BURRS PRODUCED BY END MILLING

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BURRS PRODUCED BY END MILLING

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Prepared by L. K. Gillespie, D/822, under PDO 6984405

The operation of small precision mechanisms such as timers, switches, or actuators depends on burr-free, sharp-edged component parts. Traditional methods of producing these near-perfect edges on miniature parts are costly and not as precise or repeatable as some piecepart designs require. By controlling the size of burrs produced in machining operations, burr removal costs can be lowered, and the repeatability of the resulting edges improved. This investigation sought to determine how machining variables influence burr size in end-milling operations. It was concluded that the low feed rates which are commonly used in precision miniature machining create larger burrs than do more conventional feedrates. Dull tools double the size of burrs. Increasing the radial depth of cut also increases burr size on many edges. A single end-milling cut can produce eight different burrs. Burr properties vary noticeably even along a single edge. Burrs in 1018 steel, 6061-T6 aluminum, 303 Se, and 17-4 PH stainless were typically 0.003 inch (76.2 μm) thick. Burr heights ranged from 0.0001 to 0.070 inch (2.5 to 1778 μm). Conceptual and mathematical descriptions of burr formation have been developed.

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SUMMARY

Component parts of small mechanisms have typically required near-sharp edges to assure reliable component operation. A burr-free condition is needed to minimize possible electrical and mechanical jamming of the mechanism, which would result if burrs were to break loose during operation. In the past, reliable removal of machining burrs, combined with protection of the near-sharp edge requirements, has dictated that deburring be done only by hand, which is time consuming and inherently operator variable. The repeatability of burr removal and the time required for removal are directly related to burr size. Small burrs are easily removed by many deburring processes.

The investigation, based on 6000 measurements, showed that low feedrates and dull tools are the two most significant factors which increase burr size. Burr properties also increase with increasing radial depth of cut on many edges.

A single end-milling cut can produce burrs on eight different edges. The thickness, height, and radius on the backside of the burrs are different for each edge. Contrary to popular opinion, burrs can form on the edges in which the cutter enters the part. Changing such factors as feedrates does not equally influence burr size on all edges. On some edges, such changes will decrease burr size while on others it will increase burr size or have no effect. Burr properties vary noticeably, even along a single edge.

Burrs in 1018 steel, 6061-T6 aluminum, 303 Se, and 17-4 PH stainless steel typically were 0.003 inch (76.2 μm) thick. Burr height varied from 0.0001 to 0.070 inch (2.5 to 1778 μm), depending upon edge location. The radius on the backside of the burr typically was 0.0015 inch (38.1 μm). Burr hardness has previously been found to be up to 10 Rockwell-C (R_C) points harder than the parent material.

Conceptual and mathematical descriptions of burr formation have been developed. Three distinct mechanisms are responsible for the burrs produced by end mills.

The information obtained from this study will be combined with similar data from other machining operations to determine optimum fabrication conditions.

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DISCUSSION

SCOPE AND PURPOSE

The objective of this study was to determine how conventional end-milling practices influence burr size. Specifically, the goal was to determine how burrs produced by end milling are affected by feedrate, axial depth of cut, radial depth of cut, tool diameter, workpiece material, and tool wear. Burr thickness, height, and radius were monitored at six of the 10 edges produced by end milling.

PRIOR WORK

Earlier Bendix investigations provided some background data. In a preliminary study, the effects of helix angle and feedrate were evaluated on burrs produced at two locations in 303 Se stainless steel and in beryllium copper.¹ A subsequent study evaluated the effects of end-mill diameter, radial depth of cut, and feedrate on burr heights in 303 Se stainless steel.²

In related investigations, the effects of drilling, reaming, and ball broaching parameters on burr properties have also been studied.^{3,4,5} A general theory of burr formation has been developed,^{2,6,7} and some experimental work has been reported by other agencies on drilling burrs,⁸⁻¹² punching burrs,¹³⁻¹⁹ and burrs produced by the EDM method.²⁰

ACTIVITY

All conventional machining operations produce some burrs. The size of these burrs depends upon the tool geometries used and the workpiece material properties. The cost of removing the burrs is proportional to the burr size. In many instances, on precision miniature parts, because of close tolerances, minute part size, and large burr size, the burr removal costs approach the cost of machining the parts. To minimize these fabrication costs, one has to analyze how deburring costs vary with burr size and how machining conditions influence burr size. A series of tests has been initiated to provide data on burr properties as a function of machining conditions. These tests will include the most common machining operations.

The ways by which end milling produces burrs are discussed below, and the results of four end-milling studies are presented. In the first study, 128 combinations of cutter geometry, workpiece material, and cutting conditions were used to determine

how burr properties vary with these parameters. The effects of tool wear on burr properties were evaluated in the second study. The burrs produced in Hiperco 50 were evaluated in the third study, and the impact of the helix angle was studied in the fourth test. These results were then compared to the theory of burr formation and with previously published results.

The Formation of Burrs By End Milling

An end mill can produce eight different burrs in a single slotting operation. A total of 10 different groups of burrs can be produced by an end mill, but eight is the maximum which can be produced in a single cut. These burrs all occur on different edges. For example, in a bottom-cutting profiling operation, six edges are produced, and a different group of burrs occurs on each edge (Figure 1). When a blind channel slot is produced, six edges and six groups of burrs occur (Figure 2). In a through slot, eight edges and eight groups of burrs occur (Figure 2). The height, the thickness, the radius on the back side of each burr, the hardness, and the appearance of each of these groups of burrs is different from the other groups.

Two different mechanisms are involved in the production of these burrs. The burrs along edges 3, 7, and 9 are the result of a chip's rolling over, rather than having been sheared from the workpiece. Burrs on edges 1, 2, and 10 are the result of lateral deformation due to Poisson's ratio. These two types of burrs are defined respectively as roll-over and Poisson burrs. The burrs along edges 4 and 6 result from material flowing 180 degrees to the direction of tool travel. This *entrance* burr is one form of the Poisson burr. Burrs along edges 8 and 5 vary noticeably along each edge. They are a combination of entrance burr and roll-over burr.

The Roll-Over Burr

When a cutting edge exits from a workpiece, a roll-over burr forms (Figure 3). This burr occurs when it is easier to bend the chip than it is to cut it. To illustrate the basic phenomenon, one may consider a shaping operation in which the depth of cut is constant. An estimate of burr thickness can be made if one makes the assumption that a roll-over burr occurs whenever the energy required to bend the chip is equal to or less than the energy required to cut the chip. As indicated elsewhere,^{2,6} the work to cut a length of λ can be expressed by

$$W_c = F_c \left[\lambda - \frac{t}{2 \tan \phi} \right], \text{ for } \lambda \geq \frac{t}{\tan \phi}, \text{ or} \quad (1)$$

Text continued on page 20.

Figure 1. Identification of Burr Locations in End Milling-Profiling Cut

Figure 2. Identification of Burr Locations in End Milling-Slotting Cut

Figure 3. Chip Deformation Modes

$$W_c = F_{c_i} \left[\frac{t_i}{2 \tan \phi} \right], \text{ for } \lambda < \frac{t}{\tan \phi}, \quad (2)$$

where

W_c = work in cutting,

F_c = cutting force,

F_{c_i} = instantaneous cutting force near end of cut = $\frac{F_c t_i}{t}$,

λ = burr thickness,

t = uncut chip thickness,

ϕ = shear angle in cutting = $\frac{C - \tau + \alpha}{2}$,

t_i = instantaneous uncut chip thickness near end of cut = $\lambda \tan \phi$,
(Figure 4)

C is a material constant,

τ = friction angle = $\arctan \mu$,

μ = coefficient of friction between chip and tool, and

α = tool rake angle.

The work in bending a burr of a perfectly plastic material, assuming no redundant work occurs, is given by equation 3. (Most plastic deformation operations exhibit a great deal of redundant work. This implies that such processes do not deform by paths requiring the least energy.)

$$W_B = \frac{C_1 b \lambda^2 \sigma_e \theta}{4}, \quad (3)$$

where

C_1 = redundant work factor (= 1.0 when no redundant work occurs),

W_B = work in bending,

b = length of tool engaged in cut,

(A) SHEAR PLANE IN CUTTING

(B) SHEAR PLANE INTERSECTING EDGE

(C) CUTTING FORCE AS TOOL NEARS EDGE

Figure 4. Cutting Action Near Edge

σ_e = elastic limit of perfectly plastic material, and

θ = angle through which the burr is bent ($\pi/2$ + rake angle).

Equating W_c and W_B and solving for λ , results in

$$\lambda = \left[2F_c + \sqrt{4F_c^2 - \frac{C_1 2b\sigma_e \theta t F_c}{\tan \phi}} \right] \left[\frac{1}{C_1 b \sigma_e \theta} \right] \text{ for } \lambda \geq \frac{t}{\tan \phi}. \quad (4)$$

For a strain-hardening material,

$$\lambda = \left[2F_c + \sqrt{4F_c^2 - \frac{C_1 2b\sigma_o \epsilon_f^n t \theta F_c}{(n+1) \tan \phi}} \right] \left[\frac{n+1}{C_1 b \sigma_o \theta \epsilon_f^n} \right] \text{ for } \lambda \geq \frac{t}{\tan \phi}, \quad (5)$$

where

σ_o = true material stress at a true strain of 1.0,

ϵ_f = true strain at fracture, and

n = strain-hardening exponent.

As noted elsewhere,²¹ equations 4 and 5 predict thicker burrs than one actually finds on parts when the redundant work is assumed to be zero. Recent studies²² indicate that total work can be from 1.2 to 7.0 larger than the work calculated by minimum energy principles. When C_1 is 3.0, equations 4 and 5 closely predict roll-over burr size in 303 Se stainless steel.

