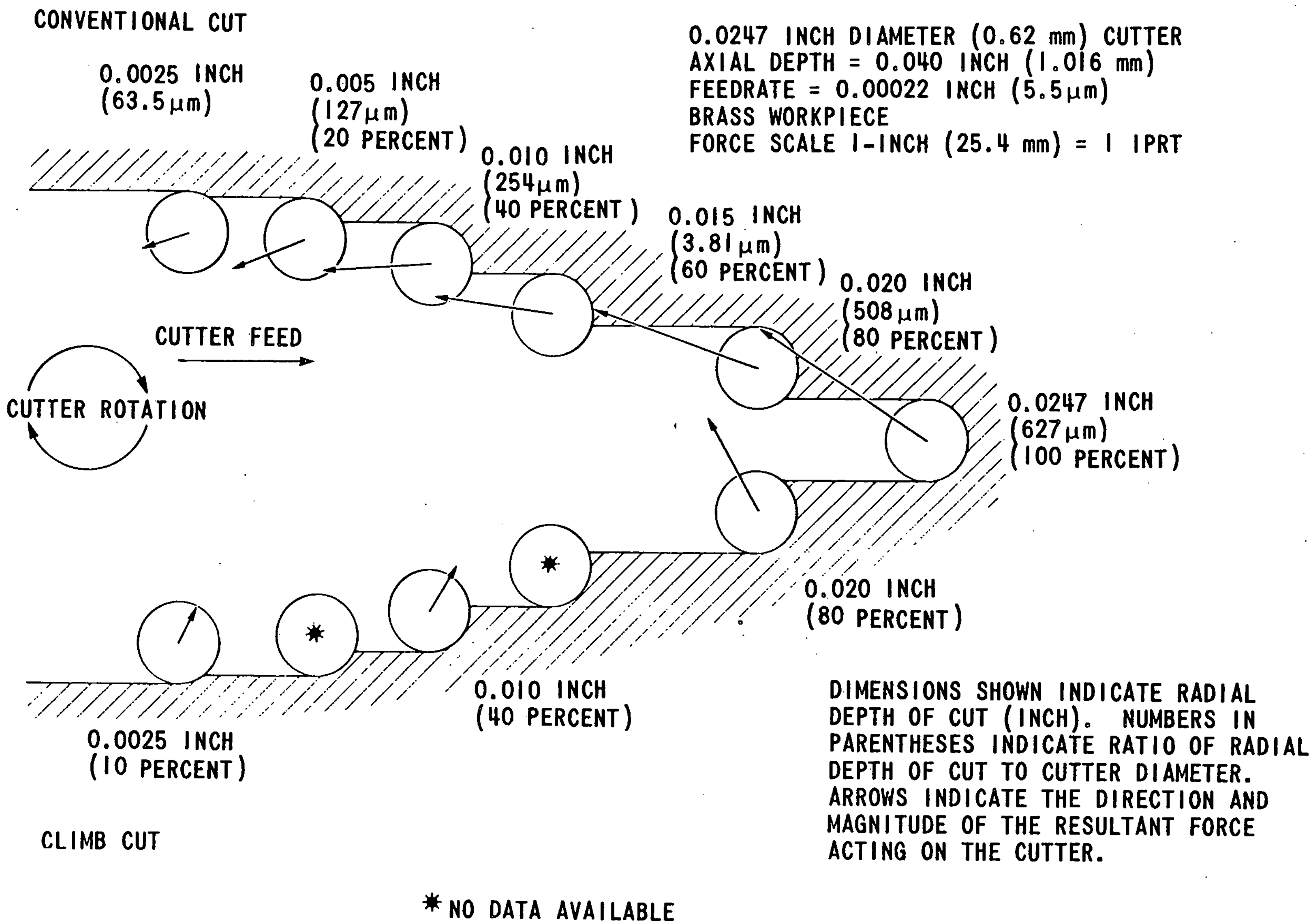


Figure 22. Measured Load Under Various Conditions

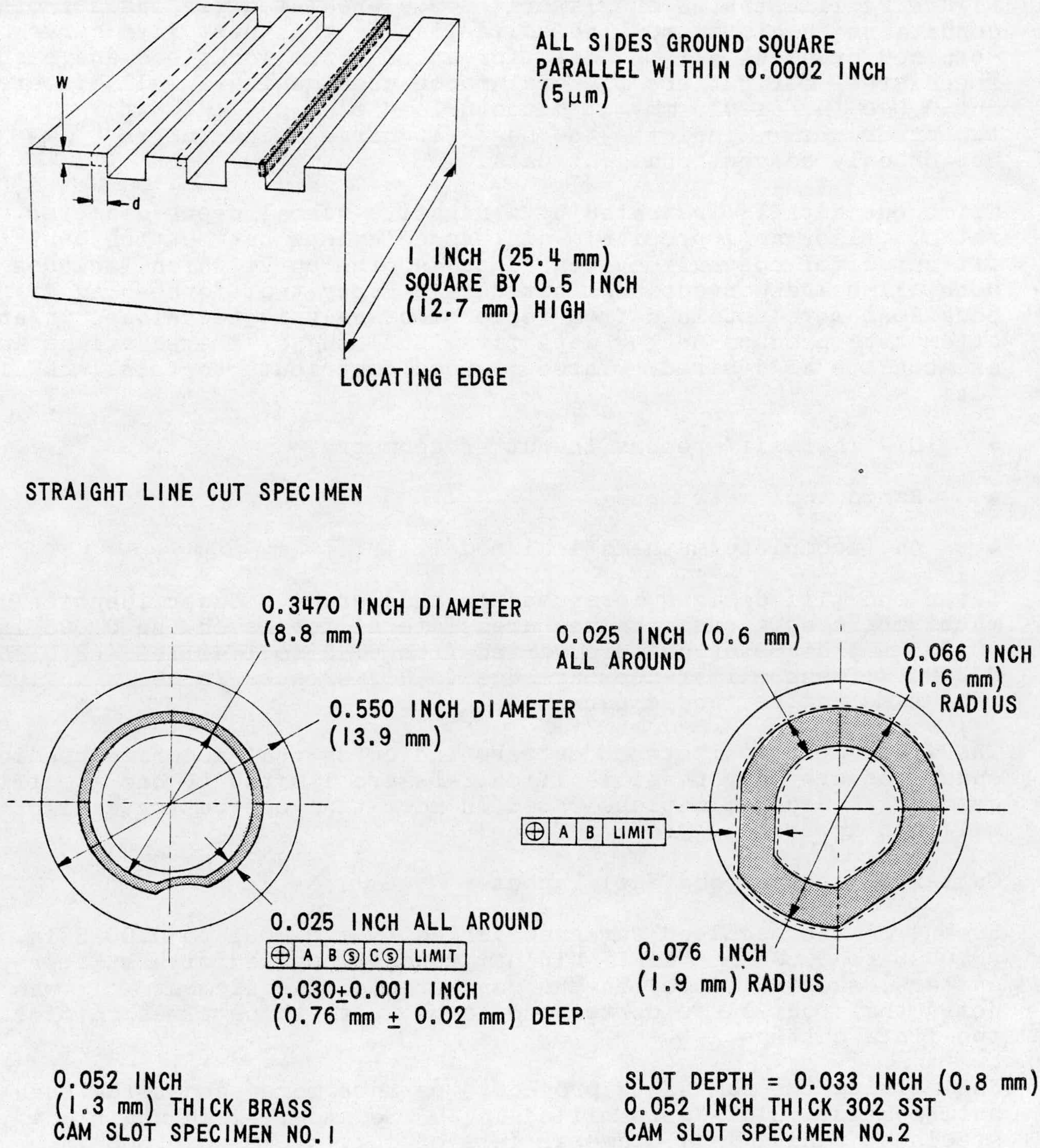


Figure 23. Specimen Geometry

Figure 24 illustrates the lateral force predicted for one set of conditions in aluminum. The solid line is the "best fit" curve obtained by using all the data for an aluminum workpiece and high speed steel cut cutters (lateral force when making a full diameter cut 0.040 in. (1.016 mm) at a tooth load of 0.00011 IPR/t). The two other curves indicate the best fit curve using only a climb cut or only conventional cut data.

Climb cut data is indicated by a negative radial depth/diameter ratio. Also, an appreciable difference exists between the best fit curve for conventional cut data and the curve which includes both climb and conventional cut data. Forty-two, force-predicting equations were obtained from regression analysis techniques in an attempt to produce better data fits, but none of the equations were as accurate as desired. Three sources contribute to this lack of fit:

- Distinct differences in cutter geometry,
- Rapid tool wear, and
- An incomplete mathematical model.

Seven end mill designs were used in this study. Under identical machining conditions, the measured lateral forces on the 0.025 in. (0.635 mm) diameter cutters varied from 0.45 to 1.40 lbs. (2.0 to 6.2 N). These differences are due to differences in helix angles, tool rake angles, and clearances.

The wide variation between cutters indicates that accurate predicting equations are only possible if cutters are limited to one specific geometry. Generalizations based on more than one cutter design will not accurately predict force.

Cutter Deflection and Wall Runout

Runout on the machined surfaces varied from 0.0001 to 0.0015 in. (0.0026 to 0.038 mm) TIR. Minimum runout resulted with stiffer cutters, shorter flute lengths, and precision equipment. It was noted that four-flute cutters could be up to three times stiffer than two-flute cutters.

End milling the cam slots proved to be much more successful than anticipated. Slots were milled in 303 Se and 17-4 PH stainless steels by taking full diameter cuts of only 0.002 to 0.006 in. (0.051 to 0.152 mm) axial depth. Depths of 0.030 in. (0.76 mm) were achieved by taking several passes of these short axial depths. Profiling cuts could not be made in these high strength materials. With additional testing, the overcut in slot width probably could be reduced from 0.004 to 0.0015 in. (0.102 to 0.038 mm). It does not appear feasible to produce straight-sided walls to tolerances of 0.0005 in. (0.0127 mm) in stainless steels with these small cutters. Such requirements do appear feasible, however, in brass and aluminum.

