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Precision Deburring Using NC and Robot Equipment

By L. K. Gillespie

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**Kansas City
Division**

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ROBOT EQUIPMENT

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Final Report
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Deburring precision miniature components is often time consuming and inconsistent. Although robots are available for deburring parts, they are not precise enough for precision miniature parts. Numerical control (NC) machining can provide edge break consistencies to meet requirements such as a 76.2- μm maximum edge break (chamfer). Although NC machining has a number of technical limitations which prohibits its use on many geometries, it can be an effective approach to features that are particularly difficult to deburr.

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SUMMARY

The components of miniature precision mechanisms typically require burr-free, nearly sharp edges to assure their dependable operation. In the past, the reliable removal of machining burrs and the assurance of part-edge sharpness have dictated that deburring be performed only by hand. This method, however, is time consuming and inconsistent.

Robots are being used for deburring in some companies, and numerical controlled (NC) machining centers have many of the same characteristics as robots. This study analyzed the capabilities and limitations of both robots and NC machining centers for providing precision deburring on precision miniature components.

At present, robot accuracy is only $\pm 203.2 \mu\text{m}$ although one new robot appears to have a repeatability of $\pm 50.8 \mu\text{m}$. In contrast, NC equipment can maintain accuracies of $\pm 2.54 \mu\text{m}$ on many geometries. NC machining equipment has a number of limitations which prevents its widespread use for deburring.

- They depend upon a preprogrammed cutter path.
- Part edges may fluctuate to the extent that preprogrammed cutter paths will not contact the edge.
- Some edges produced by a two axis machine can only be deburred by a four or five axis machine.
- Chamfering or deburring on NC machines produces typically smaller burrs than existing ones.
- Available spindle speeds are far below the most efficient cutting speeds for miniature deburring tools (3,000 versus 150,000 rpm).
- Tools appropriate for NC use often have useful lives of only a few minutes.

Despite these limitations, NC deburring can be effective for many situations, particularly those requiring edge breaks smaller than $76.2 \mu\text{m}$. NC deburring has been implemented on production parts at Bendix Kansas City. Some basic economics of NC versus hand deburring are presented.

DISCUSSION

SCOPE AND PURPOSE

This project was initiated to determine the technical and economic capabilities of NC and related robot equipment for deburring precision miniature parts.

PRIOR WORK

Six previous deburring studies have been conducted at Bendix Kansas City.¹⁻⁷⁴ In-depth research studies have been reported on seven deburring processes: vibratory deburring, centrifugal barrel tumbling, brush deburring, extrude hone deburring, hand deburring, thermal shock deburring (now known as thermal energy method, or TEM), and mechanical deburring of plastics. A current study is exploring electrochemical and electropolish deburring.

ACTIVITY

Removing burrs on many precision miniature parts is both time consuming and subject to wide variances in quality. Because deburring is entirely worker dependent, long queues often occur that greatly affect flow time. Because of thin walls, precision tolerances, fine finishes, or part geometry, many parts cannot be deburred in conventional mass finishing (such as tumbling or vibratory processes).

The only suitable deburring approach on many of these parts is to use a tool to cut off burrs. Hand deburring accomplishes this but is subject to many variables and has a relatively low efficiency. By mechanizing the process one should be able to achieve near 100 percent efficiencies, provide a guarantee that all edges have been worked on, and ensure a uniform edge break.

This project explored five aspects of mechanically deburring precision miniature parts:

- Evaluating commercially available mechanical deburring equipment in detail;
- Evaluating robot devices now available;
- Evaluating wear characteristics of mechanical cutting tools;
- Using NC milling machines as dedicated deburring machines; and

- Using the NC machine which produces parts to mechanically cut off burrs at the end of the machining cycle.

Deburring Characteristics of Precision Miniature Parts

Figures 1 through 7 illustrate a variety of miniature and small parts which have some unique deburring constraints. Figures 1 and 2 illustrate parts which are small, have thin sections, and have areas that are hard to reach. In Figure 1, for example, it is necessary to reach inside the slot to deburr the holes. The holes here are large enough to easily remove the large burr.

Most tools used to remove the large burr, however, leave a small burr which is similarly difficult to remove in a hard-to-reach area. The part in Figure 1 has the added distinction of requiring only 15 minutes to fabricate from a round slug when produced on an NC mill with automatic tool changers. The deburring time, which is by hand in order not to bend the thin flanges, takes 15 minutes a part.

While conventional mass finishing operations such as centrifugal-barrel finishing can remove many of the burrs left on this particular part, many burrs are left in other areas. Complete deburring requires that one does not affect the part dimensions by removing material, distorting it, scratching precision surface finishes, or exceeding allowable edge chamfers or breaks. If the burr is too large, mass finishing processes cannot remove it without also exceeding minimum edge break requirements. A close look at piece parts and deburring processes reveals the following:

- The burr size and location determine the deburring process parameters;
- The burr size and location determine the final edge break (for many processes);
- Almost all deburring processes affect surfaces as well as edges;
- Almost all deburring processes affect dimensions;
- Almost all deburring processes interact with the workpiece material;
- Burrs vary considerably on a single edge;
- Burrs vary considerably among edges; and
- Burrs vary considerably among parts.

In addition to removing burrs and radiusing edges, the deburring processes can:

Figure 1. Typical Miniature Part Made on NC Machine

Figure 2. Miniature Part With Hard to Reach Areas

- Change workpiece dimensions and surface finishes;
- Distort the workpiece and alter its residual stresses;

Figure 3. Aluminum Double Cam
Produced on NC
Machine

Figure 4. Miniature Solenoid
Housing

Figure 5. Miniature Part With Small Slots

Figure 6. Intricate Housing
Made on NC Machine

Figure 7. Housing With 136 Edges

- Reduce the elastic limit of the workpiece;
- Increase the fatigue strength of the workpiece;
- Change the color or luster of the workpiece;

- Impregnate material into the workpiece;
- Contaminate workpiece surfaces;
- Both reduce and increase corrosion resistance; and
- Increase electrical resistivity.

These effects, could cause several results:

- Reduce tool life;
- Impede surface finishing;
- Prevent solder and braze adhesion;
- Cause blow holes in welds;
- Burn foreign elements onto the surface in heat treatment;
- Help or hinder passivation;
- Prevent electroplates from adhering; and
- Cause "fish eye" or poor paint adhesion.

This is not to imply that the mass finishing process cannot provide the deburring required, but every part must be considered thoroughly. In some cases, hand deburring should be used so that urgently needed parts are not lost.

Figure 2 illustrates a part with features and constraints similar to that shown in Figure 1. Figure 3 illustrates yet another part that has a wide variety of surfaces, each requiring close edge breaks. In Figures 1 and 2, the parts shown were stainless steel, which is difficult to deburr because the burrs are large and hard to remove. On the part in Figure 3, the aluminum is so soft that many processes will provide too much edge break very quickly or result in scarred or scratched surfaces.