In an end-milling operation, the depth of cut varies as the cutter rotates (Figure 5). Since t and F_c must be known before burr thickness can be calculated, and since t is not constant, equations 4 and 5 are not convenient to use in production.

It is possible to use a trial and error method with these equations if t is known as a function of distance from the back edge. By inserting a value of t , calculating F_c from Merchant's equation,²³ (equation 6, below) a tentative value of burr thickness can be obtained.

$$F_c = tb\sigma_s \left[\tan \left(\frac{C+\tau-\alpha}{2} \right) + \cotan \left(\frac{C-\tau+\alpha}{2} \right) \right], \quad (6)$$

where

Figure 5. Variation in Chip Thickness

σ_s = shear strength of the workpiece, λ must then be compared with the restriction

$$\lambda \geq t/\tan\phi.$$

If λ does not satisfy this restriction, then the substitution process must be repeated with a different value of t . The difficulty with this approach is that because of workpiece tolerances on length, and the inability to start each cut with the cutter teeth in a specific position relating to the part, t cannot be conveniently described as a function of distance from the back edge.

Despite the limitations in equations 4 and 5, they are useful in illustrating how the process variables influence the results. By using an average value for uncut chip thickness, it is also possible to obtain a reasonably close approximation to burr thickness as will be shown later.

The burr forms much like a banana is peeled. As each tooth exits from the back surface of the part it adds more material to the length of the burr (Figure 6).

From a subjective standpoint, it would seem that the roll-over burr should be composed of a number of tightly stacked flaps of material (Figure 6). In practice, however, these distinct flaps have not been observed. The burrs when cross-sectioned, have a uniform cross section.

In viewing Figure 5, it appears that in removing the third chip, any burr already produced would be cut off because the depth of

Figure 6. Exaggerated Illustration of Roll-Over Burr Formed by a Number of Milling Teeth

cut is so small. This is not the case, however, because the burr will be rolled out of the path of the cutter when the second chip is rolled over. On the third pass the tooth will essentially only rub the root of the burr.

Although the discussion thus far has tacitly assumed a zero helix angle, the same effect occurs when the cutters have a helix angle.

The height of the roll-over burr is directly proportional to the radial depth of cut up to a depth of 0.6 of the cutter diameter (Figure 7). At this value of radial depth of cut, the material ahead of the cutter tears. Thus, roll-over burr height can be up to 0.6 times the cutter diameter. (The maximum chip thickness occurs directly in front of the cutter on its centerline. Thus, the maximum force and the thinnest *web* of material occurs at this point. The fact that the tear occurs past the centerline probably results from the direction of the cutting force as well as from the two factors mentioned.)

After the cutter breaks this web, the burr will bend over to edge 3. The material left near edge 4 will be removed by the cutter, since the cutter sees this edge as the *entrance* side of a climb cut (Figure 8). The long portion of the roll-over burr is often broken off in handling. Thus, it would appear to the casual observer that no burr or little burr had been produced at this edge.

Burrs can be longer than indicated if the radial depth of cut d is greater than $D/8$, where D is the cutter diameter (Figure 7). Schafer's work²⁴ indicates that whenever the angle ϕ is less than 150 degrees, a roll-over burr can form. As the angle decreases (d/D increases), the likelihood increases that a roll-over burr will form, beginning on the top surface. Thus, the burr height of the case shown in Figure 7C is the sum of the length of the backside and the top surface. In practice, this critical angle will probably vary with the material used. Once the d/D ratio approaches 0.5, the long burr is almost certain to occur. The relationship between ϕ , d , and D is

$$\phi = \sin^{-1} \left(\frac{D-2d}{D} \right) + 90 \text{ degrees.} \quad (7)$$

The height of the roll-over burr formed on edge 7 will be much shorter than that formed at edge 3. This is a result of three factors. As shown in Figure 8, as the end mill enters the workpiece, the angle ϕ at edge 7 is very large. Thus, no burr can form until the cutter has advanced at least until $\phi = 150$ degrees. Although a chip begins forming as the cutting edge enters edge 6 of the workpiece, this chip cannot roll over because the material ahead of the cutter confines the chip to the flute of the cutter.

7A. $\frac{d}{D} = 0.075$
 $\phi = 149$ DEGREES

7B. $\frac{d}{D} = 0.2$
 $\phi = 120$ DEGREES

7C. $\frac{d}{D} = 0.5$
 $\phi = 90$ DEGREES

7D.

Figure 7. Effect of Angle ϕ on Maximum Burr Height at Edge 3

Figure 8. Cutter at Entrance and Exit of Slot

This generally breaks up the chip. The chip thickness as the tool exits from edge 7 is zero, since the tool is climb-cutting at this edge (Figure 5). Therefore, it is not possible, at least, theoretically, to have a long burr at this edge. The burr which is produced is formed before the full diameter of the cutter is in the cut. Subsequent cutting edges then only burnish the side of the burr.

The roll-over burr occurring on edge 9 is formed by the flutes and the bottom of the cutter. The action that occurs is easier to visualize if one thinks of the material in front of the tool as a rubber membrane. As the bottom corner of the flute exits over edge 9, it stretches the membrane (Figure 9). Eventually, the membrane tears at the corner of the tool, and the material ahead of the end-cutting edge is rolled over the edge. Because of small differences in the height of the end-cutting edges on the end mill, subsequent teeth scrape the bottom surface and may further increase burr height or thickness.

The Entrance Burr

When the cutting edge first indents the workpiece, it is possible for another type of burr to form (Figure 10). This entrance burr consists of material which has flowed opposite the direction of the tool. It is similar to the ridge which forms around the indentation made by a Brinnell Hardness Tester.

Whether or not a burr forms at this point depends on the workpiece properties and the actual shape of the cutting edge. Assuming that a cylinder-indenting metal produces effects somewhat similar to those of a ball-indenting metal, then strain-hardening plays an important role. Based on Brinnell Hardness results, it has been shown²⁵ that a lip of material forms when the material has a low strain-hardening exponent (Figures 11 and 12). Materials having high strain-hardening exponents cause a bulge but not a sharp burr. Assuming constancy of volume, this bulge will be wide, but short. In the previous case, the burr will be long, but narrow. In the case of high strain-hardening exponents, the bulge will probably be so short that it is difficult to detect. Unlike indentors, however, after the initial entry, further advancement of the tool does not increase burr size. The entrance burr is the result of material deformation within the first few thousandths inch of the surface.

Based on work with flat-nosed indentors²⁶ a die roll rather than a burr will occur on the entrance edge if the cutting tool is very sharp, or if the cutting edge is fractured in such a way that it has a flat surface rather than a radius for the cutting edge. Occasionally a chip carried by the tool from a previous part will weld to this edge, making it appear that a burr was produced. All entrance burrs are small and easily removed.

Text continued on page 32.

Figure 9. Membrane Analogy of Material Stretching at Corner of End-Mill Tooth

Figure 10. Cutting Edge Produces Indentation Burr as it Enters Workpiece

Figure 11. Effect of Strain-Hardening Exponent on Ridging Burr Formation (From Reference 26)

Figure 12. Material Displacement, Using Spherical Indentors (From Reference 26)

An entrance burr occurs on edges 6 and 4. The burrs on edges 5 and 8 are a combination of entrance burr and roll-over burr. From Figure 1, it can be seen that at the left half, the cutter produces an entrance burr on edge 8. Since the right half of the cutter is actually exiting over edge 8, it can only produce a roll-over burr. Thus, in a slotting operation, essentially no burr will occur on half of edges 5 and 8, and a roll-over burr will occur on the other half. Because the angle at which the cutting edges exit from the workpiece varies as the tool enters and exits from the cut, the roll-over burr length will vary on these edges. It is also significant to note that the exit burr on these two edges, as well as on edge 9, is actually a series of burrs. Each tooth produces a complete burr. However, these burrs are connected to each other to form a band of burrs which extends across the tool exit portion of the edge.

The Poisson Burr

A Poisson burr forms on edges 1, 2, and 10. This burr occurs whenever the cutting edge extends past an edge of the workpiece (Figure 13). In essence, it is the lateral deformation that occurs whenever any solid is compressed. The term *Poisson burr* is derived from the fact that this burr is directly related to Poisson's ratio. The extent of this deformation is a function of the workpiece material, the size and the shape of the contacting body, and the applied load. In the case of a cutting tool in which no rubbing occurs on clearance surfaces, the effective shape of the indenter is a cylinder. Because cutting tools have cutting edge radii of 0.0002 to 0.0050 inch (5.08 to 127.0 μm), the extent of the lateral deformation (burr size) is also relatively small. The actual size of the burr is proportional to cutting edge radius and the applied pressure.

Equations 8 and 9 predict burr size when the burr formation mechanism is assumed to be similar to that of the plastic expansion of a hollow cylinder. While equation 9 underpredicts burr thickness by a factor of 20, these two equations are useful for showing the basic relationships between the significant variables. The major limitation in using these equations (other than underprediction) is in defining the magnitude of the pressure on the cutting edge of the tool.

$$b_L = \left[\frac{h(1+\nu)\sigma_e \exp(-\sqrt{3} \phi_a)}{\sqrt{3} E} \right] \left[- \frac{\sin \phi}{2 (\sqrt{3} \cos \phi + \sin \phi)} \right], \quad (8)$$

$$b_t = r \left[e^{-\sqrt{3} \phi_a} \cos \phi_a - 1 \right], \text{ and} \quad (9)$$

Figure 13. Formation of a Poisson Burr

$$\phi_a = -\sin^{-1} \left[\frac{\sqrt{3} P}{2\sigma_e} \right] + \pi/6, \quad (10)$$

where

b_L = burr length,

b_t = burr thickness,

h = depth of cut,

ν = Poisson's ratio for elastic stresses,

σ_e = yield stress of a perfectly plastic material,

E = modulus of elasticity,

r = cutting edge radius,

P = pressure on cutting edge, and

ϕ = angle defining state of plastic flow.