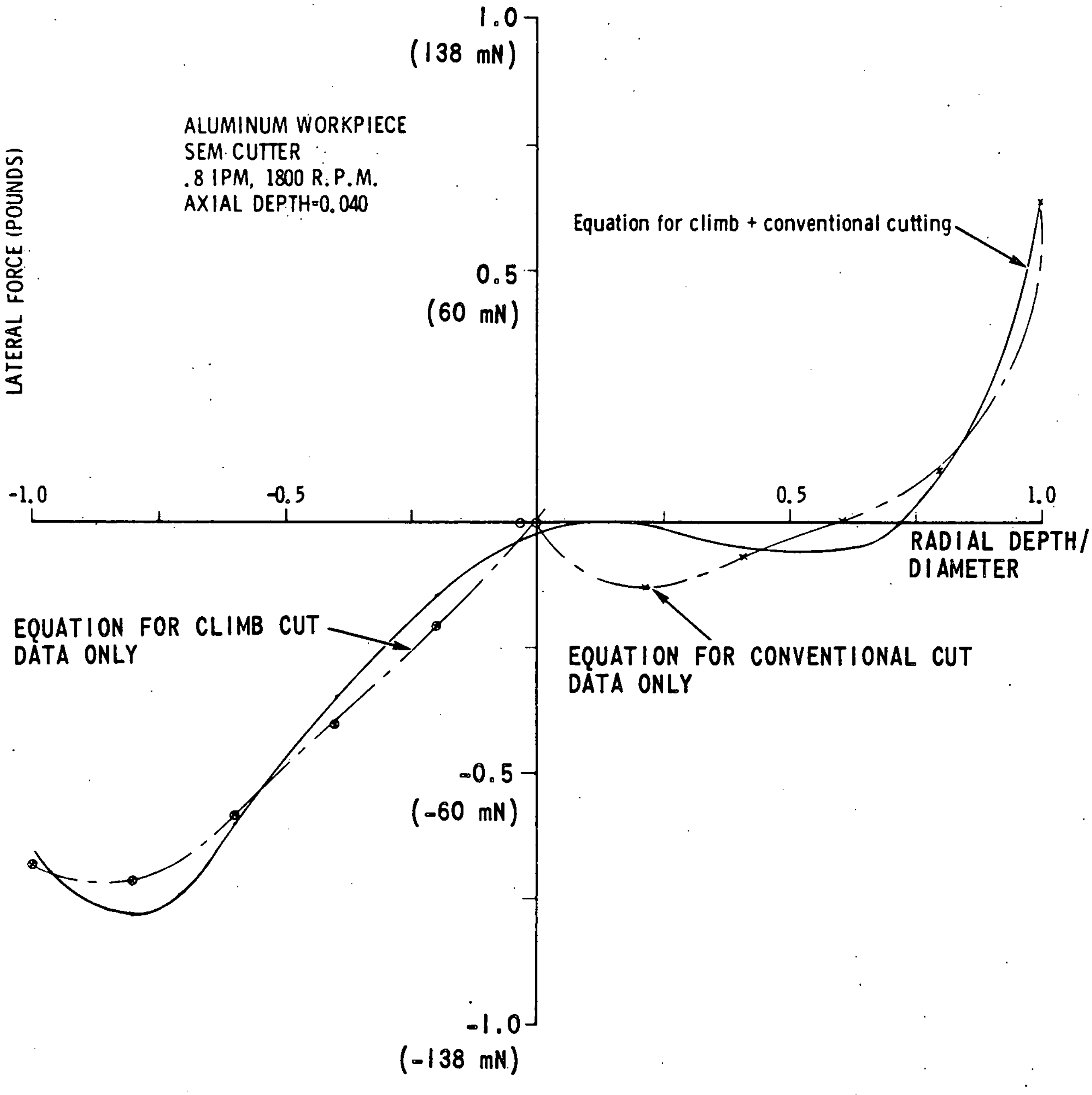


Figure 24. Predicted Lateral Force

In summary, the end milling conditions which typically produce maximum edge straightness have been identified. For 0.025 in. (0.635 mm) diameter cutters, a 0.010 in. (0.25 mm) radial depth of cut produces no net side thrust on the cutter, allowing single-pass profiling on nonferrous materials. Attempts to mill stainless steel with less than a full diameter cut have not been successful when using miniature end mills. Cam slots cut in brass tended to be 0.001 to 0.002 in. (0.026 to 0.051 mm) oversize with up to 0.001 in. wall runout. Cam slots cut into 303 Se stainless steel were up to 0.004 in. (0.1 mm) oversize with 0.001 in. wall runout.

The deflection of miniature end mills at conditions other than zero side load can generally be predicted within 0.001 in. More accurate preductions are not possible without previous empirical data on cutters of that same geometry.

## Machinability in Lathe Operations

Component parts of small mechanisms often require surface finishes of 16 to 32 μin. (0.406 to 0.812 μm), nearly sharp edges, and very small fillet radii. In addition, edges generally must be free of burrs to ensure reliable operation of the mechanism.

Because of the importance of knowing before machining is begun how workpiece material and tool geometry will affect such variables as surface finish, fillet radius, burr size, and cutting forces, this study was directed toward determining the machinability of materials that are commonly used in the production of miniature precision components. Optimum machinability was defined in terms of the variables studied.

A second goal of the study was to develop equations which would predict optimum tool geometries from a knowledge of workpiece properties.

### Background

In the production of miniature precision mechanisms, the machinability of the workpiece material determines the sequence of manufacturing operations, the machining time, and the tool design. Although machinability ratings have been established for "roughing" conditions, neither quantitative nor qualitative ratings have been established for the conditions required for machining miniature precision parts. In many instances, a material different from that originally conceived is used for components in order to minimize fabrication costs. In making such substitutions, a knowledge of the significance of the changes is of extreme importance.

Requirements such as 0.003 in. (76.2 μm) maximum fillet radius necessitate the use of turning tools having nose radii of 0.003 in. or smaller. Achieving the surface finish requirements shown in Table 10 with such a sharp-nosed tool requires slowing feedrates to less than 0.0005 ipr (12.7 μm/rev.). The close dimensional tolerance necessitates frequent tool adjustment and the maintenance of low cutting forces (large forces will bend small shafts and cause taper). Burr size must be minimized in order to utilize deburring processes that will not adversely affect dimensions while burrs are being removed. Most processes will remove burrs that are thinner than 0.001 in. (25.4 μm) without removing more than 0.0002 in. (5.08 μm) from a diameter or exceeding an edge break of 0.003 in. (76.2 μm). This is particularly important for extremely small pins. For example, pins having a diameter of 0.020 in. (0.5 mm) are very difficult to deburr without excessive stock losses when the burrs to be removed range up to 0.003 in. in thickness.

Figure 25 illustrates the need for maintaining a small fillet radius on a typical miniature part. As shown, thin working parts must have nearly sharp edges to provide sufficient bearing area. A 0.020-inch wide (0.5 mm) pawl with a 0.006 in. (127 μm) edge radius on both sides would result in a contact surface width of only 0.010 in. (254 μm) with the mating part. A 0.002 in. radius (50.8 μm) on each side of the pawl would provide a 60 percent increase in the bearing surface.

The fillet radius on a part must be smaller than the edge radius on the mating part to ensure a flush fit. With laser-welded or electron-beam-welded joints, large radii reduce the amount of metal that is available to fill the weld joint.

The fact that changing the back rake, side rake, and the other angles did not, by itself, significantly reduce the cutting force is surprising, since the literature and theory pertaining to metal cutting indicate that they are major contributors to these forces. The only obvious explanation for this discrepancy is that only the small ranges of angles that are actually used in production were utilized in this study; in contrast, many studies utilize angles which have little practical feasibility.

As shown in Figure 26, 303 Se stainless steel, which often is called "free machining," exhibited the highest cutting forces among all the materials studied. The 18-2 stainless steel, just recently developed and which reportedly is much easier to machine, required a much smaller cutting force. The 15-5 PH stainless steel, which had the highest tensile strength of all the materials studied, required roughly half the cutting force of 303 Se stainless steel. These results are not directly related to hardness, as might be assumed; the 303 Se stainless steel, inadvertently obtained in the annealed condition, was the softest material that was machined.

As previously indicated, large cutting forces tend to cause taper in workpieces, large burrs, and rapid tool wear. Consequently, they should not be used to manufacture miniature precision components.

Force alone, however, is not the only factor influencing taper size, finish, and wear. The ratio of cutting force to modulus of elasticity ($F_T/E$) is a better indicator. Table 11 indicates the values of this ratio as observed in this study.

Table 10. Typical Requirements for Turned Miniature Precision Parts

| Requirement | Value |
|---|---|
| Surface Finish | 8 to 16 $\mu$in. (0.20 to 0.41 $\mu$m) |
| Tolerances | ±0.0002 in. (±5.08 $\mu$m) |
| Maximum Fillet Radii | 0.003 in. (76.2 $\mu$m) |
| Minimum Burr Size | 0.001 in. or less (25.4 $\mu$m) |
| Maximum Edge Breaks | 0.003 in. (76.2 $\mu$m) |

Table 12 indicates the measured results for fillet radii finish, cutting force $F_T$, and burr size. This particular table also ranks materials by their "desirability" for each of these parameters.

The need for 90-degree shoulders, when combined with the need for tools having small nose radii, necessitate the use of negative side-cutting edge angles (SCEA) in order to both turn and face the part. (A negative side-cutting edge angle indicates that the point of the tool leads the cutting edge.) The negative SCEA results in a very weak tool nose which may be easily chipped and quickly worn away. These conditions, in turn, greatly affect the part dimensions.

Test Results

Five tool-geometry variables were evaluated in this study and more than 4000 measurements were made on more than 500 test samples from six different materials. In addition, the influence of the depth-of-cut and the number of specimens machined were also studied. The variables measured included three components of cutting force, fillet radius, surface finish, burr height and thickness, radial tool wear and three different values of wearland size. In-depth details of this study are reported elsewhere.[10]

The single most important factor in maintaining dimensional tolerance and surface finish is the principal cutting force $F_T$.

The single most important variable which affected this factor was the depth-of-cut. As shown in Figure 26, $F_T$ is proportional to the depth-of-cut.

While other factors influenced force $F_T$ for some materials, there was no consistent trend. When changes in the tool angles did affect the force, the effect was relatively small.

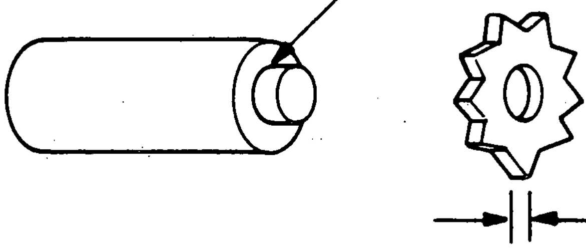


Figure 25. Illustration Showing the Need for Maintaining a Small Fillet Radius to Provide a Precision Fit of Mating Parts

In this study, it was observed that surface finishes of 22 to 42 μin. AA (0.56 to 1.07 μm) can be produced while maintaining 0.003 in. (76.2 μm) fillet radii. Tool life is extremely short when maximum fillet radii of 0.002 in. (50.8 μm) are required. Burr height and thickness were found to increase as the strain-hardening exponent of the workpiece becomes greater. Low feedrates were found to increase the unit cutting power up to three times that which normally is experienced.

Optimum tool geometries observed in this study proved to be similar to those recommended in machining handbooks for general use.

The unit horsepower required to machine the materials studied was typically 2.5 times larger than is indicated in most handbooks. This indicates that when handbook values are used to calculate the cutting force, the results will be considerably less than the measured forces if low feedrates are involved. Because of the wide range of hardness values that are available for some metals, the values will differ notably from handbook values, because handbook values are based on a single hardness value for a given metal.

While equations were developed which related performance to workpiece properties, these equations probably will provide misleading information if used with other materials.[10]

## Machining Polyimide Plastic

To minimize inertia forces, several miniature assemblies utilize some components made from polyimide plastic. This material presents some unique machining problems. Its ductility, which is similar to cast iron, frequently results in chipped edges or fractured webs. Its modulus of elasticity is less than 3 percent than that

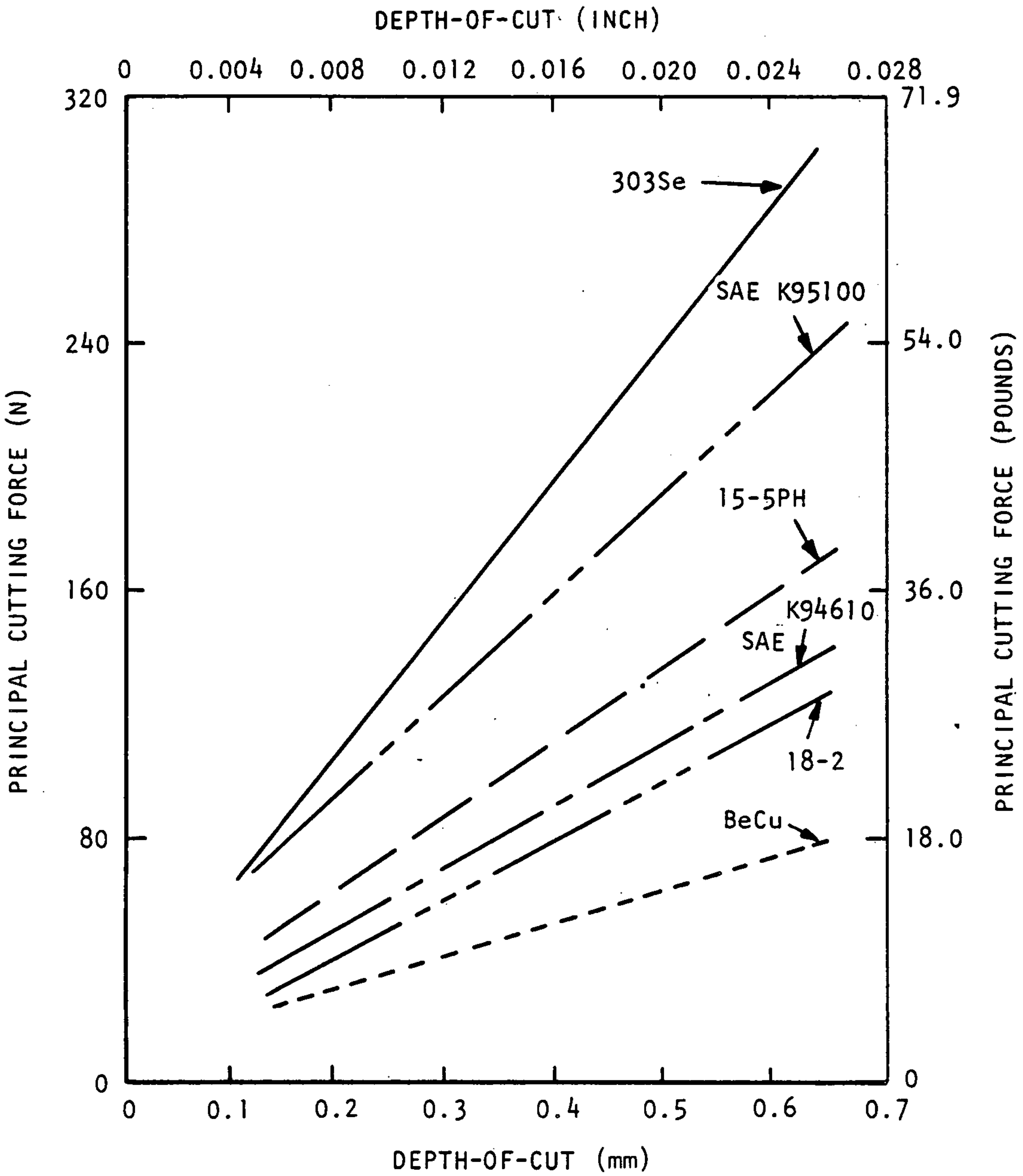


Figure 26. Effect of Depth-of-Cut on Principal Cutting Force $F_T$

of steel which allows the part to deflect during machining operations. If cutting temperature are too high, the material burns or flows.