Figure 4 illustrates a relatively small housing with a number of precision dimensions. It has 175 edges and a number of holes smaller than 1.0 mm in diameter. In this case, scratching internal surfaces while trying to deburr these holes or edges could result in parts being scrapped. This part is made of a magnetic alloy of 49 percent iron and 49 percent cobalt. It is brittle enough that, if dropped on the floor in the wrong orientation, one of the small legs will break off. Legs can be bent and cracked easily, which also accounts for part scrappage. Also, because the part contains large quantities of iron, it can

rust easily, and many processes cannot be used because the surfaces need to be kept free of particles and rust.

Figure 5 illustrates a simple stainless steel part, whose cutouts are hard to reach with conventional mass finishing.

The pie-shaped slots around the contours have been produced by electrical discharge machining, which leaves small, hard to reach spherical particles on the edges.

Figure 6 illustrates a small part with 186 edges to deburr, many involving small slots, slots intersecting holes, and other difficult to reach areas. This part is difficult to deburr by hand because of the small edge breaks and inaccessible edges.

Figure 7 illustrates a part with 136 different edges, some with tight tolerances on edge breaks and others with requirements for only 0.25-mm maximum edge breaks. The eight small 0-80 threads entering corners on this part are very hard to reach. On many other edges, small edge breaks or the combination of small edge breaks of very thin and easily distorted edges make it difficult to use conventional processes.

Consider a simple, flat, watch-like gear as an example of the problem of having too many edges in a small area. Each gear tooth has 10 distinct line or arc segments (Figure 8). A 20-tooth miniature gear would have 200 edges which, for many applications, must be burr free. Both the number of edges and the lineal quantity of the edge affect deburring quality and cost. Problems in deburring gears, though outside the scope of this report, can be compared for their similarity to problems in deburring many other precision miniature components.

Each of the parts in Figures 1 through 8 presents its own problems in deburring. In some cases, deburring requires over 2 hours per part. In others, deburring may require only 15 minutes a part, which is excessive when large quantities are involved. The question of whether machines that produce parts on NC equipment can also deburr them needs to be explored.

Observations on Commercially Available Mechanical Deburring Equipment

Almost 50 manufacturers sell equipment designed to mechanically remove burrs. The following are types of mechanical deburring:

- Cutting with a rotary cutter,
- Grinding with a small wheel,
- Honing with a small reciprocating machine,

Figure 8. Gear Edges

- Rolling burr back into parent metal,
- Trimming off excess material with dies,
- Sanding, and
- Brushing.

These techniques of mechanical deburring combine to form several types of mechanized mechanical deburring machines:

- Sheet metal edgers,
- Tube and bar end finishing machines,
- General purpose part edgers,
- Gear deburring machines,
- Cutting tool hones,
- Special design, single purpose units,
- Sanders,
- Brushing Units,
- Trimming Presses, and
- Robots.

Each machine is generally limited to a specific product.

Sheet metal edgers, as the name implies, are used to remove burrs and sharp edges from flat metal sheets. Tube and bar end finishing machines are dedicated to deburring the ends of either bars or hollow tubes. Gear deburring machines generally handle gears or closely allied configurations, and cutting tool hones deburr the edges of cutting tools. General purpose part edgers deburr sheet metal or bar stock material rather than piece parts. Trimming presses also deburr sheet metal parts (generally those drawn in cup-like shapes).

The remaining tools, which are special design, single purpose machines like sanders, brushing units, and robots, all work with piece parts.

The versatility of some of these machines can best be exemplified by the gear deburring machines. As shown in Figures 9 and 10, these machines can readily sculpture the edges of large gears very satisfactorily. The typical cycle time is 1 minute per side, even for gears above 76 mm in diameter. The advantage of the gear deburring machines is that they can readily accommodate a wide variety of sizes within the same basic family of parts. The second advantage is that these machines can use a variety of deburring tools, in addition to the cutters and grinding wheels shown in Figures 9 and 10. Brushes and soft rubber points could also be used if necessary. The gear deburring machine, however, has its limitations.

First, the commercially available equipment is all significantly larger than the typical parts produced in the miniature machining

Figure 9. Deburring Top and Bottom of a Gear in a Single Operation

Figure 10. Milling Away Burrs and Chamfering Edges on a Gear Deburring Machine

area. In many cases, the smallest gear that can be finished is 76.2 mm in diameter.

The second limitation is that these machines (in fact almost all deburring machines) require edges that are readily accessible. It is possible on larger parts to reach into relatively inaccessible areas by special setups. On miniature parts, however, one is limited by the size of tools available to perform the deburring, as well as the geometry of the parts.

The third limitation is that, in almost every case, the cutters are on a cantilever arm that is difficult to control accurately. Primarily, these machines are designed to produce from a 0.25 to a 1.58-mm edge break on parts. None of the machines is designed to hold tolerances such as a 76.2- μ m maximum edge break.

The fourth limitation of gear deburring machines is that they are designed to produce moderate to high quantities of the same types of shapes. They can accommodate lots as small as 100 parts, but the setup times can be long.

These machines cannot deburr a wide variety of edge conditions or edge geometry. As seen in Figures 9 and 10, the majority of these machines are designed to rotate the part around a specific center line. If parts do not have a rotational center line, then additional setup is required to provide a pseudo-center line.

As indicated in Figure 10, it is possible to combine a milling operation with chamfering for heavy burrs. Also, small brushes can be combined with a small grinding wheel to perform the edge finishing. With a tracer, or tracer-like attachment, one can handle the nonsymmetrical parts, provided the brushes and tools fit within the workpiece.

Many gears, particularly those used for the watch industry, are deburred on the gear hobbing machine to eliminate a second operation. Small watch pinions are deburred by automatically holding a lathe tool against the hob exit side of a part.

Rotary deburring attachments are even more commonplace on large parts (Figure 11). As the tool rotates, it shears off the burr. When the part is completely hobbled, it is also free of large burrs. Some machines retract the burr cutting tool several rotations before the end of a hobbing cycle. This allows the hob to remove remaining burrs pushed between the teeth by the skiving tool. A combination of hydraulic tool feed and spring loading maintains tool contact. Rotating milling cutters are used on larger pinions.

The problem with skiving 303 stainless steel miniature parts (particularly gears) is that the cutting or skiving forces are large enough to rotate or bend the part out of the normal rotational path. This rotation produces inaccurate gears, which may not be a problem on 416 stainless steels or other materials where the burrs are not as thick and tough as 303 stainless steel. This technique of deburring while machining is also being employed as a partial method for deburring on the NC machine cycle.

Theoretically, a general purpose machine like the gear deburring machine could be designed to finish the edges of miniature parts. But the problem of maintaining edge breaks no greater than $76.2\text{ }\mu\text{m}$ remains.

State of the Art of Robotic Devices

Most industrial robots can deburr large parts, and some have been programmed to do so. On some machines it is possible to insert a

PHOTOGRAPH COURTESY OF
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HOB HANDBOOK

Figure 11. Deburring Gears
While They Are
Being Hobbed

live spindle in the "hands" of a robot, and then, using a rotating bur tool, to chamfer all edges of a part (Figure 12). Some units can be programmed by manually leading them through a desired path the first time.