Although the cutter takes the same depth of cut on edge 1 as it does on edge 2, a significant difference in burr properties can occur. This difference is apparently the result of force differences between climb milling and conventional milling and the length of path traversed by the cutting teeth.

No upward force component exists on an end mill having a zero helix angle. Thus, any difference in burrs between edges 1 and 2 can only be the result of the type of cut (climb versus conventional). When, as is typically the case, the tool has a helix angle, there is a tendency for the helix to produce a roll-over burr on top of the Poisson Burr. (Actually, the force systems act at the same time, and thus the burr is a composite rather than one distinct burr on top of another.) When the cutting edge (along the helix) enters the cut at point 1' (Figure 4), it begins rolling up a chip. This chip is rolled approximately perpendicular to the helix angle. When the helix reaches point 1'', the maximum chip length has been produced. If this chip were uncurled before it was sheared from the edge, point 1' would be at point 1'''.

The maximum height of the burr would be

$$b_{h \max} = l, \quad (11)$$

where

l = axial depth of cut (slot depth).

The lateral dimension w to point 1''' would be

$$w = \frac{l}{\tan \theta}, \quad (12)$$

where θ is the helix angle of the tool.

In actual practice, the burr size will seldom approach that shown in Figure 14 because the severe strain induced by chip curling causes the chip to break into many pieces. In addition, for feedrates above 0.002 inch (50.8 μ m) per revolution, as each cutting edge rotates, it shears off the burr left by the previous cutting edge. On edges 1 and 2, however, each cutting edge leaves a short arc of material (and its burr) from the previous cut (Figure 15). Thus, the burr along these edges is actually a series of burrs. From Figures 14 and 15, it is apparent that burr height is proportional to the axial depth of cut, the feedrate, and the helix angle.

Figure 14. Maximum Possible Size and Shape of Helix-Generated, Roll-Over Burr

Figure 15. Enlarged View of Edges 1 and 2

High-speed movies of end mills at feedrates of 0.002 inch or less indicate that the burr formed in front of the cutter increases in height with each revolution of the cutter. Periodically, the cutter takes enough material to completely cut off this burr.

Material Effects

As a general rule, long burrs will not form in brittle materials. The heat generated in some processes, however, is sufficient to anneal the material during burr and chip formation. When this happens, a burr will occur that is larger than predicted. This is particularly true of heat-sensitive, brittle materials.

Burrs are harder than the parent material because they are the result of severe straining. Most materials strain-harden by the relationship given in equation 13.

$$\sigma = \sigma_0 \epsilon^n, \quad (13)$$

where

σ is the true yield stress,

σ_0 is a material constant,

ϵ is the true strain, and

n is the strain-hardening exponent.

Since material hardness is a linear function of the yield strength, it is obvious that the more the material is strained, the harder it will become. Because not all the material in a burr is strain-hardened equally, measurements of hardness are made at the root of the burr (Figure 16).

Climb Cut Versus Conventional Cut

Throughout this discussion, a conventional cut has been tacitly assumed. When a climb cut is utilized, the burr properties will differ from the conventional cut. The burr normally produced at edge 1 will be produced at edge 2. A similar transformation occurs at other edges. To minimize confusion, climb-milled edges in the remainder of the report will be identified as edges 2, 4, and 7, corresponding to the climb-milled edges in a slotting operation.

Test Results

Four tests were performed to determine burr properties from end milling. In the first test, 128 combinations of cutting conditions and material were evaluated. Burrs were measured at seven of the 10 edges. In the second test, effects of tool wear on burr properties were studied. In the third test, the effects of end-milling Hiperco 50 (a highly magnetic material) were recorded. In the fourth test, the effects of helix angle were briefly studied. As previously indicated, high-speed motion pictures were also taken of burrs as they formed on edges 1 and 2.

Effects of Machining Conditions

In the first test, 128 combinations of cutter diameter, axial depth of cut, radial depth of cut, feedrate, tool sharpness, and workpiece material were studied. One specimen was produced at each combination of the factors shown in Table 1. All cutters were high-speed steel and were rotated at 1115 RPM. A water soluble coolant was used on all cuts.

Figures 1 and 2 illustrate how the specimens were machined and the location of burrs studied. All specimens were ground prior to machining in the shape of a cube with 1.0-inch (25.4 mm) sides. Burr heights were then measured optically. Specimens were then cross-sectioned, mounted in metallurgical mounts, and polished to show the cross section of burrs 1, 2, 3, 5, 6, 7, and 9. Both height and thickness were then recorded on these burrs. The mounted specimens were then ground down, optically repolished, and again burr height and thickness were measured. This provided two measurements on each burr.

Figure 16. Definition of Burr Properties

The data were analyzed as a $2^5 \times 4$ factorial design, having one repeat (two measurements) for each of the 128 cutting combinations. The analysis of variance (ANOVA) of the results is indicated in Tables 2, 3, and 4. The asterisks in these tables indicate combinations which statistically affected burr size. The tool diameter, for example, influenced the height of the burr on edges 1, 2, 5, and 9, but the diameter did not affect the height of burrs on edges 3, 6, or 7.

While the ANOVA indicates statistically significant variables, it does not of itself indicate whether the variable increases or decreases the burr size. Plotting the data, however, reveals the nature of the trends. The ANOVA tables indicate the existence of a large number of higher order interactions; that is, combinations of variables which affect burr size much more than one would predict from a knowledge of average trends. Plotting these significant interactions would require at least 100 graphs. At this time, such an analysis does not seem warranted.

Text continued on page 49.

Table 1. End-Milling Conditions Used

Code Level	A	B	C	D	E	F	G
	Tool Diameter (in.)*	Depth of Cut		Feed (IPR/t)	Tool Sharpness (in.)*	Workpiece Material	Hardness (R _C)
		Axial (in.)*	Radial (Percent Diameter)				
1	0.250**	0.050	0.1	0.0005	Sharp	17-4 PH SST (H 900)	46
2	0.375**	0.100	1.0	0.0020	0.001 R	303 Se SST	24
3						6061-T6 Aluminum	63
4						1018 steel	90

*0.001 inch equals 25.4 μ m

**Bendix Kansas City tool numbers 51105222 and 5113202. Descriptions are presented in Apendix B.

Table 2. ANOVA of Burr Height

Effect	Edge Number						
	1	3	6	2	5	7	9
Tool Diameter A (A)†	*			*	***		*
Axial Depth B (B)		*		*	***		
Radial Depth C		***		-	-	-	-
Feed Rate D (C)	***		*	***		***	***
Tool Sharpness E (D)	***	***		*	***		***
Workpiece Material F (E)	*	**	*	*	**	***	
Tool Diameter x Axial Depth				*	**		
Tool Diameter x Radial Depth			*	-	-	-	-
Tool Diameter x Feed Rate			*	*			
Tool Diameter x Tool Sharpness		**			***	**	
Tool Diameter x Workpiece Material	*	**	**		***		**
Axial Depth x Radial Depth				-	-	-	-
Axial Depth x Feed Rate				**		**	
Axial Depth x Tool Sharpness					***		
Axial Depth x Workpiece Material			*		***	**	
Radial Depth x Feed Rate				-	-	-	-
Radial Depth x Tool Sharpness		***		-	-	-	-
Radial Depth x Workpiece Material		***		-	-	-	-
Feed Rate x Tool Sharpness			*				
Feed Rate x Workpiece Material	*	**		*		**	
Tool Diameter x Axial Depth x Radial Depth	*	*	**	-	-	-	-
Tool Diameter x Axial Depth x Feed Rate						*	
Tool Diameter x Axial Depth x Tool Sharpness				***	*		
Tool Diameter x Axial Depth x Workpiece Material	*	**	**	*	***		
Tool Diameter x Radial Depth x Feed Rate				-	-	-	-

Table 2 Continued. ANOVA of Burr Height

Effect	Edge Number						
	1	3	6	2	5	7	9
Tool Diameter x Radial Depth x Tool Sharpness				-	-	-	-
Tool Diameter x Radial Depth x Workpiece Material		**		-	-	-	-
Tool Diameter x Feed Rate x Tool Sharpness		*					
Tool Diameter x Feed Rate x Workpiece Material	*			*	*	**	
Tool Diameter x Tool Sharpness x Workpiece Material		**		*	***	**	
Axial Depth x Radial Depth x Feed Rate				-	-	-	-
Axial Depth x Radial Depth x Tool Sharpness				-	-	-	-
Axial Depth x Radial Depth x Workpiece Material	*	*	*	-	-	-	-
Axial Depth x Feed Rate x Tool Sharpness			*				
Axial Depth x Feed Rate x Workpiece Material				*		**	
Axial Depth x Tool Sharpness x Workpiece Material	*	**			***		
Radial Depth x Feed Rate x Tool Sharpness		*		-	-	-	-
Radial Depth x Feed Rate x Workpiece Material	*			-	-	-	-
Radial Depth x Tool Sharpness x Workpiece Material	*	*		-	-	-	-

*Indicates significant at 95-percent confidence level.
 **Indicates significant at 99-percent confidence level.
 ***Indicates significant at level much greater than 99-percent.
 †Because of the nature of the test, burr numbers 2, 5, 7, and 9 are only produced on half of the parts. The variable codes (A, B, C, D, E, and F) were renamed for these burrs, as indicated by the code letter in brackets.