This study was directed to finding machining techniques which minimized these problems. The study although brief, evaluated turning, hobbing, milling, grinding and deburring operations.

Table 11. $F_T/E$ Ratios for Average Results From Tool 3

| Material | $F_T/E$ in.$^2$ x $10^{-7}$ | $F_T/E$ (mm$^2$) | Ranking by $F_T/E$ |
|---|---|---|---|
| 15.5PH | 3.4 | (0.022) | 3 |
| SAE K95100 | 4.0 | (0.026) | 5 |
| SAE K94610 | 3.5 | (0.023) | 4 |
| BeCu | 2.2 | (0.014) | 1 |
| 303Se | 4.1 | (0.026) | 6 |
| 18-2 | 2.5 | (0.016) | 2 |

The following observations summarize the findings of this study.

- Almost all normal type machining operations can be performed at feeds and speeds and with cutting tool geometry normally used for aluminum. Coolant has little effect on quality.
- Whenever possible, cuts should be uninterrupted to prevent "pushing" of material and excessive burrs.
- Drills must be cleared often to prevent excessive heat and chip buildup.
- Boring can maintain 0.0004 in (10.2 μm) tolerances on 0.1 in. (2.5 mm) diameter holes.
- Reaming is not recommended for holes deeper than four diameters because of heat buildup, poor size control, and poor finish. Surface finishes of 5 μin. (0.125 μm) were produced by reaming.
- Generally, it is better to turn thin walled or small diameter parts to finish size in one pass so that the bar stock can support the fragile sections during machining.
- Spacers or backup material are recommended for hobbing, form milling, or other similar cuts to prevent excessive burrs. The use of metal shims results in imbedded metal chips in the parts.
- End milling caused excessive burring and chipping at all speeds and feeds. Side milling was somewhat better, but only on fairly large areas. Usually, thin unsupported sections cannot be adequately remachined by milling, partly because of the gross edge chipping which occurs.

Table 12. Results Ranked by Material, Using Optimum Tool Geometry

| Measured Variable and Measuring Units | Material Ranking | | | | | |
|---|---|---|---|---|---|---|
| | Best | Better | Fair | Poor | Worse | Worst |
| | Properties Increase in Quantity | | | | | |
| Fillet Radius | 18-2 | 303Se | BeCu | 15-5PH | K95100 | K94610 |
| μm | 35.6 | 35.6 | 48.3 | 53.3 | 55.9 | 58.4 |
| in. $\times 10^{-4}$ | 14 | 14 | 19 | 21 | 22 | 23 |
| Surface Finish, AA | K95100 | 15-5PH | 18-2 | BeCu | K94610 | 303Se |
| μm | 0.30 | 0.58 | 1.22 | 1.22 | 1.40 | 1.47 |
| μin. | 12 | 23 | 48 | 48 | 55 | 58 |
| Recommended | Decreasing Speed | | | | | |
| Cutting Speed | BeCu | 18-2 | K94610 | 303Se | K95100 | 15-5PH |
| mm/s | 1275 | 1122 | 729 | 510 | 306 | 245 |
| SFPM | 250 | 220 | 143 | 100 | 60 | 48 |
| | Properties Increase in Quantity | | | | | |
| Cutting Force $F_T$ | BeCu | 18-2 | K94610 | 15-5PH | 303Se | K95100 |
| N | 17.8 | 31.1 | 31.1 | 44.5 | 53.4 | 53.4 |
| Pounds | 4 | 7 | 7 | 10 | 12 | 12 |
| Burr Length | 15-5PH | BeCu | 18-2 | K95100 | K94610 | 303Se |
| μm | 0 | 15.2 | 33.0 | 35.6 | 45.7 | 243.8 |
| in. $\times 10^{-4}$ | 0 | 6 | 13 | 14 | 18 | 96 |
| Burr Thickness | 15-5PH | BeCu | 18-2 | K95100 | K94610 | 303Se |
| μm | 0 | 30.5 | 33.0 | 33.0 | 66.0 | 96.5 |
| in. $\times 10^{-4}$ | 0 | 12 | 13 | 13 | 26 | 38 |
| Surface Finish X Fillet Radius | K95100 | 15-5PH | 18-2 | 303Se | BeCu | K94610 |
| $\mu m^2$ | 16.8 | 30.9 | 43.4 | 52.3 | 58.9 | 81.8 |
| $in.^2 \times 10^{-10}$ | 264 | 483 | 576 | 812 | 912 | 1265 |

- Grinding of thin, unsupported sections was very successful apparently because of the small tool pressures involved. There was some evidence of wheel loading. Dry grinding appears to load the wheel less than wet grinding. Surface finishes of 20 to 40 μin. (0.5 to 1.0 m) resulted from grinding.

- Vibratory deburring was ineffective because the light parts floated in the media. Fixturing of small parts for vibratory deburring would be necessary to utilize this method.

- Hand deburring form-milled, turned, hobbed, and ground parts was no problem. In those cases where unsupported sections were machined, displaced material and chipping made deburring practically impossible.

Machining SAE K95100 High Permeability Magnetic Steel

Many of the magnetic solenoid components in miniature mechanisms are made from SAE K95100 magnetic alloy steel. Since most commercial use of this material is for laminated constructions, made from blanked parts, little machining data is available on this material. This study was designed to define appropriate machining conditions for close tolerances in this materail.

Specific areas of a typical miniature solenoid housing were selected for machining tests:

- Techniques required to produce and maintain precision bored diameters of ±0.0001 in. (25.4 μm) and thicknesses of +0.001 -0.000 in. on conventional equipment,

- Conditions required to minimize edge chipping of the material,

- Distortion associated with heat treatment and the associated amount of stock required for finish operations,

- Tool geometry and materials,

- Tool wear, and

- Feeds, speeds, and coolants.

Material Properties

SAE K95100 is the designation for 2 percent vanadium, 49 percent cobalt, and 49 percent iron alloy. The generic name for this material is 2V permendur or vanadium permendur.

This material, which has the texture and brittleness of cast iron and the strength of stainless steel, is noticeably heat sensitive. The machining chips range from a ductile spring-like chip to typical hard, brittle chips depending upon initial condition and speeds and feeds. Table 13 defines the basic properties for this material.

These test demonstrated a number of characteristics.

- A 0.003 in. (76.2 μm) maximum fillet radius can be maintained for a minimum of 20 axial in. (0.5 m) of cut in a face and turn situation using negative rake tools.

- On interrupted cuts, sharp boring tools wear or fracture such that a 0.006 in. (152.4 μm) fillet radius is the smallest radius that can be maintained by conventional tools in a 1 in. (25.4 mm) depth of cut.

- In general, machining feeds and speeds should be 30 to 40 percent of those recommended for low carbon steel. In terms of standard handbook values, feeds should be 10 to 25 percent of the published values for 0.025 in. (0.64 mm) cuts in 1018 steel, while speeds should be 20 to 100 percent of the published value.

- Grinding, turning, facing, and drilling do not represent a problem in this material.

- As expected, the heat treated material wears tools much quicker than the annealed material.

- Material creep does not appear to be significant with this material. Thin wall part diameters remained constant within 0.00005 in. (1.27 μm) for two weeks.

- Cutoff tools should be 0.06 in. (1.5 mm) wide or thicker to prevent tool breakage.

In the initial end milling test, tool and workpiece chipping were a distinct problem. A series of feed/speed/geometry tests minimized chipping. Carbide inserts provided good life, surface finish, and a ±0.001 in. (±25.4 μm) size repeatability when operated at 0.001 ipr tooth and 420 sfpm (25.4 μm/rev/tools and 2142 mm/sec.). Maintaining +0.001 -0.000 in. (+25.4 -0.0 μm) on thickness dimensions is possible but extremely difficult because of variations between tool inserts and insert seating. High speed steel end mills were not successful in this material.

Maintaining a 0.003 in. (76.2 μm) maximum fillet radius in the bottom of an interrupted cut counterbore toleranced +0.0001 -0.0000 in. (+2.54 -0.00 μm) proved to be impossible. The high shock loading caused by the interrupted cut destroyed the sharp tool nose within one or two cuts. A 0.005 in. (127.2 μm) radius appeared to be the smallest radius possible in production situations. A 0.003 in. (76.2 μm) radius was maintained in a noninterrupted cut using a negative rake tool. This tool was also used on interrupted cuts, and its design indicates it should be more successful in such applications than other tools, but it will still be a borderline condition.

Table 13. Typical Mechanical Properties

| Property | Cold Rolled | Type of Stock: Strip, Annealed | Bar, Annealed |
|---|---|---|---|
| Tensile Strength (ksi) (MPa) | 195 (1340) | 80 (550) | 56.7 (390) |
| Yield Strength (ksi) (MPa) | 185 (1275) | 48 (331) | 56.7 (390) |
| Elongation Percent in 2 in. | 1 | 0.5 | 0.78 |
| Rockwell Hardness | C35 | B97 | C31 |

The heat treat operation caused a 0.0001 in. (2.54 μm) average additional out-of-tolerance condition on counterbore diameters of 0.500 in. (12.7 mm). The range of out-of-roundness change went from a 0.0004 in. (10.2 μm) improvement to a similar worsening. Changes in overall lengths as a result of heat treating effects were not recorded. On the basis of the small changes in diameter and the recommended practice of taking only light cuts after annealing, no more than 0.005 in. (127.2 μm) stock/per side should be left for finish operations. (Heat generated in machining affects magnetic properties.)

An interesting sidelight significant in the design and manufacture of precision miniature solenoids is that the magnetorestruction properties of this material can cause a 0.000070 (seventy millionth) change in a 1 in. dimension (70 μm/m).

Some specimens which had received no cleaning and which had been lying unprotected for several months exhibited minute specks of what appeared to be rust. These specks, which were visible only under magnification and then not on all parts, were apparently the result of both handling and atmospheric moisture. To prevent rusting, all parts are currently coated with a protective oil after every operation.

## Form Grinding Aluminum

The objective of this study was to develop the capability of form grinding precision contours within 0.002 in. (50.8 μm) tolerance on aluminum alloy parts. The form grinding process provides a higher degree of precision in producing contours than other machining processes, but aluminum alloys are difficult to grind without frequent redressing of the abrasive wheel. Precision contours are typical requirements of piece parts in miniaturized mechanisms, and light materials help to minimize the momentum of the moving parts in these devices.