One major advantage of programming robots for deburring is that those robots with programmable memories can be easily adapted to other tasks. In addition, they can work in any environment. Also, being automated, they don't overlook areas that require deburring.

In addition, these machines can easily rotate tools to duplicate hand motions. Their one big advantage is that they can quickly provide almost any desired relationship between tool and part (Figure 13).

One limitation with robot application is the high cost, which ranges from \$10,000 to \$80,000. Another limitation is that while some can maintain large chamfers, none can maintain small radii such as a 76.2 μm maximum chamfer. Most robots are not designed to produce this precision.

The major limitation on the use of existing robots for deburring is their relative inaccuracy. At the present time, the most accurate positioning quoted by any known manufacturer of robots is $\pm 203.2 \mu\text{m}$.⁷⁶ This limitation has been confirmed in discussions with several manufacturers of robots. The majority of these robots are considerably less repeatable, although one yet to be marketed robot apparently has a repeatability of $\pm 50.8 \mu\text{m}$.⁷⁷

Figure 12. Robotic Arm With Live Spindle for Deburring

This limitation alone prohibits existing robot machines from use on precision miniature components. It should be noted, however, that technology is available to produce micromotion as well as gross movement. Thus, the technology is inherently present to provide precision movements. While that technology exists, it would appear that producing a machine capable of providing the necessary requirements for precision edge breaks would cost around \$250,000. At present, industrial robots are mainly used for trimming the flash, gates, and runners from large molded parts and for deburring large machined castings.^{75, 78}

Mechanical Cutters for Deburring

Bendix Kansas City uses most of the 19 types of deburring tools used commercially for hand-deburring or mechanical cutting and the majority of the 59 hand deburring subcategories. Table 1 lists these conventional chip-producing cutting tools such as knives, files, and rotary burs, as well as the abrasive or polishing tools such as abrasive-filled rubber products, hand-held stones, felt bobs, lapping compounds, and related items.

Figure 13. Motions Available on One Industrial Robot

Using mechanical cutting tools for deburring precision miniature parts has several constraints:

- Commercially available sizes (often too large),
- Aggressiveness of tools,
- Consistency of tools (repeatable performance),
- Tool wear,
- Workpiece hardness,
- Consistent burr location,
- Concentrating cutting at edges, and
- Maintaining maximum edge breaks of $76.2\ \mu\text{m}$.

Deburring results are controlled by the hardness of the workpiece and other workpiece characteristics such as the location of the burr. If the burr is not located consistently, then preprogrammed cutting will not provide the desired results. One of the major limitations of many of these cutters is that they are generating surfaces rather than concentrating cutting on the edges. Conventional and NC machining typically generate surfaces and allow edges to occur where they may. For mechanized deburring, it is necessary to know where edges are and provide consistent contact with those edges without exceeding the allowable edge breaks.

Table 1. Categories of Deburring Tools Used at Bendix

Tools	Used In Hand Deburring	Used In Machine Deburring	Used In This Study
Knives			
Triangular	X	-	-
Oval	X	-	-
Special Shapes	X	-	-
Scalpel Blades	X	-	-
Files			
Large	X	X	-
Miniature	X	X	-
Round (rattail)	X	X	-
Half Round	X	X	-
Triangular	X	X	-
Curved or Bent	X	-	-
Bur Balls, Burs, Rotary Files			
Bur Balls	X	X	X
Burs	X	X	X
Rotary Files	X	X	X
Scrapers	X	-	-
Countersink Tools	X	X	X
Brushes			
Wheel	X	X	X
Cross Hole Deburring	X	X	-
End and Cup	X	X	X
Abrasive-Filled Rubber Products			
Bullets	X	X	X
Cylinders	X	X	-
Flat Bars	X	-	-
Discs	X	X	X
Cups	X	X	X
Dental Bullets	X	X	X

Table 1 Continued. Categories of Deburring Tools Used at Bendix

Tools	Used In Hand Deburring	Used In Machine Deburring	Used In This Study
Abrasive-Filled Cotton Products			
Cylinders	X	X	X
Balls	X	X	-
Bars	X	-	-
Abrasive-Filled Cork Products			
Ball Nose Cylinder	X	X	-
Bullet	X	X	-
Abrasive Paper Products			
Discs	X	X	-
Rolls	X	X	-
Sheets	X	-	-
Cord	X	-	-
Felt Bobs			
Discs	X	X	-
Bullets	X	X	-
Cylinders	X	X	-
Lapping Compounds			
	X	X	-
Mounted Points			
Balls	X	X	X
Discs	X	X	-
Cylinders	X	X	X
Cones	X	X	X
Special Shapes	X	X	-
Hand Stones			
Bars	X	-	-
Triangles	X	-	-
Cones	X	-	-
Points	X	-	-

Table 1 Continued. Categories of Deburring Tools Used at Bendix

Tools	Used In Hand Deburring	Used In Machine Deburring	Used In This Study
Mandrels for Tools	X	X	-
Pin Vises			
Dog Nose	X	-	-
Collet	X	-	-
Motorized Tools			
Bench Motors	X	-	-
Air Motors	X	X	-
Dental Tools	X	-	-
Jitterbug			
Sanders	X	-	-
Belt Sanders	X	X	-
Reciprocating Files	X	X	-
Miscellaneous Tools			
Swivel Blade Tools	X	-	-
Back Side Cutters	X	X	X
Special Design Tools	X	X	-
Vacuum Probes	X	-	-

Many of the dental service products can be successfully used on precision miniature parts. But sometimes even minute cutters are too large for very small features and places. Special design miniature tools have been fabricated for hand deburring, but they cost from \$50 to \$100 each. For this reason, the potential capabilities of commercially available miniature tools should be investigated. This study provides a framework of reference for comparing tool performances.

Numerical Control for Deburring

Table 2 compares NC with hand deburring. While any such data is relative, it is at least useful for focusing on potentials.

Table 2. Characteristics of NC Machines and Manual .
Deburring Capabilities

Variable	Capability	
	NC	Manual
Feedrate (mm/s)	128	51
Positioning Accuracy (μm)	± 1.3	-
Tool Change Time (s)	5.5	2
Absence or Downtime (percent of hours in work)	3	8*
Efficiency	100 percent	Varies

*Assume a total of 20 days per 240-day work year for vacation, sickness, personel business, etc.

NC equipment has the capability for very high continuous feed-rates. It can maintain these feedrates on every edge of every part all day long, three shifts a day and is essentially 100 percent efficient. Once set, NC equipment will run at the same speed until the setting is changed. In contrast, manual deburring capability is affected by outside factors and will not keep a constant pace.

NC machines for deburring precision parts at Bendix Kansas City have an accuracy of $\pm 1.27 \mu\text{m}$. Assessing hand deburring repeatability is difficult, but Figure 14 illustrates some capabilities of maintaining edge break tolerances by hand. It shows that hand deburring can maintain a $76.2\text{-}\mu\text{m}$ edge break for 92 percent of the edges. A few individuals can produce edge breaks as small as $25.4 \mu\text{m}$ on a number of parts. Existing capabilities, however, are edge breaks of $50.8 \mu\text{m}$ or smaller for 69 percent of the edges.