Table 3. ANOVA of Burr Thickness

Effect	Edge Number						
	1	3	6	2	5	7	9
Tool Diameter A (A)†	*						
Axial Depth B (B)							
Radial Depth C			*	-	-	-	-
Feed Rate D (C)		**		*	*		
Tool Sharpness E (D)	***	***		**	*	*	***
Workpiece Material F (E)	*	*	**		*		
Tool Diameter x Axial Depth				*		**	
Tool Diameter x Radial Depth			**	-	-	-	-
Tool Diameter x Feed Rate							
Tool Diameter x Tool Sharpness							*
Tool Diameter x Workpiece Material		**				**	*
Axial Depth x Radial Depth				-	-	-	-
Axial Depth x Feed Rate							
Axial Depth x Tool Sharpness							
Axial Depth x Workpiece Material						*	
Radial Depth x Feed Rate				-	-	-	-
Radial Depth x Tool Sharpness		**		-	-	-	-
Radial Depth x Workpiece Material	*		*	-	-	-	-
Feed Rate x Tool Sharpness					*		
Feed Rate x Workpiece Material					*	**	
Tool Diameter x Axial Depth x Radial Depth				-	-	-	-
Tool Diameter x Axial Depth x Feed Rate							
Tool Diameter x Axial Depth x Tool Sharpness		***				*	
Tool Diameter x Axial Depth x Workpiece Material					**		
Tool Diameter x Radial Depth x Feed Rate				-	-	-	-

Table 3 Continued. ANOVA of Burr Thickness

Effect	Edge Number						
	1	3	6	2	5	7	9
Tool Diameter x Radial Depth x Tool Sharpness			*	-	-	-	-
Tool Diameter x Radial Depth x Workpiece Material		***		-	-	-	-
Tool Diameter x Feed Rate x Tool Sharpness						*	
Tool Diameter x Feed Rate x Workpiece Material	-					**	
Tool Diameter x Tool Sharpness x Workpiece Material		*					**
Axial Depth x Radial Depth x Feed Rate				-	-	-	-
Axial Depth x Radial Depth x Tool Sharpness				-	-	-	-
Axial Depth x Radial Depth x Workpiece Material			*	-	-	-	-
Axial Depth x Feed Rate x Tool Sharpness							
Axial Depth x Feed Rate x Workpiece Material						**	
Axial Depth x Tool Sharpness x Workpiece Material		**				**	
Radial Depth x Feed Rate x Tool Sharpness				-	-	-	-
Radial Depth x Feed Rate x Workpiece Material				-	-	-	
Radial Depth x Tool Sharpness x Workpiece Material				-	-	-	-

Table 3. Continued. ANOVA of Burr Thickness

Effect	Edge Number						
	1	3	6	2	5	7	9
Feed Rate x Tool Sharpness x Workpiece Material							*
<p>*Indicates significant at 95-percent confidence level. **Indicates significant at 99-percent confidence level. ***Indicates significant at level much greater than 99-percent. †Because of the nature of the test, burr numbers 2, 5, 7, and 9 are only produced on half of the parts. The variable codes (A, B, C, D, E, and F) were renamed for these burrs, as indicated by the code letter in brackets.</p>							

Table 4. ANOVA Summary of Effects on Burr Radius

Effect	Burr Number					
	1	3	2	5	7	9
Tool Diameter A (A)†						
Axial Depth B (B)	*					
Radial Depth C		*	-	-		
Feed Rate D (C)		*		*		
Tool Sharpness E (D)	*		*			
Workpiece Material F (E)	*			*		*
Tool Diameter x Axial Depth						
Tool Diameter x Radial Depth			-	-	-	
Tool Diameter x Feed Rate	*					
Tool Diameter x Tool Sharpness						
Tool Diameter x Workpiece Material						
Axial Depth x Radial Depth			-	-	-	
Axial Depth x Feed Rate						
Axial Depth x Tool Sharpness						
Axial Depth x Workpiece Material						
Radial Depth x Feed Rate			-	-	-	
Radial Depth x Tool Sharpness			-	-	-	
Radial Depth x Workpiece Material		*	-	-	-	
Feed Rate x Tool Sharpness						
Feed Rate x Workpiece Material			*	*		
Tool Sharpness x Workpiece Material						*
Tool Diameter x Axial Depth						
x Radial Depth			-	-	-	
Tool Diameter x Axial Depth						
x Feed Rate						
Tool Diameter x Axial Depth						
x Tool Sharpness	*	*		*		
Tool Diameter x Axial Depth						
x Workpiece Material						
Tool Diameter x Radial Depth						
x Feed Rate			-	-	-	

Table 4 Continued. ANOVA Summary of Effect on Burr Radius

Effect	Burr Number					
	1	3	2	5	7	9
Tool Diameter x Radial Depth x Tool Sharpness		*	-	-	-	
Tool Diameter x Radial Depth x Workpiece Material			-	-	-	
Tool Diameter x Feed Rate x Tool Sharpness		*		*		
Tool Diameter x Feed Rate x Workpiece Material				*		
Tool Diameter x Tool Sharpness x Workpiece Material		*	*		*	
Axial Depth x Radial Depth x Feed Rate			-	-	-	
Axial Depth x Radial Depth x Tool Sharpness			-	-	-	
Axial Depth x Radial Depth x Workpiece Material			-	-	-	
Axial Depth x Feed Rate x Tool Sharpness						
Axial Depth x Feed Rate x Workpiece Material						
Axial Depth x Tool Sharpness x Workpiece Material				*		
Radial Depth x Feed Rate x Tool Sharpness			-	-	-	
Radial Depth x Feed Rate x Workpiece Material			-	-	-	
Radial Depth x Tool Sharpness x Workpiece Material			-	-	-	

Table 4 Continued. ANOVA Summary of Effect on Burr Radius

Effect	Burr Number					
	1	3	2	5	7	9
Feed Rate x Tool Sharpness x Workpiece Material						*

†Because of the nature of the test, burr numbers 2, 5, 7, and 9 are only produced on half of the parts. The variable codes (A, B, C, D, E, and F) were renamed for these burrs, as indicated by the code letter in brackets.

*Indicates that the factor, or combination of factors, shown is statistically significant at the 95-percent confidence level.

To provide a readable and usable analysis, only part of the data have been presented in a graphical format:

- All the significant main effects which have been plotted are presented on subsequent pages.
- In addition to plots of significant main effects, plots of burr size as a function of tool sharpness and feedrate have been included for 303 Se and 17-4 PH stainless steel when these plots revealed some notable trends.

No plot is shown for the effect of tool diameter on the burr height at edge 3, since the ANOVA table indicated that no significant trends existed. Plots for the main effects are an average of results for all four materials used in this study. No graphs are presented specifically for aluminum or low-carbon steel. These materials were not plotted, primarily because burrs in stainless steel are more representative of typical Bendix production situations. In the interest of brevity, tool diameter, axial depth of cut, and radial depth of cut are not plotted in most cases, and also because the geometry of the part dictates these factors in production situations. Production personnel, however, can readily control feedrate and tool sharpness; therefore, graphs are presented for these factors. The fact that many combinations have not been plotted does not imply that they are not significant, but only that they are of less direct interest to production. While three factor interactions are significant, it is difficult to use them in production. Since actual burr measurements are presented in Appendix A of this report, it is possible to evaluate any combination not specifically plotted.

Average burr property data are presented in Table 5. As shown, burr height varies from 0.0001 inch (2.5 μm) to 0.0700 inch (1.778 mm), depending upon the edge on which the burr is found. Burr thickness typically varies from 0.002 to 0.004 inch (50.8 to 101.6 μm), while the radius on the backside of the burr varies from 0.001 to 0.002 inch (25.4 to 50.8 μm). Metallurgical mounts were not made of edges 4 and 6. The values shown for them in Table 5 were obtained from optical measurements prior to sectioning the samples. Burr thickness and radius could not be accurately measured without metallurgical mounts so data is not available for these properties at edges 4 and 8. Because of the extremely small size of burrs on edge 6, it was not possible to obtain measurements of burr radius on this edge.

Burr Height

The end-mill diameter influenced burr height on four edges (Figure 17). On edges 2 and 5, a larger cutter produced higher

Table 5. Typical Burr Properties From End Milling

Burr Location (Edge Number)	Burr Height (in.)*	Burr Thickness (in.)*	Burr Radius (in.)*
	17-4 PH Stainless Steel		
1	0.0081	0.0022	0.0014
2	0.0113	0.0020	0.0012
3	0.0365	0.0035	0.0018
4	0.0052	--	--
5	0.0058	0.0026	0.0016
6	0.0014	0.0013	--
7	0.0168	0.0033	0.0012
8	0.0031	--	--
9	0.0050	0.0022	0.0012
	303 Se Stainless Steel		
1	0.0087	0.0023	0.0016
2	0.0084	0.0021	0.0015
3	0.0650	0.0035	0.0017
4	0.0121	--	--
5	0.0105	0.0035	0.0023
6	0.0010	0.0009	--
7	0.0289	0.0042	0.0020
8	0.0048	--	--
9	0.0036	0.0029	0.0023

Table 5 Continued. Typical Burr Properties From End Milling

Burr Location (Edge Number)	Burr Height (in.)*	Burr Thickness (in.)*	Burr Radius (in.)*
6061-T6 Aluminum			
1	0.0053	0.0014	0.0007
2	0.0059	0.0018	0.0011
3	0.0500	0.0029	0.0015
4	0.0048	--	--
5	0.0146	0.0029	0.0014
6	0.0003	0.0006	--
7	0.0208	0.0033	0.0016
8	0.0061	--	--
9	0.0047	0.0022	0.0009
1018 Steel			
1	0.0083	0.0021	0.0014
2	0.0061	0.0023	0.0012
3	0.0699	0.0037	0.0017
4	0.0089	--	--
5	0.0165	0.0038	0.0020
6	0.0001	0.0004	--
7	0.0078	0.0033	0.0016
8	0.0022	--	--
9	0.0063	0.0026	0.0024
*0.001 inch equals 25.4 μ m.

Figure 17. Effect of Cutter Diameter on Burr Height at Edges 1, 2, 5, and 9

Figure 18. Effect of Axial Depth of Cut on Burr Height at Edges 2, 3, and 5

burrs. On edges 1 and 9, burr height decreased with increasing cutter diameter. No effect was noted on edges 3, 6, and 7. Although the changes were notable, there is nothing in the rationale of burr formation that accounts for the effect of cutter diameter.