While surface grinding literature is available for aluminum materials, none of the literature discusses capabilities for form grinding. Using available recommendations for surface grinding, 3000 parts were ground in an attempt to produce a 0.031 in. (0.75 mm) convex radius along the edge of 0.0625 in. (1.59 mm) wide 7075-T6 aluminum. Table 14 describes the conditions studied. The end of life for each test was defined as the number of parts which were ground before parts began to fall outside the ±0.001 in. (±25.4 μm) tolerance band. Surface finish was also measured and was found to correlate to wheel wear.

At the optimum grinding conditions, 200 parts each 0.2 in. (5.1 mm) long were produced before the grinding wheel had to be redressed. The conditions which produced the best tool life also produced the best surface finish of 23 μin. (0.58 μm) after 200 parts. The optimum conditions included a silicon carbide 90 grit wheel, a diamond form block dressing tool, a 0.001 ipr (25.4 μm/rev.), and a 120 grit wheel.

These conditions represent the fastest downfeed and the small grit size tested. The surface finishes obtained in this study ranged from 16 to 80 μin. (0.41 to 2.03 μm). No significant wheel loading or other problems were observed in this study.

<u>Fabrication of a Machinable Ceramic</u>

The fabrication of high purity ceramic parts normally consists of casting powdered material to a desired shape and firing it to a final hardness. If finishing operations are required, the ceramic is either treated to soften the surface so that it can be machined, or diamond wheels are used to grind to finish dimensions.[26] This technique is both involved and, if not properly completed, causes tremendous cutting tool wear.

The objective of this study was to develop techniques to produce a "machinable" ceramic material that can be machined using conventional metal working equipment and then fired to finish configurations. This effort was done in conjunction with Sandia Laboratories efforts on developing an intermediate machinable state of ceramic.[27,28] There were a number of specific objectives of this study:

- Develop a method of isostatically compressing $Al_2O_3$ (alumina) and binders into a cohesive blank,
- Develop an initial firing technique that produces a bisque from the cohesive blank that can be machined to close tolerances,
- Develop tooling concepts and machining techniques applicable to ceramics, and

Table 14. Conditions Studied in Form Grinding Study

| Variable | Range |
|---|---|
| Machine | Brown and Sharpe Model 618 with visual attachment |
| Coolant | Water soluble coolant concentrate E-55 (80/1) |
| Coolant Application | Air Mist |
| Wheel Speed | 4500 SFPM |
| Table Speed | 600 in./μin. (15 m) |
| Downfeed | 0.0002 to 0.001 in./pass (5 to 25 μm) |
| Abrasive Grit Size | 60 to 120 |
| Abrasive Material | $Al_2O_3$ and SiC |
| Dressing Method | Carbide crush roll and diamond form block |

- Develop final firing procedures that produce maximum density parts and determine shrink factors for this firing so parts can be final fired to finish configuration.

Results

A process and tooling were developed to isostatically compress alumina powder at 30,000 psi (2.068 gPa) pressure. The tooling consisted of a cylindrical fluorosilicone rubber bag filled with alumina powder and a wax binder which were compressed. The bags were formed to make a cylinder approximately 6 in. (152 mm) long. These bags produced rods 0.625 in. (15.9 mm) in diameter and 0.75 in. (19.1 mm) in diameter. The initial rods were prefired in a gas kiln at 2012°F (1100°C) for 15 minutes using a 20 micron (μm) vacuum to remove air from the powder. This hardened the material and burned out the wax binder. Several temperatures were tried later, with 1250°C (2282°F) finally accepted as the optimum temperature. After prefiring, the rods were cut into 0.5 to 0.75 in. (12.7 to 19.1 mm) long blanks (bisques).

Two separate lots of ceramic parts, each consisting of three configurations, were machined on a lathe with carbide and high speed tools. Two of the lots were machined in a low (10 to 15 percent) relative humidity environment. Half of the third lot was machined in the low relative humidity environment and the other half was machined in an environment with an average relative humidity of 40 percent.

Figure 27 illustrates the types of shapes produced. Table 15 highlights the repeatability attained on the dimensions of Figure 27A, B, and C. The 45 degree angle was held constant within less than 1 degree and the 0.006 in. (152.4 $\mu$m) fillet radius was within tolerance. As seen in Table 15, a ±3 $\sigma$ tolerance of ±0.003 in. (±76.2 $\mu$m) can be maintained on most dimensions. The bisque machined easily with no tendency to chip or crack.

The part shown in Figure 27B was machined from a 0.75 in. (1.90 mm) diameter bisque.

The part shown in Figure 27C was machined from the same lot of parts as those shown in Figure 27A. The dimensional characteristics are shown in Table 15. In this case, both part thickness and outside contour had a wide variance in size. In addition to the problem of maintaining such a thin dimension, these parts broke very easily while being handled.

Standard high speed steel and carbide tools were used to machine these parts. Little tool wear was apparent on these tools, but it should be noted that only a few parts were machined. In this condition, the material had a consistency similar to chalk, but no problem was experienced with airborne dust. Due to the very soft condition of the parts, only optical means could be used to inspect the parts.

After machining, the parts were fired at 3002°F (1650°C) for 2-1/2 hours, after which they were again inspected.

A factor determined by dividing the before-fired dimension by the same feature dimension after final firing was used to define shrink. While data was maintained for each part, only averages are shown in this report. The part drawing dimension multiplied by this shrink factor gives the dimension required before final firing.

As an example for the part shown in Figure 27A, the 0.125 (3.2 mm) dimension, on the average, shrank 13.11 percent (shrink factor of 1.15), thus one should machine this dimension to 0.144 (3.65 mm) and let the final firing reduce the size to 0.125.

The shrink factor varied more than expected on both lots of parts. On thin cross sections, warpage combined with shrink to give some unrealistic shrink factors. The nominal value of shrink was fairly constant and was usually between 12 and 14 percent. The shrink variation was such that tolerances of ±0.005 in. (127.0 $\mu$m) on dimensions between 0.250 and 0.750 in. (6.35 to 19.05 mm) could be held. On features below 0.100 in. (2.5 mm) the tolerance capability was ±0.003 in. (±76.2 $\mu$m). Standard industrial tolerances on ceramic parts are 1 percent but not less than ±0.005 in (0.127 mm).

The probable causes of the large shrink variation were defined as inconsistent bisque density out of the isostatic press, uneven temperature distributions during prefiring, uneven temperature distribution

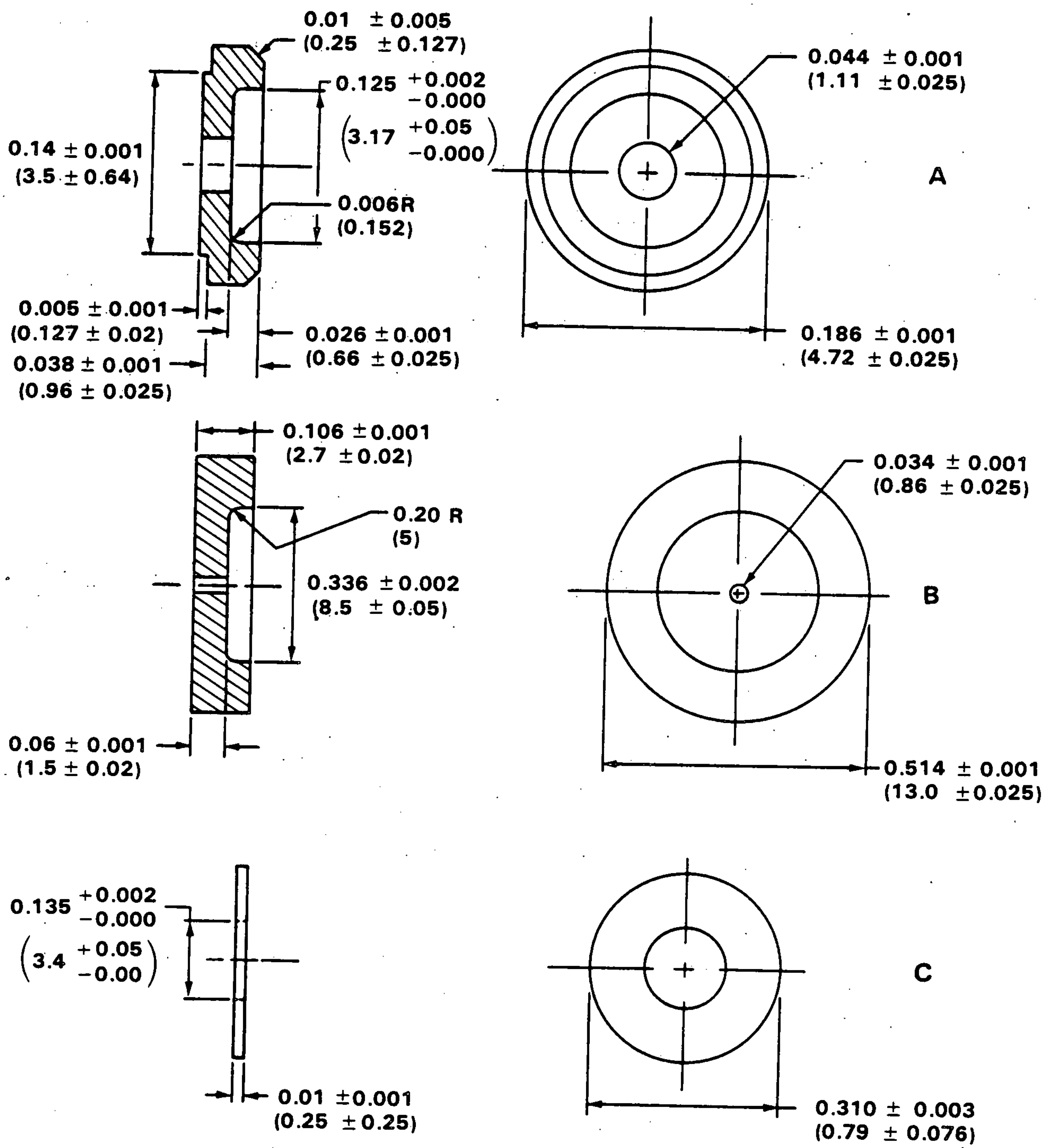


Figure 27. Three Part Configurations Machined From Bisque

during final firing and/or friction between the ceramic pad and the actual part during final firing. The normal method of firing ceramic is in a gas kiln or an electric furnace backfilled with wet hydrogen. A vacuum electric furnace was used for this endeavor, which could have introduced some additional variables.

Table 15. Repeatability of First Lot Part Dimensions Before and After Final Firing

| Figure Reference and Characteristics | Dimensions | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | 0.005/ 0.015* | 0.125/ 0.127 | 0.037/ 0.038 | 0.025/ 0.027 | 0.004/ 0.006 | 0.139/ 0.141 | 0.043/ 0.044 | 0.185/ 0.187 |
| | Before Final Firing | | | | | | | |
| 27A | | | | | | | | |
| Nominal | 0.0056 | 0.1248 | 0.0388 | 0.0256 | 0.0058 | 0.1404 | 0.0462 | 0.1861 |
| Standard Deviation | 0.0011 | 0.0003 | 0.0011 | 0.0005 | 0.0015 | 0.0014 | 0.0010 | 0.0005 |
| n = 11** | | | | | | | | |
| | After Final Firing | | | | | | | |
| Nominal | 0.0049 | 0.1084 | 0.0351 | 0.0230 | 0.0039 | 0.1231 | 0.0401 | 0.1644 |
| Standard Deviation | 0.0009 | 0.0011 | 0.0017 | 0.0002 | 0.0005 | 0.0014 | 0.0008 | 0.0029 |
| | 0.513/ 0.515 | 0.105/ 0.107 | 0.334/ 0.338 | 0.033/ 0.036 | | | | |
| | Before Final Firing | | | | | | | |
| 27B | | | | | | | | |
| Nominal | 0.5138 | 0.1053 | 0.3360 | 0.0341 | | | | |
| Standard Deviation | 0.0006 | 0.0014 | 0.0009 | 0.0003 | | | | |
| n = 6 | | | | | | | | |

Table 15 Continued. Repeatability of First Lot Part Dimensions Before and After Final Firing

| Figure Reference and Characteristics | Dimensions | | | |
|---|---|---|---|---|
| | 0.513/ 0.515 | 0.105/ 0.107 | 0.334/ 0.338 | 0.033/ 0.036 |
| | After Final Firing | | | |
| Nominal | 0.4467 | 0.0920 | 0.2909 | 0.0294 |
| Standard Deviation | 0.0016 | 0.0014 | 0.0017 | 0.0006 |
| | 0.009/ 0.011 | 0.307/ 0.313 | 0.135/ 0.137 | |
| | Before Final Firing | | | |
| 27C | | | | |
| Nominal | 0.0102 | 0.3101 | 0.1378 | |
| Standard Deviation | 0.0017 | 0.0025 | 0.0010 | |
| n = 6 | | | | |
| | After Final Firing | | | |
| Nominal | 0.0092 | 0.2740 | 0.1205 | |
| Standard Deviation | 0.0005 | 0.0039 | 0.0009 | |

*See Figure 27 for metric conversions. One inch = 25.4 mm.