These quantitative capabilities are based on tests of simple cubes and cylinders with two or eight edges per part. The long deburring times required indicate that such edges could perhaps be produced faster on NC equipment. In many instances, hand deburring takes 10 times longer than NC equipment deburring. When tools were changed by hand, NC machining was slower, but now a number of machines can change tools quickly and automatically. Hand deburring, however, retains one advantage: it can reach difficult areas some NC machines cannot. These spatial limitations of NC equipment are described later.

Figure 14. Capabilities for Maintaining Precision Miniature Edge Breaks by Hand Deburring

Machine Test 1

In the first test, the part shown in Figure 15 was chamfered using the cutters shown in Figure 16. This initial test established the problems in using chamfering tools on outside contours.

An attempt was made to maintain 76.2- μ m maximum edge breaks in this test. Spindle speeds of 3000 rpm were used and, in most instances, feed rates were 2.55 mm/s. Table 3 highlights some of the observations for each cutter. The following observations were also made.

When using NC equipment as a dedicated deburring machine (as opposed to a machine which cuts and deburrs in the same setup) the flatness of the parts plays an important role. The test samples were sheet metal parts which were blanked, machined, then ground flat and lapped to provide smooth surfaces and sharp but nearly burr-free edges. These flat parts warp easily and, in this instance, out-of-flat conditions of 50.8 μ m and more were observed. Consequently, the edge breaks produced by the machine were inconsistent. Three steps can be taken to prevent this:

1. Perform the deburring on the same setup as the machining;
2. Use hand deburring which can accommodate changes in the geometry readily; or
3. Provide suitable fixturing to hold all edges in the same plane.

Interference between the tool and the part is possible when one has a number of small diameter cutouts on a contour and must use a cone-shaped chamfering tool. The equipment cannot be programmed for contact on just any point on a cone-shaped tool. As seen in Figure 17, sharp turns such as D₃ (C₄ in Figure 15) require that a diameter less than or equal to D₃ be chosen on the cutter. Otherwise, the chamfer in the area defined by D₃ will be larger than it is on the rest of the part. If necessary, the working diameter on a cutter can be changed by axial movement, which can be a significant problem when a cutter other than that for which the tape was designed is used.

The rotary burs sometimes contain minute burrs. Figure 18, for example, shows a rotary cutter with some obvious burrs. The burrs on this cutter seem to improve performance.

For cone-shaped tools, such as those used in most rotary burs, the velocity of the cutting edge is a function of the distance from the center of the tool. On the very small rotary burs the spindle speed may be slow enough that the feed rate is excessive.

Figure 15. Configuration of Specimen for On-Machine Test 1

- A. WHITE DENTAL STONE
- B. DIAMOND-COATED MANDREL
- C. CONE-POINTED BUR
- D. FINISHING BUD BUR
- E. CENTER POINT REAMER
- F. STUMP FILE BUR
- G. NORTHPROP PODIATRY BUR

Figure 16. Tools Used for On-Machine Test 1

For example, when end milling 303 stainless steel with an HSS cutter, the recommended cutting velocity is 382 mm/s. Slower velocities can be used; higher velocities will cause rapid degradation of the cutter. On a 6.35-mm-diameter cutter this cutting velocity corresponds to a spindle speed of 1146 rpm. In many cases, however, the actual cutting diameter of a rotary bur is significantly smaller than the shank diameter. Very small cutters must be used for small chamfers on miniature parts with intricate cutouts.

Table 3. Observations From First NC Test

Tools Used	Bendix Code Number	Tool Material	Feed (mm/s)	Observation
Center point reamer	50900492	Carbide	1.02	Tool produces obvious new burrs.
Size 18 bud shape bur		Tungsten Vanadium steel	2.55	Tool has groove in it after 0.508 m of cut.
Finishing bur #232		Tungsten Vanadium steel	2.55	No bur produced after 0.305 m of cut.
Finishing bur #229		Tungsten Vanadium steel	2.55	Produced only small burrs after 0.635 m of cut.
Cone-shaped bur	52620490	Tungsten Vanadium steel	2.55	Groove is worn in tool but it still works after 1.016 m of cut.
Diamond-coated flame	10200595	Diamond steel	2.55	Small burr produced after 0.711 m of cut.
White dental stone	10604301	Aluminum oxide	2.55	Wore out in 0.051 m of cut.

*All tests were run at 3000 rpm.

Figure 17. Cutter and Part Diameters

Figure 18. Burrs on Teeth of Rotary Bur

As shown in Figure 19, when cutting at 382 mm/s on the shank diameter, portions of the tool will be rotating only 95.2 mm/s. Closer to the center line of the cutter, cutting speed is reduced.

Slow cutting velocities, while not detrimental, may increase wear. For example, if the tool was located at a contact point P1 corresponding to diameter D1 (Figure 17), a feed rate of 2.55 mm/s may not be excessive. Closer to the center of the cutter, however, the feed rate may be excessive because the teeth are necessarily very small and the cutting velocity is very low. Thus, there may be more wear than with conventional diameter cutters. Table 4 provides some values of cutting velocity as a function of diameter and spindle speed.

Many of the rotary bur tools are designed to run at low pressures but at high speeds. Most NC machine tools are not designed to run above 4,000 rpm. As a result, the tools are not being used at the speeds for which they were designed. For example, many hand held air motors used for hand deburring operate up to 50,000 rpm. The recommended rotational speed for solid carbide burrs 1.58-mm in diameter is 98,000 rpm for coarse cuts in stainless steel.^{79, 80} Dental motors use such tools at speeds of up to 400,000 rpm.

Measuring 76.2- μ m edge breaks can be a difficult task on complex shapes. In many cases, the chamfer is so small and light reflection so poor that obtaining accurate readings of chamfer size is almost impossible. On those edges that can be viewed on comparator charts, accurate readings can be obtained on a projection view (as opposed to a reflection).

In all conventional cutting, a burr is produced by using a cutting tool. These miniature parts are no exception. The miniature rotary burs, stones, and other tools all left a small projection of material at the edges they produced. These projections were at the most 12.7- μ m high. Typically, on the first part produced by a cutter, no burr was visible at 30 power magnification, but within two or three parts (305- to 381-mm of cut) a burr was visible with the naked eye and could be detected with a fingernail.

One of the limitations of many of the abrasive stone deburring tools is their excessive wear rates. In conventional hand deburring, excessive wear is not a major problem because an individual readily compensates by applying more pressure or moving the tool laterally on the part. But with an NC preprogrammed path, the tool will be worn after just a few inches of cutting. As a result, the tool will no longer contact the edge. Providing additional tool offsets would be time consuming because of the short life of the miniature stones used for deburring.