Increasing the axial depth of cut reduced burr height on edges 2 and 5, but increased it on edge 3 (Figure 18). From the nature of the cutting action, the burr produced by the bottom of the cutter (edge 5) should be independent of axial depth of cut as should the roll-over burr produced at edge 3. From the discussion of burr formation, increasing the depth of cut should increase the height of the burr at edge 2. Figure 18 fails to confirm any of these observations, however.

Increasing the radial depth of cut increased the height of the burr at edge 3 (Figure 19). This is consistent with the theory of the formation of this burr.

Increasing the feedrate lowered the burr height on most edges (Figure 20). This is probably the result of two factors. At low feedrates, cutter rubbing occurs, which increases burr formation forces. On edges 1 and 2, low feedrates do not allow the tool to cut away the burr formed by the previous flute. High-speed movies indicate that at low feedrates the burr height in front of the cutter grows with each pass of a flute.

Dull tools create higher burrs (Figure 21). This is particularly evident for the burr produced on edge 3. Burr height doubled when the cutting edge radius increased from near zero to a 0.001-inch (25.4 μm) radius.

Burr height was a function of workpiece material as well as edge location (Figure 22). As a general rule, the shortest burrs occurred on 17-4 PH stainless steel and 6061-T6 aluminum.

While burr height in the two stainless steel materials often followed similar patterns, there were many differences (Figures 23 to 31). For example, on edge 1, a sharp tool at a low feedrate resulted in the smallest burr (Figure 23). On edge 2, a sharp tool and a fast feedrate produced the smallest burr (Figure 24). On edge 3, minimum burr height is a function of workpiece material (Figure 25).

Burr Thickness

Increasing the cutter diameter decreased the thickness of the burr on edge 1 (Figure 32), but did not affect the thickness of any other burr. Increasing the radial depth of cut increased

Figure 19. Effect of Radial Depth of Cut on Burr Height at Edge 3

Figure 20. Effect of Feedrate on Burr Height at Edges 1, 2, 6, 7, and 9

Figure 21. Effect of Tool Sharpness on Burr Height at Edges 1, 2, 3, 5, and 9

the thickness of the burr at edge 6 (Figure 33), but did not affect the thickness of any other burr. The axial depth of cut did not affect any burr thicknesses.

Increasing the feedrate resulted in thicker burrs on edges 3 and 5 but resulted in a thinner burr on edge 2 (Figure 34). Other edges were not affected. By theory, burr thickness at edge 3 should increase with feedrate as should thickness at edges 5, 7, and 9. The thinner burr at edge 2 is probably the result of decreased rubbing. It will be noted that the primary burr formation at edge 2 is due to the Poisson effect, while the roll-over burr phenomenon is responsible for the burr at edges 3, 5, 7, and 9.

Dull tools produced thicker burrs on all edges excepting edge 6 (Figure 35). This is in agreement with the general theories of burr formation.

As a general rule, burrs in aluminum were thinner than those in other materials (Figure 36). There was little difference in the average burr thickness of the other three materials.

With only three notable exceptions, burr thickness in 303 Se and 17-4 PH were practically identical (Figures 37 to 43). Low feedrates and dull tools typically resulted in the thickest

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Figure 22. Burr Height as a Function of Workpiece Material

Figure 23. Edge 1: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 24. Edge 2: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 25. Edge 3: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 26. Edge 4: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 27. Edge 5: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 28. Edge 6: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 29. Edge 7: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 30. Edge 8: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 31. Edge 9: Effect of Feedrate and Tool Sharpness on Burr Height

Figure 32. Edge 1: Effect of Cutter Diameter and Burr Thickness

Figure 33. Edge 6: Effect of Radial Depth of Cut on Burr Thickness

Figure 34. Effect of Feedrate of Burr Thickness at Edges 2, 3, and 5

Figure 35. Effect of Tool Sharpness on Burr Thickness

Figure 36. Effect of Workpiece Material on Burr Thickness

Figure 37. Edge 1: Effect of Feedrate and Tool Sharpness on Burr Thickness

Figure 38. Edge 2: Effect of Feedrate and Tool Sharpness on Burr Thickness

Figure 39. Edge 3: Effect of Feedrate and Tool Sharpness on Burr Thickness

Figure 40. Edge 5: Effect of Feedrate and Tool Sharpness on Burr Thickness

Figure 41. Edge 6: Effect of Feedrate and Tool Sharpness on Burr Thickness

Figure 42. Edge 7: Effect of Feedrate and Tool Sharpness on Burr Thickness

Figure 43. Edge 9: Effect of Feedrate and Tool Sharpness on Burr Thickness

Figure 44. Edge 1: Effect of Axial Depth of Cut on Burr Radius

burrs while high feedrates with sharp tools produced the thinnest burrs. For the conditions tested, the worst burrs were twice as thick as those produced under the best conditions.

Burr Radius

As indicated in Table 4, no single variable affected the radius on the backside of the burr on all edges. The tool diameter did not influence the burr radius on any edge.

Deeper cuts produced small burr radii on edge 1, (Figure 44). Dull tools increased the burr radius on edges 1 and 2 (Figure 45), but not elsewhere. Increasing radial depth of cut increased the burr radius on edge 3 (Figure 46). Increasing the feedrate increased the burr radius of the roll-over burrs on edges 3 and 5 (Figure 47). As a general rule, the smallest burr radii occurred in 6061 aluminum and the largest in 303 Se stainless steel (Figure 48). This result, which corresponds with the strain-hardening exponents, implies that materials with high strain-hardening exponents tend to develop large burr radii.

On edges 1 and 2, the burr radii for the two stainless steel materials were nearly identical (Figures 49 and 50). High feedrates and sharp tools produced the smallest burr radii. On the other edges, a notable difference existed between the two materials (Figures 51 to 54).

Effects of Tool Wear on Burr Properties

The second test was a study of how burr properties vary with end-mill wear. A high-speed steel, four-flute, end mill was used to mill a 0.200-inch-deep (50.8 mm) full-diameter slot in 303 Se stainless steel. A spindle speed of 845 rpm and a feed of 0.0005 IPR/t ($12.7 \mu\text{m}/\text{rev}/\text{tooth}$) was used. A water-soluble spray mist coolant was used throughout the cuts. Burrs on edges 1 and 2 were measured at various points throughout the cut. A total of 261 inches of cut were made in this study. Burr height was measured optically after machining. Both height and thickness were also measured subsequently from metallurgical mounts.

An analysis of burr height variations as a function of length of cut traversed indicated that no real correlation existed. The data from this study are presented in Appendix A, Table A-2. Linear regressions of the data could only account for 4 percent of the data scatter. The average height of burrs at location 1 was 0.0062 inch ($157.5 \mu\text{m}$). At location 2, the average burr height was 0.0033 inch ($83.8 \mu\text{m}$). The standard deviation of the data was 0.0034 and 0.0027 inch (84 and $69 \mu\text{m}$), respectively. The typical wide variation in height results are shown in Figure 55.

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Figure 45. Edges 1 and 2: Effect of Tool Sharpness on Burr Radius

Figure 46. Edge 3: Effect of Radial Depth of Cut on Burr Radius

Figure 47. Edges 3 and 5: Effect of Feedrate on Burr Radius

Figure 48. Edges 1, 5, and 9: Effect of Workpiece Material on Burr Radius

Figure 49. Edge 1: Effect of Feedrate and Tool Sharpness on Burr Radius

Figure 50. Edge 2: Effect of Feedrate and Tool Sharpness on Burr Radius

Figure 51. Edge 3: Effect of Feedrate and Tool Sharpness on Burr Radius

Figure 52. Edge 5: Effect of Feedrate and Tool Sharpness on Burr Radius

Figure 53. Edge 7: Effect of Feedrate and Tool Sharpness on Burr Radius

Figure 54. Edge 9: Effect of Feedrate and Tool Sharpness on Burr Radius

Figure 55. Burr Height at Edge 1 as a Function of Length of Cut

Similar wide data scatter was observed for burr thickness and radius. No correlation was observed between these properties and length of cut or between the various burr properties. The average burr thickness was 0.0032 inch (81 μm) at edge 1, and 0.0013 (33.0 μm) at edge 2. The standard deviation of these measurements was 0.0019 and 0.0009 inch (48.3 and 22.9 μm), respectively. The average burr radii were 0.0008 inch (20.3 μm) at edge 1 and 0.0026 inch (66.0 μm) at edge 2. The standard deviation of these measurements was 0.0010 and 0.0024 inch (25.4 and 61.0 μm), respectively.

End Milling Hiperc 50

While in general it is true that large burrs do not occur in brittle materials, there are some notable exceptions. Hiperc 50 which, with an elongation of less than 0.5 percent, in a 2-inch (50.8 mm) gage length, is considered a brittle material, is one of these exceptions.

Finish pass profiling cuts of 0.002- to 0.003-inch radial depth (50.8 to 76.2 μm) were taken on a slotted cylinder (Figure 56). These cuts were made with a high-speed, steel, four-flute end mill at 0.00011 inch/rev/tooth (2.79 $\mu\text{m}/\text{rev}/\text{tooth}$) at 4500 rpm with a water-soluble coolant. The axial depth of cut was 0.080 inch (2.03 mm). As shown in Table 6, burr thicknesses were typically 0.0021 inch (53.3 μm), and burr heights ranged from 0.0058 to 0.0201 inch (147.3 to 510.5 μm). Although the machining conditions are sufficiently different to prevent direct comparison with the previous data, it is instructive to note that these burrs are roughly half the size of those produced in the ductile materials. The hardness of the burrs averaged R_c52 , while the parent material was only R_c30 .