**n = Number of samples inspected.

The second lot of parts was machined to the same part configurations as the first, except the dimensions were adjusted upward by the use of the shrink factors obtained from the first lot of three shapes. The bisque was fired at 2282°F (1250°C) instead of the 2012°F (1100°C) for the first lot. This higher firing temperature was desired to increase the density of the material and hopefully decrease the shrink variation seen during final firing.

Table 16 highlights the net results of Lot 2. As seen there, while the shrink factor is reasonably uniform, it ranges from 1.05 to 1.25. Thus, to obtain a 1.00 in. (25.4 mm) diameter with no previous experience it would be necessary to begin with a diameter somewhere between 1.05 and 1.25 in. (26.7 and 31.8 mm). The average shrink factor of all measurements was 1.157, and the composite standard deviation of this factor was 0.061.

For specific dimensions, it is apparent that the repeatability ($\sigma$) of shrinkage is typically 0.02 or less. Thus, within a specific lot of parts, dimensions should shrink so that 99.7 percent of all parts will shrink within a band of ±0.06. Thus, if the average shrinkage for a specific feature is 1.157 and the initial diameter is 1.157 in. (29.39 mm), then 99.7 percent of all parts should fall within the size range 1.000 +0.055 -0.050 in. (25.4 +1.3 -1.27 mm). Smaller initial sizes would be affected proportionate to their size.

In using this information, it is significant to note that two other factors will increase the variation in actual part sizes in production. Final part dimensions depend on maintaining tight dimensional tolerances during machining. This study did not explore the machining tolerances required to maintain a given final dimension. In addition, lot-to-lot variations were not evaluated in this study; although, despite heat treat differences, the first and second lots experienced similar average shrinkages. Finally, a brief investigation of the values in Table 15 indicates that at least half of all parts made were out of the desired tolerance range on at least one dimension. In actuality, no part was within the desired tolerance for all dimensions.

To hold the initial slugs of material while machining, the Sandia method of using a heat sensitive vinyl acetate cement to mount the small bisques to metal pads for holding in fixtures was used. The metal pads were heated with a hot plate prior to mounting. The three different part configurations were machined from the bisque with no significant problems on the first two parts (Figure 27A and B). Tolerances of 0.002 in. (50.8 $\mu$m) were held in many places on the machined parts. The third part (the thin disk) was very easily destroyed and more work would be required to develop a better process for this part. All of the machining tests performed were on a small lathe.

Table 16. Repeatability of the Second Lot Part Dimensions After Firing for Parts Machined in the 40 Percent Humidity Area

| Figure Reference and Characteristics | Dimensions | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | 0.005/ 0.010* | 0.125/ 0.127 | 0.037/ 0.038 | 0.025/ 0.027 | 0.004/ 0.006 | 0.139/ 0.141 | 0.043/ 0.044 | 0.185/ 0.187 |
| 27A | | | | | | | | |
| Nominal | 0.0077 | 0.1364 | 0.0394 | 0.0246 | 0.0059 | 0.1255 | 0.0425 | 0.1855 |
| Standard Deviation | 0.0010 | 0.0014 | 0.0020 | 0.0011 | 0.0013 | 0.0015 | 0.0009 | 0.0014 |
| Shrink Factor | | 1.07 | 1.17 | -** | - | 1.25 | 1.20 | 1.14 |
| Shrink Factor Standard Deviation | | 0.02 | 0.10 | - | - | 0.01 | 0.02 | 0.01 |
| n = 7*** | | | | | | | | |
| | 0.513/ 0.515 | 0.105/ 0.107 | 0.334/ 0.338 | 0.033/ 0.036 | 0.059/ 0.061 | | | |
| 27B | | | | | | | | |
| Nominal | 0.5458 | 0.105 | 0.3358 | 0.0350 | 0.0668 | | | |
| Standard Deviation | 0.0014 | 0.0027 | 0.0025 | 0.0007 | 0.0057 | | | |
| Shrink Factor | 1.15 | 1.15 | 1.24 | 1.22 | 1.10 | | | |
| Shrink Factor Standard Deviation | 0.005 | 0.030 | 0.004 | 0.020 | 0.030 | | | |
| n = 6 | | | | | | | | |

Table 16 Continued. Repeatability of the Second Lot Part Dimensions After Firing for Parts Machined in the 40 Percent Humidity Area

| Figure Reference and Characteristics | Dimensions | | |
|---|---|---|---|
| | 0.009/ 0.011 | 0.307/ 0.313 | 0.125/ 0.127 |
| 27C | | | |
| Nominal | 0.0118 | 0.3076 | 0.1249 |
| Standard Deviation | 0.005 | 0.0033 | 0.0026 |
| Shrink Factor | 1.05 | 1.14 | 1.16 |
| Shrink Factor Standard Deviation | 0.004 | 0.014 | 0.022 |

*See Figure 27 for metric conversions. One inch = 25.4 mm.

**Dashes indicate values not calculated.

***n = Number of samples inspected.

The final firing technique used involved laying the ceramic parts on small mounts made of bisque ceramic cylinders approximately 0.5 in. in diameter and 0.33 in. high (12.7 by 8.5 mm). The ceramic part was separated from the mount by a thin layer of tabular alumina powder. This powder was used as a separator between the part and the base because it will not fuse during the firing cycle. After final firing, the parts were removed from the mount with a light tap or light forcing, and the remaining alumina powder was removed by scraping.

The ceramic machining endeavor was initiated to learn about the method of bisque machining and was not intended to completely develop a working process. The completed work was successful in that some of the problem areas needing more investigation were outlined. The two problems requiring solutions before a production process can be based on this approach are shrinkage and a method of accurate nondestructive measurement of intricate parts in the bisque state.

Fixturing and Handling Miniature Components

Fixturing and handling of paper thin or pencil-eraser-size parts in a manner to prevent them from being damaged requires special consideration because of the small size and close tolerances of the parts. Thin and soft parts are easily damaged by unsuitable clamping and handling methods. Small parts are difficult to install in fixtures. Clamping is difficult because the clamps that provide the required holding force tend to cover a large portion of a small part. Small-diameter locating pins in fixtures are easily bent by cutting or clamping forces. Small and thin parts, are difficult to pick up and transport by conventional techniques.

This study explored fixturing and handling approaches suitable for precision miniature parts made from magnetic and non-magnetic materials.

An analysis of available fixturing and handling methods[11] revealed 30 approaches that are applicable to small parts; the majority of these have limited application for very small parts. Electrostatic, electromagnetic, and vacuum chucks require larger surface areas than are typically available on miniature parts. Strap clamps, thumbscrews, and most hydraulic or pneumatic clamps often interfere with continuous cutting. Adhesive-bonding and potting in low-melting-temperature alloys require time-consuming secondary operations for pouring, bonding, and removal.

The use of tooling bosses, which are machined-away after the part is completed (Figure 28), was found to have widespread application in eliminating most of the fixturing, clamping, and handling problems that are encountered in the manufacture of many miniature precision parts. This approach is useable on both N/C and conventional equipment. The parts can be easily colleted and were

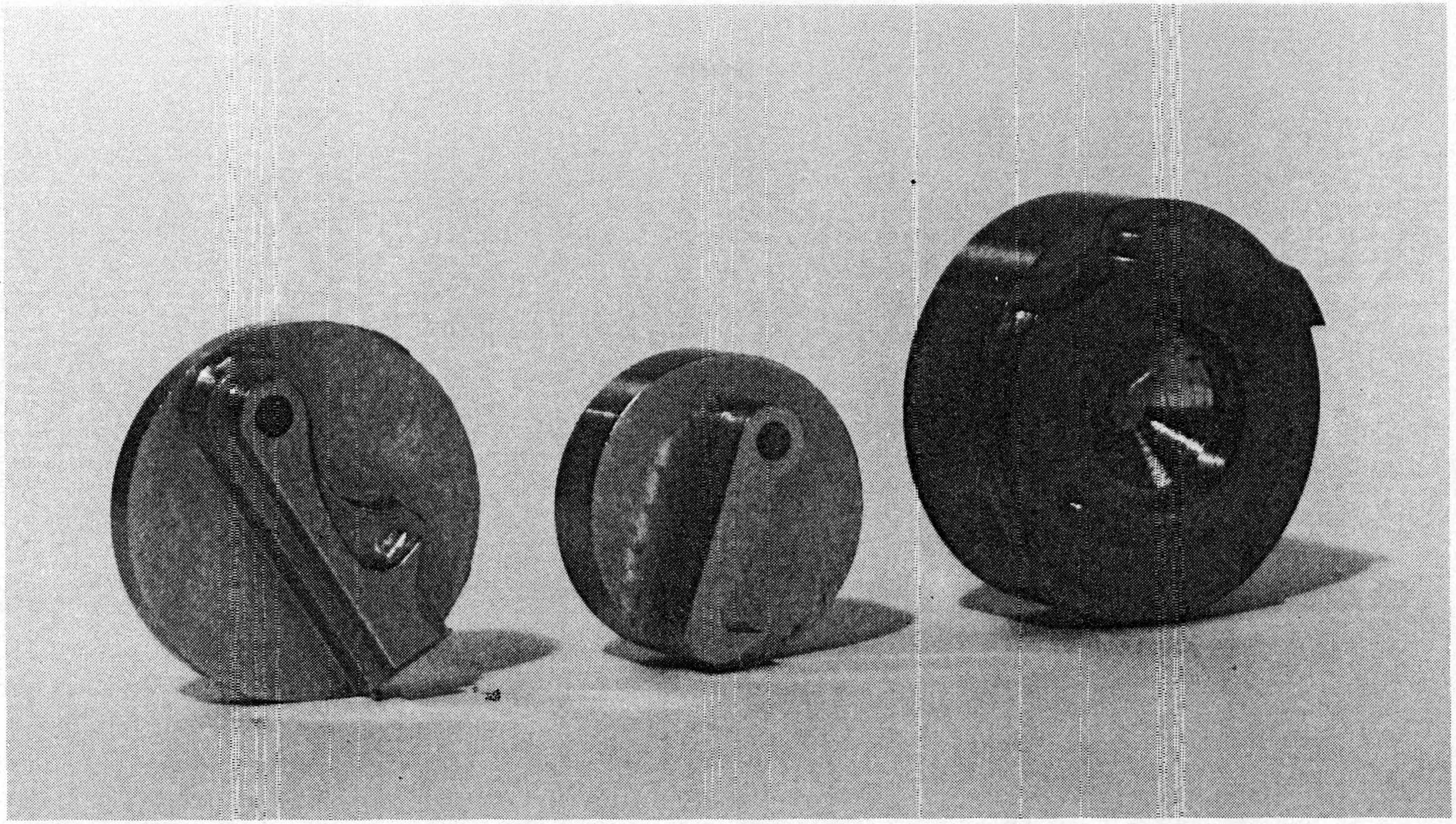

Figure 28. Parts Produced Through the Use of Tooling Bosses

oriented by a tooling hole in the boss or in the part. While a variety of other approaches were studied and are used at Bendix, this approach has proven to be one of the most economical for many small parts.

Economic Optimization

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. This study represented an attempt to identify techniques specifically applicable to miniature piece parts.