DIAMETER	(mm)	VELOCITY (mm/s)
D ²	1.56	95.4
D ³	3.15	191.2
D ⁴	5.08	306.0
SHANK	6.35	382.0

Figure 19. Cutting Velocity as a Function of Tool Diameter

One of the limitations of using NC machines for deburring is that different tools are required for parts with many holes or cutouts. Bendix NC machining centers are limited to 20 tool changes on a part. Often 10 to 15 tools are needed to machine the part. Then, another 10 would be required to totally chamfer edges on the same setup, which would exceed the capacity of the machine. Even manually loaded machines may require 20 to 30 different holders for a single job. And most of the time this is not feasible.

Table 4. Surface Velocity as a Function of Tool Diameter
(Cutting Velocity* in Surface mm/s)

Diameter (mm)	Spindle Speed (rpm)				
	1000	2000	3000	4000	5000
0.254	13.5	26.9	40.4	53.8	67.3
0.508	26.9	54.0	71.1	107.7	134.6
0.787	42.1	84.2	126.2	168.3	210.3
1.575	84.1	168.3	252.4	336.6	420.7
3.175	168.2	336.6	504.8	673.1	841.4
6.350	336.6	673.1	1009.7	1346.2	1682.75

*Cutting velocity (mm/s) = (0.053)(tool diameter)(rpm)

Basic Tool Movements for Deburring

Although most deburring is done with tapered tools, effective deburring demands a variety of tool axes and motions. These include deburring with the flat end of some tools with the cylindrical portion in either of two axes or with brushing (Figure 20).

Special motions can be used on some features. The top surface of a hard bur can be used to deburr the bottom side of a hard to reach hole (Figure 21a). In this case the tool must be used, not as a countersink tool, but to profile the hole edges. Double sided chamfering tools are available to chamfer both the top and bottom of rectangular stock or related features (Figure 21b). But the smallest commercial standard cutters, which are 19.05-mm in diameter, are too large for most miniature parts.

NC machines can be programmed to generate edge breaks as well as surface dimensions (Figure 22). The end mill or slotting cutter exits one surface, begins its motion at 90 degrees for the next surface, and traverses the desired chamfer or radius. When properly done, no burr is left to remove. Nevertheless, this approach has several disadvantages:

- Possible rough surface finish on edge,
- Loss of tolerance as cutter deflection catches up,
- Noticeably lengthened programming effort, and

**A. USE END OF MOUNTED POINT
FLUSH WITH TOP SURFACE**

**B. USE SIDE OF MOUNTED
POINT, CYLINDRICAL BUR,
OR MUSLIN-FILLED CYLINDER**

D. BRUSH EDGES TO RADIUS

**C. USE TAPERED CONE TO
CHAMFER (ROTARY BUR,
COUNTERSINK, OR MOUNTED
POINT)**

Figure 20. Tool Orientations for Deburring

A. INSERT HART BUR (INVERTED CONE) IN HOLE AND TRANSLATE AROUND HOLE TO DEBURR WITH SIDE 1 OF CUTTER

B. CHAMFERING TOOL FOR DEBURRING TWO SIDES OF SHEET METAL

Figure 21. Special Tools and Motions for Deburring

- Significantly increased machining time.

On precision screw machine parts with tolerances of $\pm 2.54 \mu\text{m}$, maintaining surface tolerances without considering edge requirements is difficult. On conventional screw machines, adjusting

THE CUTTER THAT PRODUCES AN
EDGE IS PROGRAMMED TO MACHINE
A SPECIFIC CHAMFER AS IT BEGINS
A NEW SURFACE

Figure 22. NC Machine Programmed to Generate Edge Breaks

cams and tooling to generate the desired edge size frequently upsets the critical diameter settings. NC machines can eliminate some of the tool adjusting, but because of cutter deflections, they cannot prevent it, particularly on deep pockets.

Precision Countersinks

Figure 23 illustrates a miniature part with a small chamfer required on one hole. The $63.5\text{-}\mu\text{m}$ tolerance on this chamfer is adequate. But there are problems.

Figure 23. Miniature Part With Small Chamfer

- Because this is a toleranced feature (as opposed to a maximum edge condition), it must be produced by machine to ensure conformance.
- Because of the minute size of the chamfer, some conventional approaches are not feasible.

- Because of stock tolerances, 50.8- μ m chamfer tolerance is lost.

With the indicated tolerance this chamfer might be consistently provided by hand. With only a 25.4- μ m tolerance, however, hand finishing is not reliable.

On parts like those in Figure 23, the normal deburring practice is to use vibratory deburring or centrifugal barrel tumbling to provide the necessary edge radius. The requirements are to not exceed a 127.0- μ m edge break on the outside contour while providing a 76.2- to 203.2- μ m break on one specific hole. Meeting these two constraints in a single process, however, is not feasible. The mass finishing processes do not normally work well in small holes or in hard to reach crevices. They concentrate action on the outside edges, so that a 127.0- μ m break in the holes will cause a 203.2-mm break on the outer edges. This may be close to, but not within, the requirements.

On a die stamped part (Figure 23), the die action normally provides enough die break or roll to produce at least a 76.2- μ m radius. However, on this part the die roll produced a 25.4- μ m radius. This may be close to the desired requirements, but many miniature parts after mass finishing have a geometry which prevents successful deburring by tumbling. As a result, other means must provide the necessary edge break.

The following are common techniques to provide precision countersink depths:

- Using a special tool which locates from the top surface of the part;
- Using a precision NC machine to assure repeatability of countersink tool depth and to control stock thickness;
- Using a precision NC machine to assure repeatability of countersink tool depth and to provide controlled surface location with back loaded fixtures; and
- Machining the part completely in one setup so that stock tolerances are not a factor in countersink depths.

One common technique for providing precision countersink depths is to use a "microstop" or aircraft countersink stop tool. These tools have a positive stop built into them; the tool provides a consistent countersink dimension, which can be easily adjusted if needed. As shown in Figures 24 and 25, the smallest of these tools is about 12.7 mm in diameter. As long as the parts are bigger and these tools can rest against part surfaces, a consistent countersink size is ensured.

Figure 24. Adjustable Microstop Style
Countersink Tool and Stop

On precision miniature parts, however, as shown in Figures 1 through 5 and Figure 23, the parts are so minute and delicate that these types of devices are not appropriate. Though some form of integral tool and tool stop can be designed, the different sizes make the designing expensive. For this reason, one is almost obligated to rely on controlled tool locations from NC machines.

As seen in Figure 26, the $\pm 25.4 \mu\text{m}$ tolerance on part thickness on datum B uses $50.8 \mu\text{m}$ of the countersink depth tolerance. While such depths can be controlled to a $25.4\text{-}\mu\text{m}$ total tolerance, it is very difficult without the dedicated equipment.

Figure 25. Piloted Microstop
Style Countersink
and Stop

An alternate but more costly approach loads the part into a fixture so that surface A is always independent of surface B (Figure 27). Additional tolerance can be gained by controlling the part thickness more closely than the drawing stipulates, but this takes more time.

While the part shown in Figure 23 is obviously best suited to be blanked, many other shapes could be produced on an NC machine. The stock used would be faced to establish datum A, and then all features would be machined with respect to datum A (Figure 28). Datum B would then be machined with respect to datum A after all other machining was completed.