The largest single factor in the size of these burrs must be the rubbing which occurs when low feedrates are used. The material gets hot, then softens when rubbing occurs, and becomes a plastic rather than a brittle material in the area where the burr is produced. While the obvious solution to minimize this problem is to increase the feedrate, this is not always possible because feedrate increases can raise cutting forces which distort thin walls. As a general rule, however, increasing feedrates up to 0.001 inch/rev/tooth (25.4 $\mu\text{m}/\text{rev}/\text{tooth}$) reduces cutting forces.

Effect of Helix Angle

The effect of the helix angle on burr size was briefly studied in one test. In this study, a full-diameter slot was produced in the end of a 303 Se stainless steel bar, at a feedrate of 0.0011 inch/rev/tooth (27.9 $\mu\text{m}/\text{rev}/\text{tooth}$) and a spindle speed of 1750 rpm. Cutter diameters varied from 0.250 to 0.375 inch

Figure 56. Specimen Used in Hiperco 50
End-Milling Study

(6.35 to 9.53 mm). The helix angles used included 32, 0, and -13 degrees where a negative angle implies a left-hand spiral right-hand cut.

While the left-hand spiral cutter produced slightly shorter burrs on edges 1 and 2 than did the conventional cutter, it did not eliminate the burr (Table 7). This is consistent with the theory of burr formation when a large roll-over burr does not occur on these edges. The reverse helix tool produced a much longer burr at edge 7 than did the other cutters. The zero degree helix tool produced much higher burrs on edges 1 and 2 than did the standard or the reverse helix, which was unexpected.

The Appearance of Milling Burrs

Burrs exist in many forms. For example, if entrance burrs exist at edge 6 they are small mounds of material. The roll-over burrs are long flaps of material having a rectangular cross section. The burrs on edges 1 and 2 can be a short, uniform, triangular

Table 6. Properties of Burrs Produced by End Milling
Hiperco 50

Property	Burr Size (in.)*			
	Edge Location			
	3	4	6	7
Height	0.0201	0.0065	0.0058	0.0179
Thickness	0.0020	0.0021	0.0008	0.0022
*(0.001 inch equals 25.4 μ m)				

spike, as shown in Figure 16, or they can have a loose, feathery appearance, as shown in Figure 57. On some parts, only one or two strands are evident, while on other the entire edge is covered with these feathery burrs. Although these projections are easily wiped off, the root of the burr, in the form of a triangular spike, is still present.

The burrs illustrated in Figures 58 and 59 were produced by slotting a hollow cylinder at 0.00005/inch/rev/tooth (1.27 m/rev/tooth) and 2720 rpm. The four-flute, solid-carbide cutter was 0.069 inch (1.75 mm) in diameter and had a 30-degree helix. The workpiece material was in the H900 condition.

The appearance of the burr on edge 1 can be significantly different from that on edge 2, as shown in Figures 58 and 59. Figure 58 is a photograph of the burr on edge 1, in 17-4 PH stainless steel. The burr on edge 2 in this slotting application is obviously much larger and stiffer. In both cases, the obvious part of the burr is formed by chip roll-over. The *fingers* projecting from both are the result of tears occurring in the chip. All burrs produced with a dull tool at these edges had the feathery appearance. Although the burrs produced by the sharp tools also had some of this appearance, it was very minute. Figures 60, 61, and 62 provide some additional comparisons of burrs at these edges.

The burrs on edges 5, 8, and 9 assume at least two forms. Figure 63 illustrates the scallop nature of burrs produced at edge 9 by a face mill. In this type of application, burr height is a function of cutter diameter and location relative to the edge of the part, in addition to the parameters already indicated. In general, the burrs on these edges are not as regular, as shown in Figure 60.

Text continued on page 86.

Table 7. Effect of Helix Angle on Burr Size

Diameter (in.)*	Helix Angle (Degrees)	Location							
		1	2	3	4	5	6	7	8
		Burr Height (in.)							
0.265	32	0.0030	0.0045†	0.200	0	0.0026 max	0	0.0280	0.0015 max
0.250	0	0.0350	0.0157††	**	0	0.0060 max	0.0020	0.0220	0.0055 max
0.375	-12	0.0024	0.0013	0.325	0	0.0060 max	0	0.1000	0.0020 max
		Burr Thickness (in.)							
0.265	32	***	0.0015	0.0010	0	0.0030	0	0.0070	0.0010
0.250	0	0.0023	0.0010	0.0020	0	0.0025	0.0080	0.0060	0.0020
0.375	-12	0.0020	0.0015	0.0030**	0	0.0018	0	0.0050	0.0016

*0.001 inch equals 25.4 μ m.

**The large portion of this burr broke loose in handling.

***Not accurately determined.

†Individual fragments are up to 0.060 inch long.

††Individual fragments are up to 0.150 inch long.

Figure 57. Feathery Burr on Edge 1, Produced by Face-Milling Low-Carbon Steel

Figure 58. Feathery Burr on Edge 1, Produced by Slotting 17-4 PH Stainless Steel

Figure 59. Feathery Burr on Edge 2, Produced by Slotting 17-4 PH Stainless Steel

Figure 60. Small Burrs Produced on Edge 1 With Sharp End Mill in 1018 Steel ($R_c 20$)

Figure 61. Feathery Burr on Edge 1, Produced by Dull End Mill in 1018 Steel ($R_c 20$)

Figure 62. Feathery Burr on Edge 1, Produced by End Milling 6061-T6 Aluminum

Figure 63. Uniform Burr Formed on Edge 9, Produced by a Face Mill in 1018 Steel

Effects of Measurement Approaches

Data on burr properties are dependent upon the technique used to measure the burrs.²⁸ Measurement of the burrs on edges 1 and 2, in particular, are susceptible to the technique used. As an example, Table 8 presents the results of optically measuring the burrs from the end-mill wear test prior to mounting and after encapsulation. As shown, the measurements made from metallurgical mounts are much smaller than those made prior to mounting. The standard deviation of the data is also much smaller for the mounted specimen. The reason for this can be appreciated by analyzing the previous photographs. Defining the average burr height is very difficult when one has an edge to evaluate like that of Figure 57. By cross sectioning and mounting this edge, one has only a single projection to view, which simplified the measurement. At the same time, however, it is apparent that the height data will depend upon where the cross section is made (Figure 57). If the burr were more uniform, the difference between techniques would be less noticeable. Unfortunately, on many edges burr height varies considerably.

Another decision which has to be made is whether to measure the height of the individual projections or the height of the basic group the projections are in. Figure 64 illustrates the difference in these two approaches. Based on the mechanism by which the burrs form, the group height is a more meaningful measurement. If the tears did not occur, the group height would be the only burr height (Figure 59).

From a theoretical standpoint, the burrs on edge 5 should be similar to those shown in Figures 65A or 65B. While most were similar to these two, a burr was often observed on the right-hand side of the edge as shown in Figures 65C and 65D. Similar although smaller effects were observed on edge 8.

In the first study, an ANOVA was prepared for the measured data, then samples were ground down, and a second set of data was obtained. An ANOVA was then performed on the combined two sets of data. No significant differences were observed between the two ANOVAs, although more interactions appeared significant on the data set with repeated data. This indicates that repeated measurements are not necessary in a study of this magnitude and nature. As previously indicated,²⁷ this is not always the case.

Analysis of Previously Published Data

Only two reports have been published on the burrs produced by end milling. In the first report,¹ the effects of helix angle and feedrate on burr thickness, height, and hardness were briefly studied. Beryllium copper and 303 Se stainless steel were used

Table 8. Influence of Measuring Technique on Observed Burr Length

Feature	Burr Height (in.)*			
	Edge Number			
	1		2	
	Optically	Mount	Optically	Mount
Average Value	0.0135	0.0062	0.0196	0.0033
Standard Deviation	0.0083	0.0034	0.0098	0.0027

*0.001 inch equals 25.4 μm .)

in this study, and burrs were monitored on edges 1 and 9. Feed-rates varied from 0.0008 to 0.0015 inch/rev/tooth (20.3 to 38.1 μm /rev/tooth).

The helix angle did not affect the height or thickness of the burrs. Low helix angles appeared to result in softer burrs on edge 9 in beryllium copper. Slow feedrates tended to increase burr height on both edges in beryllium copper, but they did not influence the results in 303 Se stainless steel. Slow feedrates did increase the hardness of burrs in the stainless steel workpieces. At slow feeds, burr hardness was roughly five R_c points higher than the original workpiece hardness, while the increase was roughly one point at the faster feedrate.

The fact that these results are not entirely consistent with the results of the current study is due to the brevity of the previously reported study. Only eight samples were evaluated versus 128 in the current study. Helix angle effects do warrant additional study, however, even though the data reported to date does not show dramatic reductions.

In the second reported study², the effects of cutter diameter, radial depth of cut, and feedrate on burr height were evaluated in 303 Se stainless steel. Thirty-six combinations were evaluated. Burr height was measured with mechanical height gage indicators. As a general rule, increasing feedrate lowered burr height or produced no change. Burr heights also tended to increase radial depth of cut.

Figure 64. Possible Definitions of Burr Height for Feather-Like Burrs

Although radial depth of cut affected only the height of the burr on edge 3 in the current study (Table 2), it should be noted that Table 2 is based on the average results of four materials. A separate examination of the data for 303 Se stainless steel only indicates that burr height on edges 1, 3, and 6 increases by at least a factor of 2 when radial depths of cut increase from 10 to 100 percent of the cutter diameter. Increasing feedrates, as previously indicated, does lower burr height. As shown in Table 9, the burr heights from the published study are considerably smaller than those from the current study, even though the same range of cutting conditions was used.

If feathery or flexible burrs are present, as in Figure 57, it is easy to see why mechanical indicators will not indicate the true burr height on some edges. These burrs simply bend over in such a way that the true height is not recorded. From the standpoint of burr removal, however, readings from mechanical indicators may be more significant since they indicate the height of the *tough* portion of the burr.