Introduction

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 29, 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, were covered briefly in this study.[12]

Optimization Approaches

There are at least ten basic approaches to optimizing fabrication economics (Figure 29). These involve tooling, processes, computer-aided manufacturing, and evolutionary changes initiated by production operators.

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 19 and 25. Many of these components have tolerances of ±0.0002 in. (5.08 μm). Their shapes often dictate the use of sharp-nosed tools (as opposed to commercial 0.030 in. (0.762 mm) nose radii). The sharp-nosed 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 published cutting tool improvements have involved roughing cuts in which large amounts of material

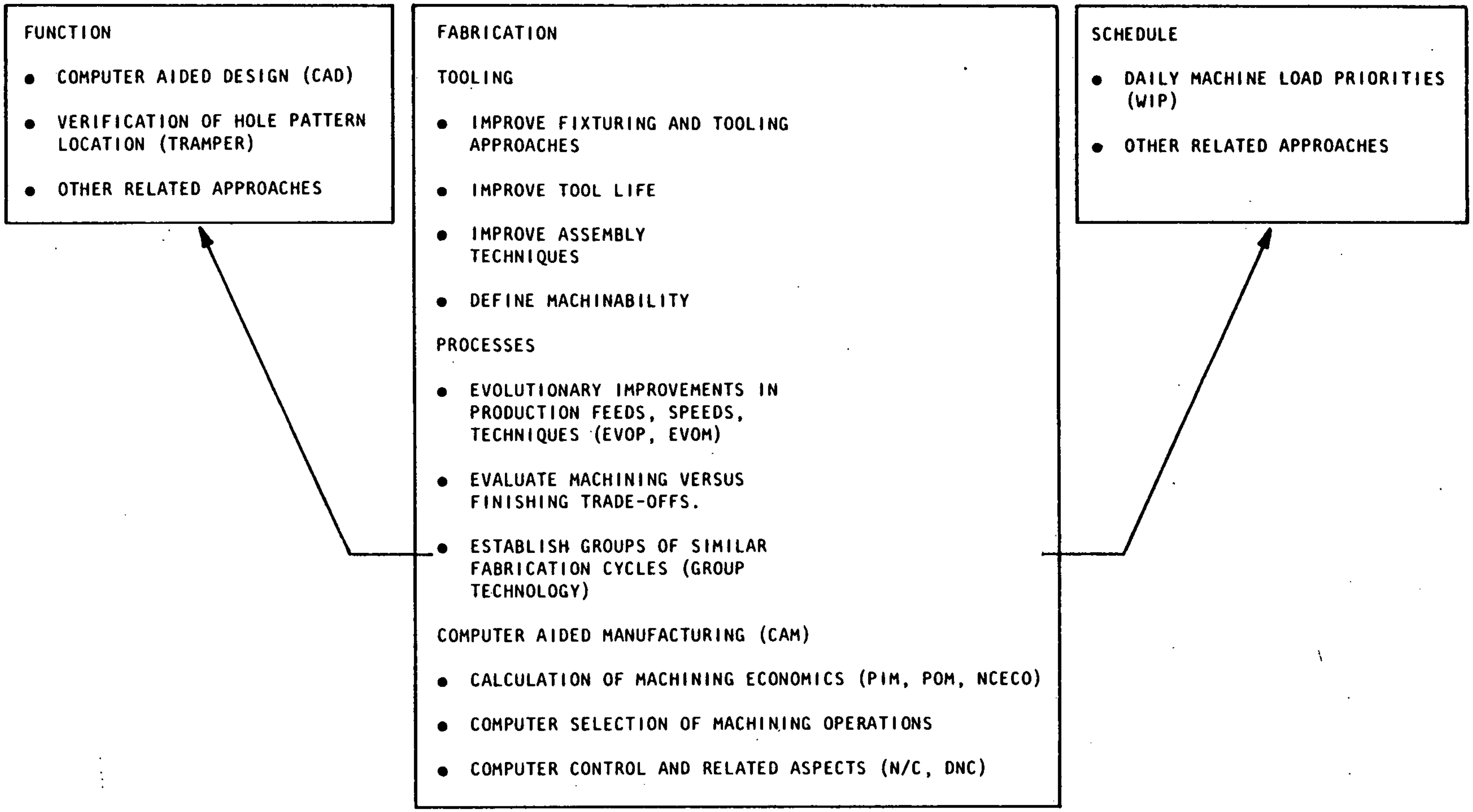


Figure 29. Approaches to Economic Optimization

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. The introduction of micrograin carbide material is one cutting tool advancement which has benefitted small screw machine parts. 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,[10] 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.

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 from testing and the need for special test samples. However, in a few situations, optimizing <u>single</u> operations can result in <u>higher total</u> 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 operations are involved.

While improving cutting tool life and geometry may help optimize machining economics on precision parts, on many precision parts, fabrication can best be optimized by improving fixturing, handling, and assembly techniques. As noted recently,[29] "The average work-piece in a batch-type production shop spends only 5 percent of its time in producing machines, and productive work is being done on the part only 30 percent of this actual time in the machines."

For this reason, such optimization approaches as group technology and direct numerical control provide significant potential for the future. Also, the use of computer-aided tool design will help in the reduction of design time, flow times, and process prove-in time. Bendix has implemented each of these concepts in the precision miniature fabrication area.

## Assembly Techniques

The assembly of precision miniature components is a tedious task requiring skill, clean room facilities and approaches, the use of microscopes, and special handling considerations. These factors if not adequately controlled result in fatigue problems or loss of precision or efficiency. This study was devoted to the development and evaluation of a clean-bench work station for the efficient assembly of miniature parts and comfort of the operator and the evaluation of new hand tools for the assembly operations.

## Introduction

Miniaturization affects assembly operations in the same manner as machining operations. A number of considerations must be made:

- The operator must be able to pick up and handle small, delicate parts without breakage or damage;
- He must accurately locate, hold, or fasten parts in an assembly;
- The operator must be provided with a sharply defined view of the assembly at all times; and
- A high level of physical comfort for the operator must be maintained for long periods of time.

To meet these requirements, an adjustable table clean bench was designed and evaluated on a prototype mockup. In addition, a large number of new tools and equipment were evaluated for the assembly of miniature mechanisms.

A number of tools were found to offer advantages in the specific types of applications described.

- Magnetic tweezers can be used for ferrous parts that are difficult to pick up or are too delicate to handle by other methods.
- Four-prong tweezers are useful for handling odd-shaped parts and bearings.
- Electronic tweezers provide a reverse action; they open when squeezed. Their gripping action can be adjusted to limit the pressure applied to delicate parts and they can be modified to provide positive holding (eliminate slipping out).
- Vacuum tweezers can be used to handle parts that are fragile, nonmagnetic, or difficult to pick up.
- Hemostats are useful for maintaining a grip on a part in instances where the tool must be manipulated extensively during the assembly operation.
- Inspection mirrors, having a diameter of 0.375 in. (9.5 mm), can provide increased visibility when the interior of an assembly is viewed.

In addition to the evaluation of purchased tools, a vacuum screwdriver was constructed which was effective in handling miniature screws. This device was too large to use under a microscope, however.

A long-working-distance, operating room microscope was evaluated for assembly work and was found to be noticeably superior to conventional bench microscopes. This long objective microscope provides significantly greater depths of field than less expensive scopes and it allows for coaxial or nearly coaxial lighting which improves vision in many situations.

## Swaging and Staking

Because of impact pressure and punch size, many mechanical staking, or riveting, methods are impractical on miniature assemblies. Areas to be staked or swaged may be inaccessible to conventional punch design because of part size, material, and design, and the use of such punches may also damage the parts involved (ceramic or plastic parts for example). The orbital riveting process with its low tool pressures and lack of impact was investigated in this study to determine if the process would work on critical miniature electro-mechanical assembly work.

### Introduction

The orbital riveting process roll-forms the rivet or pin into the desired shape by constant pressure of the tool point. A rotating punch, held at a 4-degree angle to the vertical axis and mounted in a vertical rotating spindle, is brought to bear on the part. During the forming cycle, the tool spins around the radius of the part being headed. Only a small protion of the part is contacted at any time by the punch. Consequently, less pressure is required to form the rivet head, and distortion of the rivet's grain structure is minimized.

Four rivet joint configurations with diameters of 0.060 in. (1.5 mm) or less and five materials, typically found in miniature assemblies, were made into samples and assembled on an existing machine. Pull tests then determined the holding ability of each. The results showed orbital headform riveting to be a useful method for many applications in miniature mechanisms assembly.

### Results

The orbital headforming machine was found capable of producing good staking results on pins of 0.060 in. diameter (1.5 mm) or less. The following observations were made.

- The quality of the staked joint depends on using a tool tip with a good surface finish and edges with a smooth radius.

- The best staking is obtained when the time control is the limiting factor ending the machine cycle. The machine had three separate limit controls of the staking operation. A dial sets the extreme downward travel of the staking tool during the machine cycle; a control limited the tool pressure on the rivet and cut off the cycle if the limit was reached; and if neither the pressure or travel limit was exceeded, an adjustable time control cut off the machine cycle. The three controls and the compressed air line pressure to the machine were varied to provide the best stake for each sample configuration.

- Greater deterioration of the joint metal generally occurred on aluminum and brass than on the stainless steel samples.

During the staking process, fragments, slivers, splitting, and galling occurred to some extent on the samples. However, improved punch design would alleviate the particle and galling problem while a post-machining annealing to eliminate any work hardening occurring during machining would prevent split rivets.

Figures 30 and 31 highlight the swaged shapes studied and the strength of the resulting joint.

## Press Fit Small Pins

This study was conducted to determine whether interference-fit conditions produced by available manufacturing techniques would keep miniature pins from moving axially after their installation in mating collars. The amount of interference-fit, lubrication, pin press-in rate, outer diameter of collar, axial length of engagement between pin and collar, and different material combinations were evaluated.

### Introduction

If the general rule of maintaining an interference of 0.001 in. per in. (25.4 mm) of diameter were followed for small pins, a 0.020-inch-diameter (0.508 mm) pin would have only an interference of 0.00001 in. (0.508 μm) with its corresponding hole. This approaches the practical size-tolerance limit for making the pins and leaves no hole-size tolerance to maintain the correct interference conditions. Samples having interference-measurement intervals of several ten-thousandths inch, therfore, were tested to determine the effect of interference on the holding power between the mated parts and on the force required to press them together.

### Results

An equation was derived to define the holding power of a press-fit joint; however, poor sample quality due to limitations of available