Example of NC Geometry Limitation

Figure 29 indicates the edge numbers for the part shown in Figure 1. This simple part has 15 different edges. It is machined completely on an NC machine (Figure 30), and then cut below the bottom leg. Edges 12, 13, and 14 have not yet been produced, and so are not available for deburring on the NC machine.

**TO MAINTAIN PRECISION CHAMFERS, TOLERANCE BUILDUP MUST
BE ELIMINATED FROM OTHER SURFACES**

Figure 26. Cross Section of a Part With Typical Dimensions

Figure 30 also shows that edges 7 and 11 are not deburrable unless the part is rotated 90 degrees. A tool cannot get underneath the middle leg to deburr the hole in the bottom leg or to deburr the bottom of the hole in the middle leg.

Table 5 illustrates three more edges which cannot be totally deburred on the NC machine. On edges 6 and 10, as the cutter tries to traverse them, it digs into the surface near edges 8, 9, and 15. It will leave a groove not allowed in the drawing.

As shown in Figure 31, the cutter cannot deburr all of leg 4 because part of it falls beneath the top leg. The cutter would have to be shortened to fit underneath the top leg since the dimension between edges 3 and 4 is only 1066.8 μm (Figure 29).

Thus, because of the fixturing and the geometry, a machine cannot totally deburr even many simple parts. The part, however, could be placed in a fixture 90 degrees to the existing one and a bur ball used to deburr the holes. But hand deburring would be cheaper and faster. Also, a fourth axis could be used on the NC machine to rotate the part into proper position, but an extra axis is seldom available.

As shown in Table 5, five different tools are required to chamfer this part. The T-slot cutter required for edges 8 and 9 is the same used to produce the slot. The other four tools are needed to produce surface dimensions. For edges 1, 4, and 10 the pointed end of a hart rotary bur would be used (Figure 32). For edges 3 and 6, the shank side of the hart bur would be used (in this case a different hart bur than that used for edges 1, 4, and 10). Because two hole sizes are involved, one must use two different bur balls to provide the equivalent of a 45-degree chamfer.

Figure 27. Back Loaded Part

Theoretically, it is possible to use the same tool to chamfer both edges 1 and 3. But all tool dimensions would have to be consistent. If a tool is programmed to contact a point A on the cutter for top surfaces and point B for bottom surfaces, any difference in dimensions from point A to B on various cutters would show up as a variance in the chamfer.

Deburring Without Chamfering

Figures 33 and 34 are magnified illustrations of typical burrs produced on the part shown in Figure 29 under conventional machining techniques. The total machining time to produce the part in Figure 30 from a round slug is 15 minutes per part on an NC machine with an automatic tool changer. With an average operator it can be hand deburred at a rate of approximately 12 minutes per part. With the use of the machining cutters, the parts were completely deburred (Figure 35). After the part was totally machined, one of the initial cutters made a second pass over the edges it had initially generated. Intervening cutters had thrown the burrs into the path of the repeated cut, which removed the large burrs.

This technique will not provide a chamfer on a part unless the tool is programmed to do so (as was the case for edge 8).

**ALL DIMENSIONS ARE
FROM DATUM A SURFACE**

Figure 28. Part Made From Slug on NC Equipment

However, it will provide a reasonably clean edge that facilitates both mechanized and hand deburring on any part. The effect is that a burr is chased back and forth until the first burr is at least partially cut off and bent into another plane as a cutter passes the surface. Although this process does not totally remove the burr, it reduces it so that subsequent deburring is much more effective. The cost effectiveness of this approach has not yet been demonstrated.

The Use of Multiple Deburring Tools

In most instances, because chamfering cutters produce burrs, deburring on an NC machine must be followed by some form of secondary or "finish" deburring (Figure 36). Although the NC machine can reduce deburring time, the manual operation, which is edge blending, removing secondary burrs, and verifying burr removal, must still be done separately.

On-Machine Test 2

Figure 37 illustrates a miniature part similar to the one in Figure 30. The cycle time taken to machine from a solid slug, to

Figure 29. Identification of Edges

chamfer, and to blend the indicated edges was 6 minutes (3 minutes for deburring). A hart-shaped HSS bur tool chamfered edges 1, 2, and 3. Then a brown, abrasive-filled rubber dental point in a spring-loaded chuck removed the majority of the chamfer burr. A bur ball was used to chamfer the large hole.

It is estimated that this 3-minute NC machine deburring would take 4 minutes by hand. The time difference may offer no advantage, but the consistency of the machine does for required chamfers of $76.2 \mu\text{m}$ or less. The combination of the spring-loaded chuck and the abrasive-filled rubber tool would not be used on actual parts. Chamfering time, then, would be reduced to approximately 1.5 minutes per part.

Despite the simplicity of this part, the 0.5-mm dimension between the hub and the contour limits the size of tool that can be used. Attempts to use larger tools by offsetting the tool radially and then lowering it results in too large a chamfer in the radius beneath the "beak".

Figure 30. Part is Machined Completely in One Operation

Table 5. Approach to NC Chamfering of the Part Shown in Figure 30

Edge Number	Feature	Tool		Chamfer		
		Type	Number	Complete	Most	None
1	Leg 1	hart bur	1	X		
2	Hole	bur ball	2	X		
3	Leg 1	hart bur	3	X		
4	Leg 2	hart bur	1		X	
5	Hole	bur ball	4	X		
6	Leg 2	hart bur	3		X	
7	Hole		By hand			X
8	End of cut	T-slot cutter	5	X		
9	End of cut	T-slot cutter	5	X		
10	Leg 3	hand bur	1		X	
11	Hole		By hand			X
12	Leg 3		By hand			X
13	Hole		By hand			X
14	Hole		By hand	X		
15		T-slot	5

Figure 31. Hart Shaped
Rotary Bur

Tool Wear and Aggressiveness

For minute parts, the most appropriate cutters are dental tools. All of the tools in Figure 16, for example, except the center point reamer, are dental tools. Conventional metalworking cutters are not available in these small sizes and shapes. While there is no known literature on the life of the tools in industrial applications, some useful dental studies are available.

A number of studies on the performance and wear of rotary dental tools and rotary dental mounted points indicate that steel or carbide burs have a very short life. A typical life of one of these metal burs for cutting dental tissue would be at the most 5 to 10 minutes. This material has properties similar to Meehanite SH 100 (Rockwell C 23 to 25).

Most of these tools are used by dentists at speeds of up to 250,000 rpm; at slower speeds the tools will dull quickly. The amount of time required to make a fixed length of cut ($127 \mu\text{m}$) as a function of the number of cuts made is shown in Figure 38. At a speed of 100,000 rpm, the first cut required 20 seconds to complete. The tenth cut with the same tool required 120 seconds to complete.

The use of dental and industrial burs involves surface applications whereby material is removed by the majority of the face of

Figure 33. Burrs Produced With No Deburring on NC Machine

the cutter. In deburring applications, the contact between the material and the cutter is a straight line rather than a surface contact. Tools, therefore, wear more quickly or at least develop pronounced grooves more quickly than published studies indicate.

As in the case of any tool, the rake and relief angles greatly influence the life of the cutters. Other studies indicate a general inconsistency in the geometry and life of some cutters.

The typical metal removal rate for miniature dental burrs in brass would be up to 100 mg per minute (0.000220 lbs. per minute). At this rate it would take 76 hours to remove one pound of material.

Figure 34. Burrs Produced by NC Machine With No Deburring Cycle

The one consistent factor in the dental tool studies is that one obtains longer tool life by exerting lower pressures against the part. Conventional NC machines, however, are designed to provide constant tool path rather than constant tool pressure. So pressure is not conveniently controlled.

As indicated, the dental tools tended to develop grooves or worn areas after 152.4- to 254.0-mm of cut. For the part shown

Figure 35. Part With Extra Tool Passes to Cut Off Large Burrs

in Figure 37, cutters are changed every 20 to 30 parts. This represents a life of 381- to 508-mm of cut. A carbide hart-shaped burr used on the part shown in Figure 37 was able to produce over 120 parts (approximately 2.3 m of cut) when the cutter was adjusted every 30 or 40 parts to provide a fresh area of contact.

Economics

Technical capabilities and limitations are not the only driving forces in prescribing processes. In most industrial settings, there are several considerations:

- Economics,

Figure 36. Typical Deburring Flow

Figure 37. Edges Chamfered on NC Machine

- Machine availability,
- Flow times,
- Reliability of hand deburring, and
- Queues.

The requirement for a 76.2- or 127.0- μm maximum edge break for a part like the one in Figure 37 can be met by manual techniques. Assuming that an NC machine is available and that flow times and queues are not problems, the economics of NC deburring need to be evaluated.

The following equation provides a reasonable estimate of cost for NC and hand deburring. In this equation it is important to note

Figure 38. The Effect of Use on Tool Wear

that C_o represents overhead costs for the individual performing the work and C_D includes such factors as machine cost amortized over its life, maintenance, accessories, and support devices.

$$C = \left[C_L + C_o + C_D \right] \left[\frac{T_f}{60} + \frac{T_R}{60L} \right] + \frac{C_t}{L} \quad (1)$$

Where

C = Cost per part (\$)

C_L = Hourly labor rate (\$/hr)

C_o = Cost of operator overhead (\$/hr)

C_D = Machine depreciation cost (\$/hr)

C_t = Cutting Tool cost (\$)

T_f = Time required for tool feed or travel (min.)

T_R = Time required for tool presetting, replacement, and accuracy checkout (min.)

L = Life of cutter (number of parts)

Table 6 illustrates the comparative costs. The values for C_D were based on the assumption that a \$100,000 NC machining center has a life of three shifts, 200 days per year, for 10 years. Accessories and related overhead for the machine are assumed to add \$1.00 per operating hour. Because the tools must be accurately controlled, the first part machined after a tool change represents a trial cut. Ten minutes are required to make the change and verify the tool adjustment. Under these assumptions, deburring costs would be \$0.60 per part.

Hand deburring, on the other hand, costs \$0.50 a part. The edges numbered in Figure 37 could be completed in three minutes and the tool could be set up in one minute (no setup accuracy is required). The cost of the tools--a knife and a brush--would be a total of \$7.00, and the composite life 100 parts. Deburring would cost \$0.90 per part if a vendor machining a part set an overhead rate of \$25 per machine hour.

These comparisons show that hand deburring is the least expensive approach. However, cost may not always be the most important factor. For instance, if a part configuration becomes more complex, if edge break requirements drop below 76.2 μm , or if enough precision deburring personnel are not available, then NC machining is the only viable process. Also, if the life of the tools used for NC deburring were doubled, then NC and hand deburring would cost the same.

With edge requirements of a 127.0- μm maximum or greater, NC deburring remains economically competitive only on complex parts like those in Figures 4, 5, and 6. Even in these instances, NC deburring would probably only be performed on the more difficult or time consuming features. When edge break requirements approach a 50.8 μm maximum, machined edges are often required.

This analysis of costs has ignored the extra programming time and flow time required for NC deburring. At the same time, any form of deburring on critical parts requires engineering planning or thought if the most consistent and economical approach is to be selected.

Positive Characteristics of Hand Deburring

NC deburring has some major advantages in specific situations. At the same time, hand deburring has some positive characteristics.

Table 6. Example Data of Deburring Costs

Item	Example Number*		
	1	2	3
C _L	8.00	8.00	25.00
C _O	2.00	2.00	0
C _D	3.00	0.01	0
C _t	2.00	7.00	0
T _f	1.5	3.0	1.5
T _R	10.0	1.0	10.0
L	15	100	15
C	\$ 0.60	\$ 0.50	\$ 0.90

*1 is NC Machine
 2 is By Hand
 3 is Commercial Rate

- It does not tie up equipment required for precision machining.
- It can concentrate all action at edge.
- It does not require tooling, tape, and machine available lead time (short turnaround time for small quantities).
- It does not normally require expensive holding fixtures.
- It can quickly reorient parts with respect to tools since no fixtures are involved (an NC approach may require 5 axis).
- It adapts to all edge conditions (versus machine preprogrammed motion).
- It can accommodate tool shortages by substituting tools or technique.

Basic Considerations When Using NC to Remove Burrs

- All chamfering cutters will provide two new burrs on each edge (generally smaller than the initial burr).

- If one has a thick burr, but must maintain a small edge break, chamfering may not remove all the original burr (Figure 39).
- Rotary burrs are designed to be used at high velocities and low forces. Many NC spindles will not approach the recommended cutting velocities for these tools.
- When deburring and machining are performed on the same setup, one has better control or visibility on appropriate tool change times. If dull tools cause too large a burr the burrs will not be removed by machining chamfering.
- Abrasive stones or abrasive-filled rubber tools generate a large number of fine abrasive particles which can become lodged in collets, holding fixtures, and machine ways.
- The rubber in some abrasive-filled rubber products reacts with coolants to produce sticky machine ways.
- Thin flanges may distort during machining to the extent that chamfering tools may not even touch the edges, especially when flanges are less than 0.75-mm thick and chamfers of 76.2- μ m maximum are required.

Limitations of Geometry When Using NC to Remove Burrs

The use of NC deburring requires several considerations.

- In which planes will the burr exist?
- Which type of tool will fit within the required space (Figures 20 and 21)?
- Can the edge produced be deburred with a machine that has only three axes of movement (Figure 40)?
- Is the cutter geometry compatible with all the contour it must produce (Figure 17)?
- Will the cutter be worn before it completes all edges of a single part?
- If parts were partially produced in another operation, is edge location consistent (Figure 26)?
- On small diameter holes, does one plunge down to provide a chamfer or should one traverse the profile?
- Does the number of tools required for deburring exceed the available tool changer capacity?