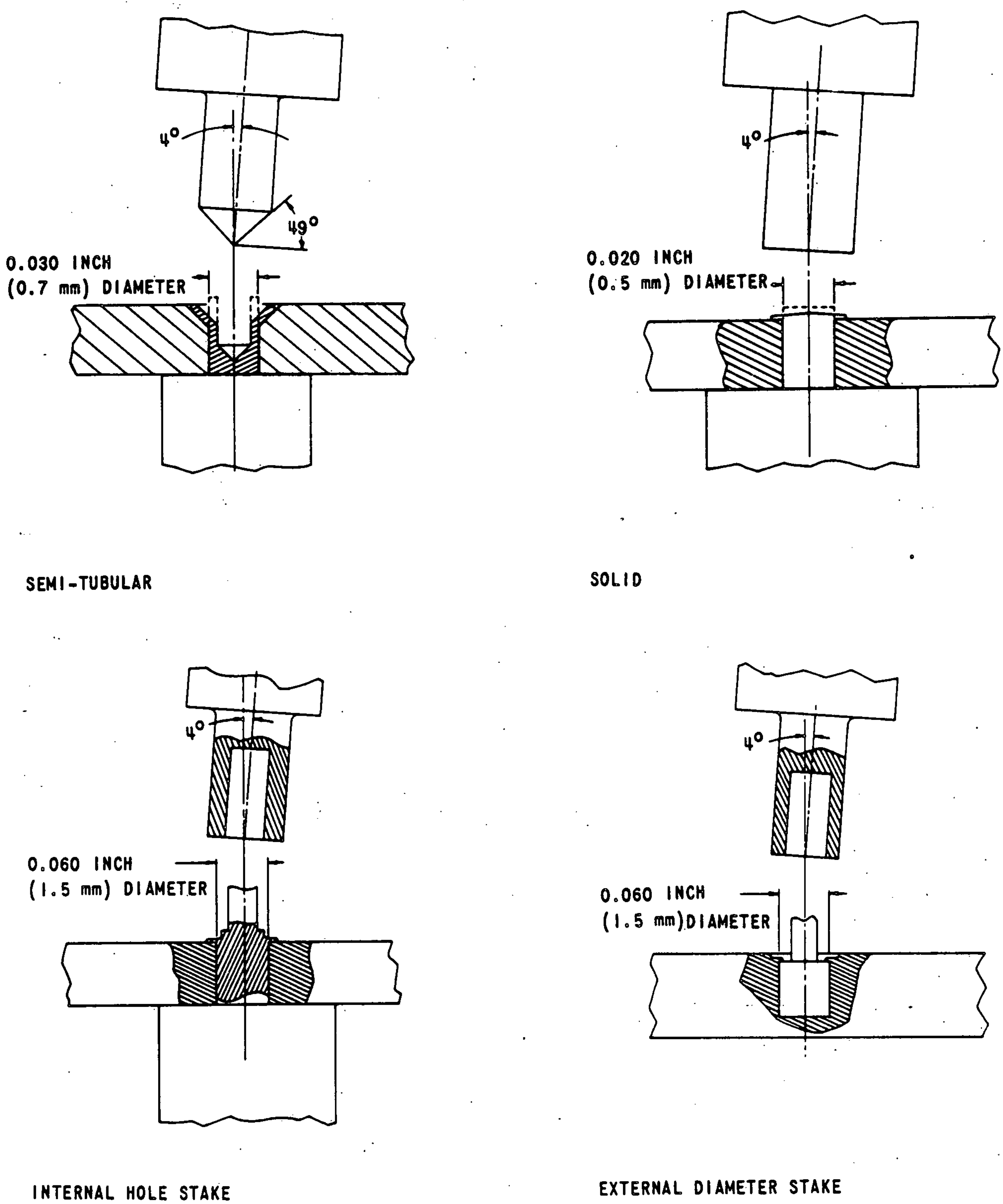


Figure 30. The Four Rivet Joints Used

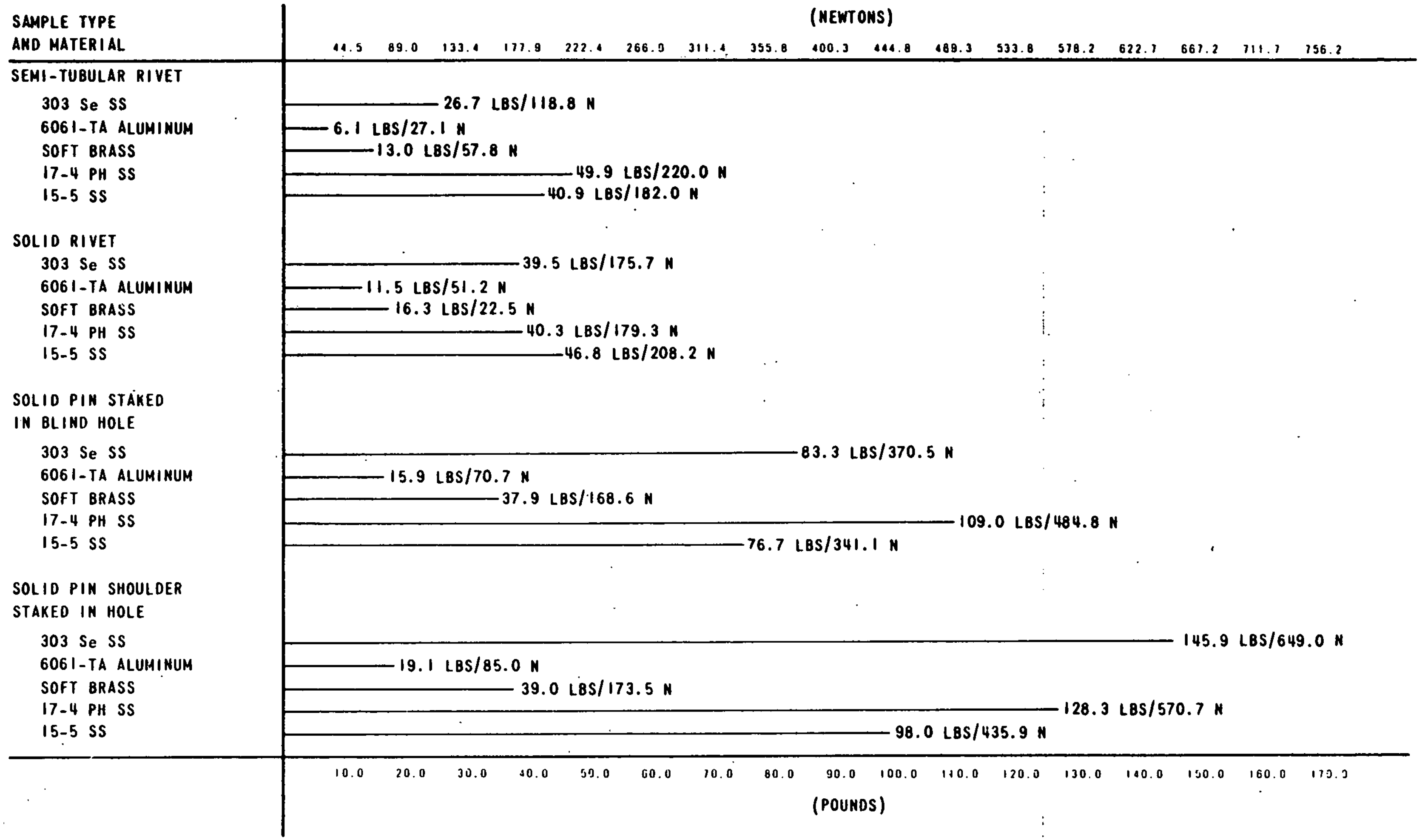


Figure 31. Pull Test Data

hole-measuring techniques caused considerable variation of the data from predicted results.[13] Rough surface finish and nonuniformity of inside collar diameter revealed a need for processing refinements.

The 0.020 in. (0.508 mm) pins were affected more by the surface finish and collar-size problems than were the 0.060 in. (1.52 mm) pins. This possibly was because diametral interference was the only significant variable which affected the press-in force and holding power of the joint. The 0.060 in. (1.5 mm) pins were affected by the depth to which the pin was pushed (length of engagement) and the outer diameter of the collar. The conclusion, therefore, was reached that the smaller the pin diameter, the more subject the joint is to hole-finish and size-uniformity conditions.

Neither the use of alcohol as a lubricant nor a variation of the press-in rate had a significant effect on the press-in force or the holding power of the sample joints.

Additional testing was performed with 0.031-inch-diameter (0.78 mm) samples in which the holes had been ball-broached to determine whether better surface finish and a more uniform hole size would improve the holding power. The results obtained were inconsistent and indicated that the hole size could not be measured accurately enough with available measuring equipment to maintain proper interference fit. The consensus was that a more accurate method of measuring small holes must be developed before any additional productive study of interference fit is possible.

When press-fit parts having diameters less than 0.060 in. (1.5 mm) are to be fabricated, the recommendation is made that such other pin-retention methods as staking, bonding, or welding be considered.

These results were based on the following material combinations:

- 420 annealed stainless steel pin in SAE K95100 heat-treated collar (materials of equal yield-strength),
- 303 Se annealed stainless steel pin in 7075-T6 aluminum collar (pin-to-collar yield strength approximately 1:2), and
- 17-4 PH stainless steel pin (Condition H-900) in 6061-T6 aluminum collar (pin-to-collar yield strength approximately 4.5:1).

Pin engagements of 0.020 to 0.100 in. (0.5 to 2.5 mm) were studied with press-in rates up to 20 inches per minute (8.5 mm/sec.). Interferences used ranged from 0.000 to 0.0007 in. (0 to 17.8 μm) and the outside diameter of the receiving collar varied from 1.2 to 4.0 times the pin size. To verify holding power, the pins were pushed out in the direction opposite to the push-in direction.

Approximately 60 percent of the 0.060-inch-diameter (1.52 mm) pins installed in aluminum collars shaved a ring of collar material out of the hole. Consequently, the actual interference of the joint was impossible to ascertain.

Figure 32 illustrates the effect lubrication, axial length of engagement, and outer collar diameter had on the push out force for 17-4 PH stainless steel pins in 6061-T6 aluminum.

## Miniature Screw Assembly

One perennial area of concern with miniature threaded fasteners is stripping of threads in a fully assembled unit. While some mathematical relationships have been derived for larger size fasteners, no published data was available to predict safe torque limits for the 0.6, 0.8, and 1.0 unified national miniature (UNM) screws commonly used in miniature electromechanical devices.

### Background

The experiment was established in the two-level factorial design form. The variables studied were head style (pan head or fillister); length of thread engagement (twice the diameters of 2/3 diameter); lubrication (standard or silver-plated screw); and tap drill size (oversize or standard--oversize on two diameters deep holes only.

The oversize tap drill was tested because of the better yield obtainable by tapping into an oversize hole, resulting in less tap breakage. It was desired to learn if the partial threads obtained had any significant effect on joint strength.

All screws were made from 303 Se stainless steel. The five materials most commonly found in miniature mechanisms were selected for the internal threads:

- Annealed 302 stainless steel;
- T6510 7075 aluminum;
- H-900 17-4 PH stainless steel;
- Beryllium copper; and
- SAE K95100 armature steel.

### Results

An analysis of variance of the test results indicated that for the conditions studied only screw size affected failure torque values.[14] To provide safe torque limits, a curve and equation was established

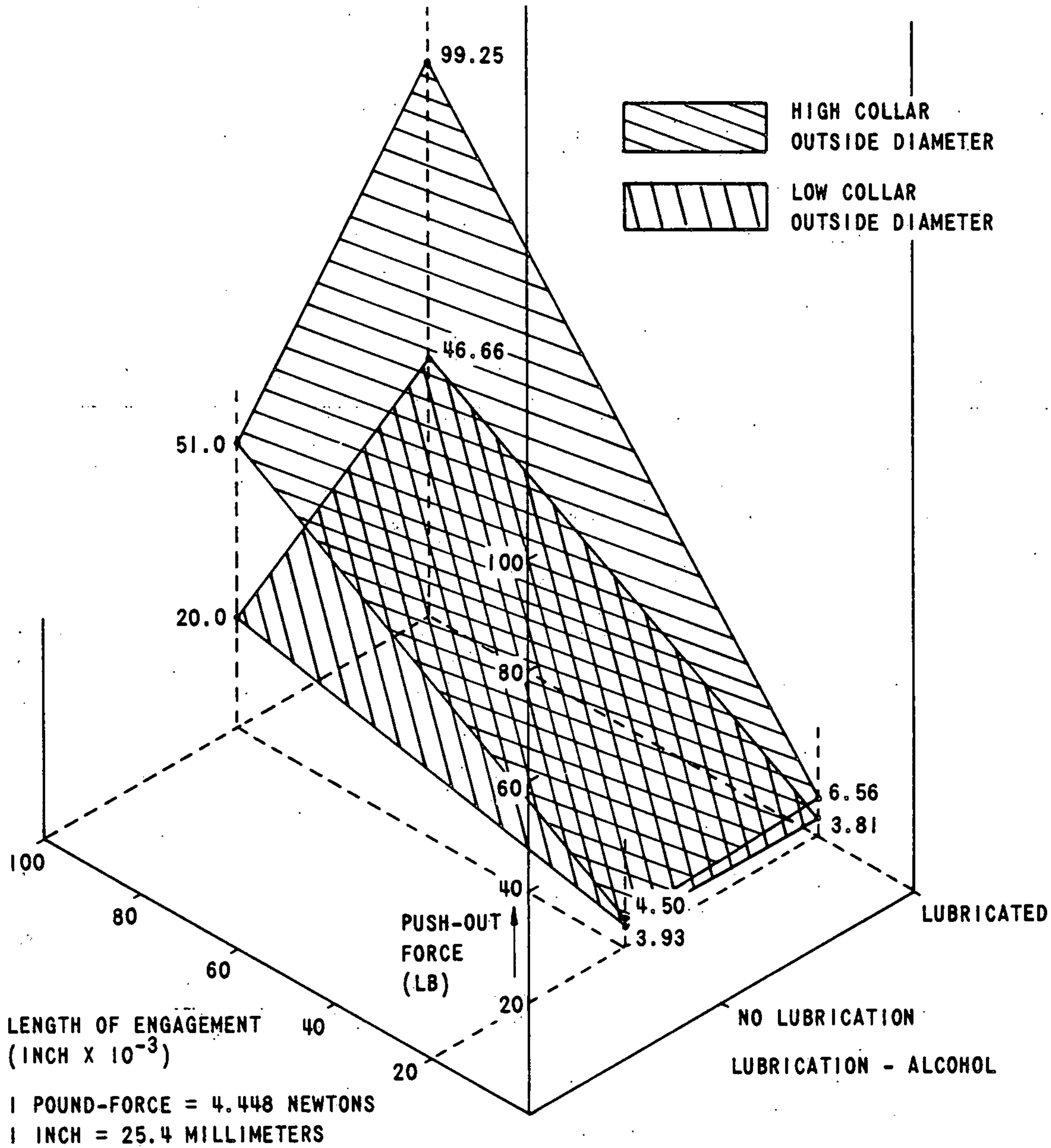


Figure 32. Comparison of Variable for High and Low Collar Outside Diameter, 0.060 in. (0.15 mm) Pin, Push-Out Force

based on allowing half the torque which caused thread or screw failure (Figure 33). In addition it was found that screws could be torqued to the recommended value, removed, and reinstalled with the same torque without galling or thread damage.