Figure 39. A 75- μm Chamfer on a 125- μm -Thick Burr Still Leaves a Noticeable Burr

- Does the combination of small tool size, working space, and available spindle speed result in large feed rates per tooth (Figure 19)?

Miniature tools and parts have several subtleties. For example, a bur ball is commonly used to chamfer holes. Because a sphere is performing the cutting, the resulting chamfer will not have uniform X and Y axes lengths. To approximate a 45-degree chamfer with a bur ball, one must select a ball approximately twice the hole diameter. When the correct diameter is not available, it is desirable to know the relationships among hole size, ball size, and the possible X and Y dimensions. These relationships are defined in the Appendix. The Appendix also contains definitions of some commercially available rotary bur sizes which could be used on NC equipment.

Figure 40. Deburring Feature May Require More Than Three Axes of Machine Motion

ACCOMPLISHMENTS

This project has defined the technical and economic capabilities of robot and NC equipment for deburring precision miniature parts. The burr related problems on miniature parts were defined. Also analyzed were the capabilities of commercial robots, the relationship between deburring tools and part geometry, and the economics. The results of this study have been implemented on production parts.

FUTURE WORK

Although no further work is planned on this subject, more extensive studies of cutter tooth geometries, material, and cutter

life are warranted. As robot precision capabilities increase, additional efforts should be directed to them.

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Appendix

BUR BALL CHAMFER CHARACTERISTICS

Figure A-1. Bur Ball and Hole Characteristics

$$by = \frac{D_1}{2} - dy - a$$

$$a = \left[\left(\frac{D_1}{2} \right)^2 - \left(bx + \frac{D}{2} \right)^2 \right]^{1/2}$$

$$by = \frac{D_1}{2} - dy - \left[\left(\frac{D_1}{2} \right)^2 - \left(bx + \frac{D}{2} \right)^2 \right]^{1/2}$$

$$h = \frac{1}{2} \left[D_1 - (D_1^2 - bx^2 - by^2)^{1/2} \right]$$

bx = CHAMFER SIZE IN "x" DIRECTION
by = CHAMFER SIZE IN "y" DIRECTION
h = VARIATION OF ARC FROM CHORD

Figure A-2. Relation Among Chamfer, Ball Size, and Hole Diameter

Figure A-3. Relation Between X and Y Chamfer Size as a Function of Ball to Hole Diameter

HART SHAPE

INVERTED CONE

ROUND EDGE CUTTER

KNIFE EDGE CUTTER

Figure A-4. Typical Rotary Bur Configurations

Table A-1. Relationships Among Bur Ball Dimensions

Diameter		Chamfer (μm)		Deviation From Straight Line
Hole, D (mm)	Ball, D (mm)	x	y	(μm)
0.508	0.8128	25.4	22.9	0
0.508	0.8128	76.2	81.3	2.54
0.508	0.8128	127.0	175.3	15.20
0.508	1.5748	25.4	10.2	0
0.508	1.5748	76.2	30.5	0
0.508	1.5748	127.0	55.9	2.54
0.762	1.5748	25.4	15.2	0
0.762	1.5748	76.2	48.3	2.54
0.762	1.5748	127.0	86.4	2.54

Table A-2. Standard Miniature Bur Ball Sizes

Size Code Number*		Ball Diameter (mm)	Available In Carbide**
Busch	Domestic		
9/0		0.24	
8/0		0.30	
7/0		0.35	
6/0		0.40	
5/0		0.5	
4/0	1/4	0.6	X
3/0	1/2	0.7	X
2/0	1	0.8	X
0	-	0.9	X
-	2	1.0	X
1	2	1.05	X
2	3	1.20	X
3	-	1.35	X
-	-	1.40	X
4	4	1.50	X
-	-	1.56	X
5	5	1.65	X
6	6	1.85	X
-	-	2.00	X
7	77	2.10	X
8	8	2.30	X
-	-	2.34	X
9	9	2.55	X
10	-	2.70	X
11	10	2.85	
12	11	3.00	
-	-	3.125	X
13	-	3.25	
14	-	3.50	
15	-	3.75	X
-	-	3.91	X
16	-	4.00	X
17	-	4.25	
18	-	4.50	
19	-	4.75	

Table A-2 Continued. Standard Miniature Bur Ball
Sizes

Size Code Number*		Ball Diameter (mm)	Available In Carbide**
Busch	Domestic		
-	-	4.76	
20	-	5.00	X
-	-	6.25	X

*Most suppliers of industrial miniature rotary burs use the Busch numbering system or indicate actual size. The tungsten-vanadium HSS burs are generally available in 1.59- and 2.44-mm diameter shanks. The unnumbered carbide tools are available in 2.38-, 3.12-, 4.76-, and 6.35-mm-diameter shanks. The number of teeth on a tool can vary significantly among suppliers.

**All are available in HSS.

Table A-3. Standard
Miniature
Hart Bur
Sizes (mm)*

Size Code Number	Largest Head Diameter
0	0.9
1	1.05
2	1.20
3	1.35
4	1.50
5	1.65
6	1.85
7	2.10
8	2.30
9	2.55
10	2.70
11	2.85
12	3.00
13	3.25
14	3.50
15	3.75
16	4.00
17	4.25
18	4.50
19	4.75
20	5.00

*Available only in HSS.

Table A-4. Standard Miniature
Round Edge and Knife
Edge Rotary Burs
(Available only in
HSS)

Cutting Diameter (mm)	Thickness (mm)
7	1.5
10	2.0
12	2.25
14	2.75

Table A-5. Standard Miniature Inverted Cone Rotary Burs

Size Code Number*		Maximum Head Diameter** (mm)	Available In	
Busch	Domestic		HSS	Carbide
4/0	33 1/4	0.6	X	
3/0	33 1/2	0.7	X	X
2/0	34	0.8	X	X
0	-	0.9	X	
1	35	1.05	X	X
2	36	1.20	X	X
3	-	1.35	X	
4	37	1.50	X	X
-	-	1.56	X	X
5	38	1.65	X	X
6	39	1.85	X	X
7	40	2.10	X	
8	41	2.30	X	X
-	-	2.34	X	X
9	42	2.55	X	
10	-	2.70	X	
11	43	2.85	X	
12	44	3.00	X	
-	-	3.12	X	X
13	-	3.25	X	
14	-	3.50	X	
15	-	3.75	X	
16	-	4.00	X	
17	-	4.25	X	
18	-	4.50	X	
19	-	4.75	X	
-	-	4.76	X	X
20	-	5.00	X	
22	-	5.20		X
-	-	6.24		X

*Most suppliers of industrial miniature rotary burs use the Busch numbering system or indicate actual size. The tungsten-vanadium HSS burs are generally available in 1.59- and 2.44-mm-diameter shanks. The unnumbered carbide tools are available in 2.38-, 3.12-, 4.76-, and 6.35-mm-diameter shanks. The number of teeth on a tool can vary significantly among suppliers.

**Head length is approximately equal to head diameter. Taper is typically a 10-degree included angle.

BDX-613-2431

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EQUIPMENT, L. K. Gillespie, Final, May 1980.

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