Friction Reduction

Electromechanical devices must continue to be reliable after extended storage and after exposure to extreme temperatures and atmospheric conditions. Bonded dry films are one of the few lubricants that can be used under such conditions: oils and conventional fluids are unsatisfactory because they can evaporate (perhaps creating friction-caused malfunctions) or migrate to electrical contacts (creating high contact resistances). Available dry powder lubricants are unsatisfactory because they also have a propensity to migrate.

The mechanisms' tolerances and clearances require that bonded film lubricants be applied in thin films of 0.0002 to 0.0005 in. (5.08 to 12.7 μm) and exhibit a low friction coefficient both at the light loads of ambient environments and the higher load of high-g environments.

In this study, ten commercially available, bonded dry-film lubricants were evaluated for use. A tribometer utilizing the oscillating-bar concept was developed to determine the friction coefficients of lightly loaded samples (as low as 5 gram loads) by several methods. Interaction among friction-influencing variables was investigated, mean and standard deviations were calculated for comparison, and wear characteristics of the lubricants were determined.

The following lubricants were studied:

- Product A--An organic, thermosetting, resin-bonded solid film lubricant consisting of approximately 90 percent molybdenum disulfide ($MoS_2$) and 10 percent graphite, by weight, and cured at 350° to 375°F (176° to 191°C) in one hour. This is the most frequently used lubricant at Bendix when the high cure-temperature is permissible.

- Product B--A thermosetting, resin-bonded solid film lubricant of the type described in Mil-L-8937. It cures at 300°F (148°C) in one hour and is from 0.0002 to 0.0005 in. (5.08 to 12.7 μm) in thickness.

- Product C--A solid film with lubricant solids of 100 percent $MoS_2$ in a resin binder that cures at 375°F (191°C) in one hour. The typical thickness is from 0.0002 to 0.005 in. (5.08 to 127.0 μm).

- Product D--A solid film lubricant made from a combination of lubricating pigments, a low-tempeature thermosetting resin and $MoS_2$. Its typical thickness is from 0.0002 to 0.0005 in.

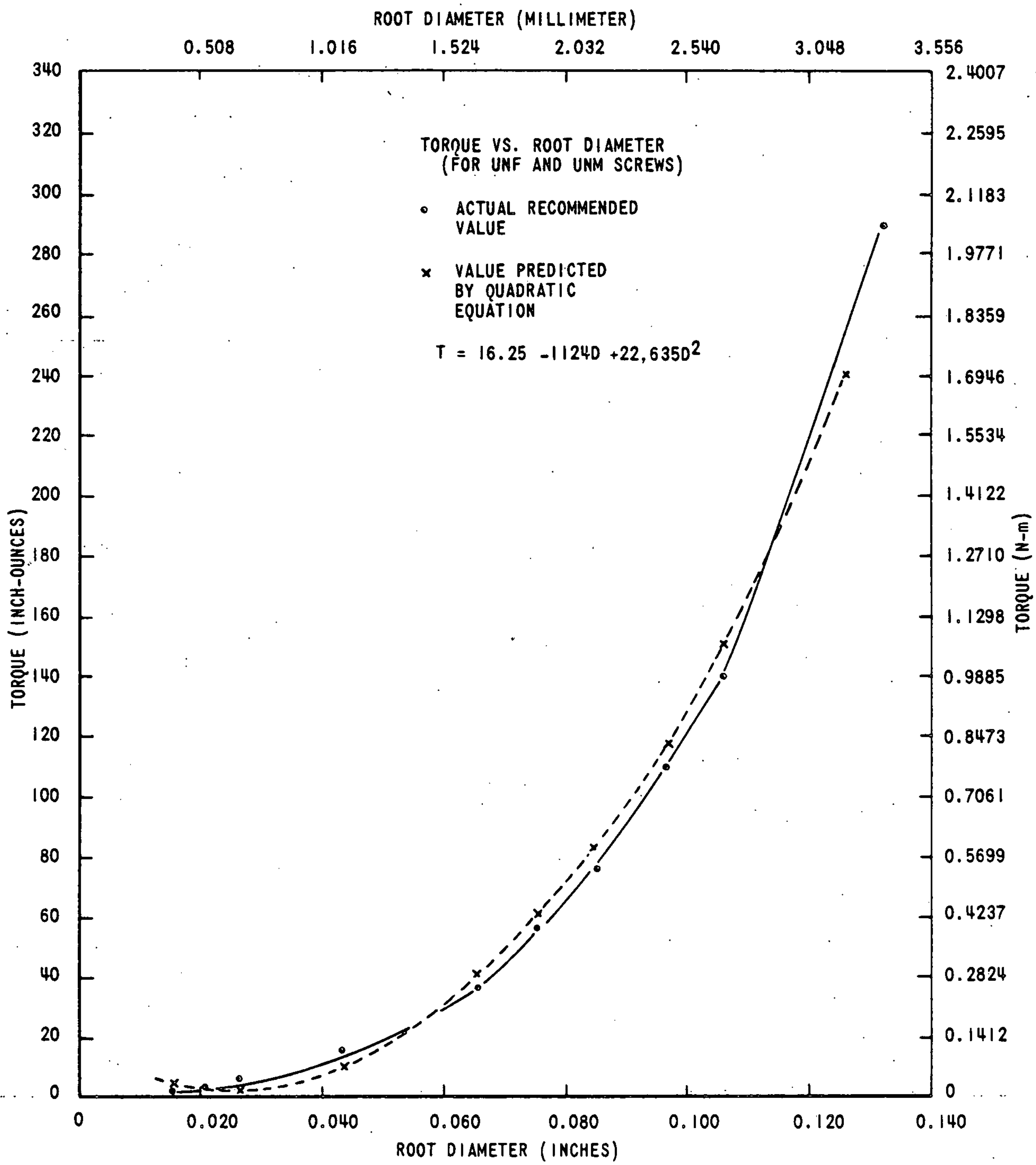


Figure 33. Plot of Screw Root Diameter Versus Recommended Torque Value Compared to Quadratic Equation Curve

- Product E--A resin-bonded solid lubricant of $MoS_2$ and graphite that cures at 250°F (121°C). The typical thickness is from 0.0002 to 0.0005 in. (0.005 to 0.0127 mm).

- Product F--A new, bonded, solid-film lubricant of $MoS_2$ and antimony oxide ($Sb_2O_3$) in a silicone binder that cures at 480°F (248°C) in 0.5 hour, or 24 hours in air.

- Product G--A new, bonded, solid lubricant using new high-adhesion thermosetting resins that cure at 375°F (191°C) in one hour, new micron-size solid lubricants, new milling techniques, and new plasticizers and solvents.

- Product H--A formula consisting of 77 percent $MoS_2$, 5 percent graphite, and 18 percent sodium silicate binder.

- Product I--A formula of 37 percent $MoS_2$, 30 percent $Sb_2O_3$, and 30 percent polyimide binder.

- Product J--A formula with a lubricant-to-binder ratio of 10 parts $MoS_2$, 1 part graphite, 3 parts bismuth, and 7 parts sodium silicate binder.

Five methods of friction measurement were used in this study:

- Oscillating mode with sliding friction;

- Stationary mode with sliding friction (dynamic force gage method);

- Tilt mode with sliding friction (tilt method);

- Stationary mode, static friction (static force gage method); and

- Tilt mode, static friction.

The following friction influencing variables were evaluated for the better lubricants: substrate (material under film) finish, substrate hardness, film burnishing, and mating-part finish and hardness. Sets of 303 and 440C stainless steel hardened to $R_C$ 60 and 6061-T6 aluminum tester rollers were used. One set of the test rollers had a 4 $\mu$in. (101 nm) AA finish, and the other set had a 30 $\mu$in. (762 nm) AA finish. Test bars each of hardened steel, unhardened steel, hardened aluminum, and unhardened aluminum were vapor-blasted, half with 500-grit abrasive and the other half with 220-grit abrasive, before the lubricant was applied.

In general, the different methods of measuring the friction coefficient (force gage, tilt, and oscillation) yielded different overall average values of the friction coefficient. The results of the experiments also showed that different variables affect the friction coefficient differently from experiment to experiment. An exception to this is roller finish, which is a significant factor in each dynamic friction experiment, with the 30 AA finish yielding a significantly lower friction coefficient than the 4 AA finish. However, roller finish was not a significant factor in any of the static friction experiments.

The results of the factorial design experiment showed that the interaction of the variables is very complex; an average coefficient cannot be accurately predicted for any friction system. The experiment did reveal, however, that a surface finish of 30 $\mu$in. AA results in lower dynamic friction coefficients than a 4 $\mu$in. AA finish for both 303 stainless steel, Condition B, and 440C stainless steel, $R_C$ 55 to 64.

The following general observations were made using Product A which proved to be one of the two lowest friction materials. Product G performed best in many tests.

- The friction coefficient is not significantly affected by polishing.
- Sliding velocity had little effect on the friction coefficient (for the range studied).
- The friction coefficient decreased as the load increased.
- Compacting the lubricant had no effect on its friction coefficient.
- Static coefficients of friction ranged from 0.109 to 0.240 and dynamic friction coefficients ranged from 0.178 to 0.220.

Complete details of this study are presented in references 17, 18, and 19.

## ACCOMPLISHMENTS

This project documented the capabilities and limitations of 25 different aspects of manufacturing miniature parts. It explored the machinability and moldability of several new materials. It resulted in the development of some new instruments and equipment. In addition to providing quantitative information on various capabilities, it provided information on trade-offs in the design or manufacture of precision miniature parts. In a more general sense, the development also defined why precision miniature parts are often difficult to fabricate, inspect, and assemble.

FUTURE WORK

The original objectives of this project have been met, but the tests and seven years of fabrication experience on these extremely demanding parts have highlighted several additional areas which need to be explored. Among these are verifying surface finish on miniature shoulders, diameters and in holes; continuing efforts on tapping precision miniature threads and drilling miniature holes, fixturing and handling miniature parts, assembling parts and joining requirements for welding and staking. Friction reduction, contact loop resistance reduction, and burr removal are still problem areas requiring additional study for many situations.

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BDX-613-2388

FABRICATION FOR PRECISION MECHANISMS, L. K. Gillespie, Final, March 1980.

Miniature precision actuators, timers, and switches present a variety of manufacturing challenges due to part minuteness and the combination of miniaturization and precision. The study explored 25 manufacturing problem areas associated with these miniature mechanisms. Topics included small hole drilling and tapping, machinability of various materials used in miniature assemblies, press fit tolerances, swaging, fixturing and handling, and friction reduction. Plastics, ceramics, and metals were studied. Each of the 25 topics is summarized.

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MECHANICAL: Small Mechanisms

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