Production Implications

The impetus for this study was a need to determine what could be done to minimize the size of milling burrs. Short, thin burrs can easily be removed by almost any deburring process without

65A. TYPICAL BURR APPEARANCE
(SPECIMEN 177)

65B. BURR CONFIGURATION ON
SPECIMEN 176

65C. BURR CONFIGURATION ON
SPECIMEN 175

Figure 65. Shape of Burrs Observed on Edge 5 (Plan View)

Table 9. Burr Heights Obtained in Two Similar Studies

Burr Location	Burr Height (in.)*	
	Method of Measurement	
	Mechanical Indicator**	Optical From Mounts***
1	0.0010	0.0087
2	0.0030	0.0084
3	0.0850	0.0650
4	0.0001	0.0121
5	0.0024	0.0105
6	0.0002	0.0010
7	0.0600	0.0289
8	0.0007	0.0048
9	0.0029	0.0036
10	0.0020	†

*0.001 inch equals 25.4 μm .

**From Reference 2.

***From Table 5.

†Not measured.

noticeably affecting part dimensions. Burrs in the order of 0.004 inch thick (101.6 μm), however, cannot be removed by most mechanized processes without at least 0.0002 inch (5.08 μm) stock loss. On many precision miniature parts, such stock loss is not allowable.

Based on the studies described, burr size can be minimized by three basic approaches.

1. Use feedrates above 0.0005 inch/rev/tooth (12.7 μm /rev/tooth). A feedrate of 0.002 inch/rev/tooth (50.8 μm /rev/tooth) appears to be a reasonable optimum rate.
2. Use sharp tools. Dull tools double burr height and thickness.
3. Use the smallest radial depth of cut possible.

While helix angles somewhat affect burr properties straight flute or reverse spiral cutters do not prevent burr formation.

The fact that eight burrs, each having a different thickness, height, and hardness, are produced in a single cut is of major significance in precision deburring efforts. In a mechanized process, each edge will respond differently because of burr size variations. Vibratory deburring a sharp edge, for example, may produce a 0.005-inch (127 μm) radius, while a burr 0.004 inch thick by 0.020 inch high (101.6 by 500 μm) still remains attached to the part. Under such conditions, it is not possible to produce burr-free edges having 0.002 inch (50.8 μm) maximum edge radii without reverting to manual techniques. Despite popular opinion to the contrary, burrs can form on the edge produced as the cutter enters the workpiece. However, when they occur, these burrs are small.

Burr properties are not very consistent. On a single edge, burr height can vary from 0.001 to 0.060 inch (0.025 to 1.500 mm). Burr thickness and radii also vary significantly, although the actual magnitudes are much smaller. The standard deviation of burr property measurements is often the same order of magnitude as the average value. As an example, the average burr height on edge 1, in the tool wear test, was 0.0032 inch (81.3 μm). The standard deviation of these measurements was 0.0019 inch (48.3 μm). Thus, 95 percent of the readings varied between zero and 0.0070 inch (177.8 μm). Such wide variation along a single edge also affects precision deburring.

While changing machining parameters reduces the size of some burrs, it may increase the size of other burrs. Thus, while increasing feedrate reduces the size of most burrs, or the burrs of most interest, it will increase the size of some and result in no change in others.

Burrs are harder than the parent material in any strain-hardening material. In 303 Se stainless steel, this increase varies from 2 to 10 R_c points.

ACCOMPLISHMENTS

Feedrate and tool sharpness have been shown to be the two most significant variables affecting the size of burrs produced by end milling. Slow feedrates and dull tools caused higher and thicker burrs. Increasing the radial depth of cut also has been shown to increase the size of some burrs.

The effects of feedrate, tool sharpness, axial depth of cut, radial depth of cut, and tool diameter were evaluated in 17-4 PH

and 303 Se stainless steel, 1018 steel, and 6061-T6 aluminum. Burr size in 303 Se stainless steel was not affected by the tool wear resulting from producing 220 inches (5.58 m) of cut. Burr size did increase when tools developed a 0.001-inch (25.4 μm) radius on the cutting edge.

It was concluded that reverse helix tools do not prevent burrs, although they may reduce the size of some burrs.

The thickness, height, and radius on the backside of the burrs produced by end milling have been documented by 6000 measurements. Burrs were produced on up to eight different edges with a single cut, and the properties of each of these burrs were different. Burr properties have been shown to be highly variable.

Burrs have been shown to exist on all edges produced by a cutter. Conceptual and mathematical descriptions of burr formation have been described. Three distinct mechanisms were found responsible for the burrs produced by end mills.

FUTURE WORK

No additional work on end-milling burrs is planned, although additional information on helix-angle effects would be useful. Similarly, more detailed information on feedrate effects would be useful.

Additional tests are in progress to determine how machining variables affect the burrs produced by turning and drilling. An analysis will also be performed of economic trade-offs between machining and deburring costs.

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Appendix A

EFFECTS OF MACHINING AND END MILLING ON BURR MEASUREMENTS

Table A-1. Effect of Machining Conditions on Burr Height

CODE NO.	CUT NO.	EDGE NUMBER						
		1	2	3	5	6	7	9
111111	14	214,250		303, 405		9, 16		220, 46
111112	57	41, 81		255, 239		0, 0		26, 21
111113	114	14, 37		383, 240		0, 0		22, 5
111114	157	38, 8		330,2696		0, 0		11, 37
111121	2	217,226		368, 432		25, 26		149,176
111122	52	155,187		282, 233		43, 49		14, 23
111123	102	124, 50		249, 163		0, 0		35,123
111124	152	170,213		396, 306		3, 0		211, 97
111211	7	8, 24		272, 240		6, 84		22, 9
111212	65	62, 18		295, 242		0, 0		16, 15
111213	107	8, 0		8, 250		0, 0		28, 0
111214	165	76, 15		218, 280		0, 0		9, 13
111221	15	61, 67		370, 312		0, 0		29, 49
111222	66	101, 66		272, 310		0, 0		16, 29
111223	115	145, 17		308, 272		0, 0		78, 39
111224	166	96, 75		279, 333		0, 0		119, 24
112111	36	14, 4	185, 60	121, 0	15, 16	6, 0	449,449	
112112	73	48, 85	106,104	8, 11	122, 33	11, 0	326,326	
112113	139	121, 18	55, 79	0, 0	7, 0	0, 0	60, 60	
112114	173	106,135	12,500	13, 84	15, 17	0, 0	62, 62	
112121	32	3, 16	138,120	819, 883	189,154	23, 7	323,323	
112122	80	386,298	86,110	1767, 777	211,310	8, 10	361,361	
112123	132	75,104	44, 65	1815,1087	194, 77	0, 0	428,428	
112124	180	32, 47	79, 0	1257, 0	161,234	0, 0	97, 97	
112211	31	5, 0	0, 5	15, 51	79, 81	0, 0	51, 51	
112212	83	79, 85	3, 20	1675,1581	58, 42	2, 6	100,100	
112213	131	5, 3	21, 33	27, 9	10, 15	0, 0	33, 33	
112214	183	61, 7	52, 43	6, 0	74, 38	0, 6	36, 36	
112221	21	68, 65	56, 55	20, 6	105,106	0, 3	67, 67	
112222	78	231,167	35,121	300, 569	431,299	2, 0	52, 52	
112223	135	295, 72	32, 68	2080,1908	79, 79	0, 32	115,115	
112224	178	27, 68	47, 9	1592,1698	647, 87	0, 3	19, 19	
121111	1	8, 13		214, 220		0, 0		88, 73
121112	55	23, 55		310, 550		0, 0		33, 70
121113	101	0, 2		0, 20		0, 0		0, 0
121114	155	0, 12		8, 12		5, 0		12, 16
121121	4	111, 98		287, 283		33, 24		84, 69
121122	53	170,126		301, 255		18, 11		141,151
121123	104	80, 53		297, 250		0, 0		30, 71
121124	153	173,191		317, 283		0, 0		297, 45
121211	10	80, 30		294, 250		11, 8		17, 25
121212	61	40, 74		285, 211		18, 0		22, 34
121213	110	38, 32		264, 268		0, 0		30, 32
121214	161	0, 10		239, 212		12, 0		58, 27
121221	8	98, 91		336, 255		6, 20		135, 73
121222	58	67, 65		176, 236		34, 27		38, 43
121223	108	69, 46		314, 213		0, 0		70, 17
121224	158	226, 68		182, 321		0, 0		95, 49
122111	23	113, 28	53, 47	1435,1394	20, 51	5, 0	15, 15	
122112	81	217,112	98, 87	1465,1445	76, 64	40, 2	681,681	
122113	137	28, 32	4, 24	4, 14	8, 12	0, 0	160,160	

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH 2.54 MICROMETERS.

TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES

**CODE NUMBERS ARE IDENTIFIED IN TABLE 4 IN THE MAIN BODY OF THIS REPORT

Table A-1 Continued. Effect of Machining Conditions on Burr Height

CODE NO.	CUT NO.	EDGE NUMBER						
		1	2	3	5	6	7	9
122114	181	37, 0	63, 0	12, 0	9, 15	2, 0	156,156	
122121	29	266,999	146,132	1136,1650	51, 72	3, 9	108,108	
122122	72	2, 87	109, 91	1980,1959	75,267	29, 35	80, 80	
122123	129	7, 78	12, 80	16, 18	117, 53	0, 0	398,398	
122124	172	22, 81	23, 85	2316,2589	92,113	0, 0	97, 97	
122211	30	10, 43	5, 26	272, 14	9, 11	0, 4	43, 43	
122212	85	76, 80	61, 88	783,1500	16, 26	134, 0	236,236	
122213	130	20, 75	6, 5	45, 5	29, 24	0, 0	226,226	
122214	185	58, 32	14, 30	1862,1761	56, 24	0, 0	39, 39	
122221	35	48, 65	65, 50	36, 79	143,101	15, 0	120,120	
122222	71	129, 31	83,135	1169,1089	230,110	0, 0	99, 99	
122223	140	7, 62	43,146	43, 25	49, 74	0, 6	202,202	
122224	171	131, 89	38, 61	1689,1606	64, 73	0, 0	46, 46	
211111	13	8, 21		465, 393		8, 0		4, 16
211112	64	98, 30		239, 375		18, 8		52, 45
211113	113	32, 10		337, 323		0, 0		6, 15
211114	164	8, 13		250, 330		1, 2		7, 16
211121	6	13, 18		511, 444		6, 12		68, 61
211122	56	59, 56		302, 332		10, 3		16, 90
211123	106	44, 81		521, 325		0, 0		187,116
211124	156	251,229		390, 267		0, 0		83,139
211211	5	0, 0		546, 133		0, 9		2, 5
211212	59	4, 3		127, 108		5, 0		6, 3
211213	105	4, 0		10, 0		0, 0		8, 7
211214	159	4, 0		396, 377		0, 0		43, 0
211221	16	60, 95		311, 314		0, 0		10, 18
211222	60	8, 12		176, 108		0, 0		9, 5
211223	116	54, 70		468, 300		0, 0		40, 58
211224	160	104, 61		361, 380		4, 0		32, 46
212111	28	263, 8	477,520	121, 38	23, 10	37, 50	403,403	
212112	82	37, 82	40, 52	18, 18	102, 0	0, 0	261,261	
212113	128	49, 12	75, 73	14, 11	11, 7	0, 5	232,232	
212114	182	8, 10	29, 25	3, 7	25, 57	0, 0	88, 88	
212121	25	350,177	465,421	8, 12	0, 0	61, 11	452,452	
212122	75	349,158	522,125	2329,1600	10, 5	13, 12	546,546	
212123	125	34,106	102,148	1256,1058	702,927	46, 64	323,323	
212124	175	146, 59	68, 25	841, 785	900,870	10, 0	144,144	
212211	22	5, 11	0, 24	13, 13	6, 0	12, 40	21, 21	
212212	84	92, 64	58, 71	2815, 147	76,104	0, 8	107,107	
212213	136	8, 0	9, 35	36, 96	29, 24	9, 19	122,122	
212214	184	45, 16	43, 59	8, 0	25, 12	0, 0	41, 41	
212221	27	38, 65	11, 19	7, 23	61, 78	0, 8	47, 47	
212222	76	55, 44	77, 51	2067,2112	34, 15	13, 0	96, 96	
212223	127	38, 50	68,111	1282,1350	854,787	7, 20	181,181	
212224	176	225,138	157, 96	1898, 846	572,397	0, 0	139,139	
221111	9	29, 27		375,4796		52, 51		75, 22
221112	62	51, 81		390, 334		8, 12		73, 51
221113	109	7, 21		310, 12		0, 0		0, 13
221114	162	3, 3		4, 0		0, 0		8, 63
221121	3	26, 75		430, 250		18, 0		12, 17
221122	51	97, 94		584, 350		9, 4		13, 47
221123	103	186,195		465, 276		0, 0		64,164

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TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES
**CODE NUMBERS ARE IDENTIFIED IN TABLE 4 IN THE MAIN BODY OF THIS REPORT

Table A-1 Continued. Effect of Machining Conditions on Burr Height

CODE NO.	CUT NO.	EDGE NUMBER						
		1	2	3	5	6	7	9
221124	151	495,100		457, 396		0, 0		72, 70
221211	11	5, 4		279, 226		0, 0		0, 3
221212	54	5, 17		345, 313		0, 0		9, 21
221213	111	4, 10		345, 294		0, 0		61, 9
221214	154	13, 20		10, 0		0, 0		61, 19
221221	12	73, 83		438, 317		0, 7		10, 18
221222	63	66, 74		427, 318		0, 3		13, 23
221223	112	47, 98		391, 350		0, 0		77, 50
221224	163	152, 87		295, 4712		0, 0		204, 23
222111	33	29, 45	42, 377	16, 24	41, 50	82, 0	220, 220	
222112	74	8, 31	23, 69	56, 22	126, 10	14, 0	175, 175	
222113	133	10, 2	86, 45	10, 0	16, 12	0, 0	76, 76	
222114	174	10, 0	40, 0	10, 24	35, 47	0, 0	94, 94	
222121	34	60, 55	3, 0	6, 18	161, 69	21, 16	144, 144	
222122	77	111, 152	96, 53	10, 8	120, 136	15, 15	202, 202	
222123	134	174, 88	168, 77	2861, 2722	120, 108	0, 0	531, 531	
222124	177	81, 100	105, 90	2767, 1510	166, 166	0, 0	40, 40	
222211	26	74, 21	21, 21	19, 21	70, 18	10, 5	74, 74	
222212	86	44, 12	18, 14	24, 11	39, 50	3, 0	239, 239	
222213	126	3, 0	10, 8	22, 19	25, 22	0, 0	93, 93	
222214	186	40, 0	20, 0	13, 15	21, 32	0, 0	44, 44	
222221	24	59, 53	57, -0	12, 19	58, 0	10, 8	73, 73	
222222	79	71, 55	35, 34	1567, 1428	84, 100	0, 0	339, 339	
222223	138	134, 105	58, 108	3600, 2348	92, 108	0, 4	55, 55	
222224	179	407, 207	74, 79	2933, 1547	117, 125	0, 6	66, 66	

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Table A-2. Effect of Machining Conditions on Burr Thickness

CODE NO.	CUT NO.	EDGE NUMBER							
		1	2	3	5	6	7	9	
111111	14	21, 38		67, 50		11, 23		16, 23	
111112	57	17, 26		33, 20		0, 0		12, 20	
111113	114	19, 19		23, 25		0, 0		12, 24	
111114	157	8, 9		15, 27		0, 0		10, 3	
111121	2	56, 64		57, 52		24, 39		47, 53	
111122	52	20, 31		21, 52		10, 15		28, 61	
111123	102	11, 10		23, 57		0, 0		31, 20	
111124	152	17, 22		35, 51		11, 0		30, 78	
111211	7	16, 14		17, 50		15, 44		11, 36	
111212	65	11, 21		46, 19		0, 0		16, 22	
111213	107	9, 0		12, 40		8, 0		4, 0	
111214	165	5, 14		12, 47		0, 0		18, 17	
111221	15	17, 28		87, 80		0, 0		12, 20	
111222	66	8, 39		54, 46		0, 0		18, 26	
111223	115	11, 31		41, 36		0, 0		21, 38	
111224	166	30, 75		37, 74		0, 0		29, 27	
112111	36	10, 9	25, 33	15, 0	10, 9	22, 0	50, 50		
112112	73	10, 20	15, 22	16, 3	11, 25	10, 0	33, 33		
112113	139	12, 9	4, 14	0, 0	15, 0	0, 0	9, 9		
112114	173	8, 58	12, 55	23, 25	13, 25	0, 0	10, 10		
112121	32	10, 19	26, 51	32, 54	42, 61	8, 49	38, 38		
112122	80	37, 78	25, 44	67, 88	36, 68	3, 3	45, 45		
112123	132	15, 15	18, 29	32, 42	25, 40	0, 0	28, 28		
112124	180	16, 15	14, 0	42, 0	48, 66	0, 0	17, 17		
112211	31	13, 0	0, 7	15, 18	24, 28	0, 0	6, 6		
112212	83	10, 27	16, 9	42, 66	17, 39	10, 41	20, 20		
112213	131	32, 14	15, 19	24, 21	16, 23	0, 0	30, 30		
112214	183	11, 29	8, 12	8, 0	20, 67	0, 20	60, 60		
112221	21	8, 61	14, 32	41, 47	23, 38	0, 20	33, 33		
112222	78	36, 65	16, 49	82, 41	60, 89	11, 0	45, 45		
112223	135	13, 27	17, 27	39, 57	29, 48	0, 5	37, 37		
112224	178	60, 23	9, 30	53, 50	30, 49	0, 3	33, 33		
121111	1	15, 20		15, 16		0, 0		14, 39	
121112	55	6, 25		7, 20		0, 0		16, 35	
121113	101	0, 8		0, 14		0, 0		0, 0	
121114	155	0, 24		27, 20		4, 0		23, 12	
121121	4	13, 26		55, 29		10, 15		20, 35	
121122	53	10, 31		27, 31		17, 11		33, 39	
121123	104	12, 20		18, 38		0, 0		21, 35	
121124	153	15, 25		40, 49		0, 0		39, 83	
121211	10	48, 36		137, 40		31, 32		10, 36	
121212	61	20, 13		38, 39		17, 0		20, 22	
121213	110	6, 12		24, 17		0, 0		4, 9	
121214	161	0, 24		19, 23		5, 0		10, 3	
121221	8	20, 31		44, 61		20, 43		32, 47	
121222	58	27, 31		10, 61		15, 49		39, 72	
121223	108	12, 26		27, 32		0, 0		22, 38	
121224	158	21, 55		66, 42		0, 0		30, 29	
122111	23	31, 38	19, 29	50, 45	17, 54	5, 0	3, 3		
122112	81	7, 70	15, 33	58, 62	35, 44	26, 50	124, 124		
122113	137	8, 2	7, 7	5, 19	12, 18	0, 0	22, 22		

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TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES
**CODE NUMBERS ARE IDENTIFIED IN TABLE 4 IN THE MAIN BODY OF THIS REPORT

Table A-2 Continued. Effect of Machining Conditions on Burr Thickness

CODE NO.	CUT NO.	EDGE NUMBER							
		1	2	3	5	6	7	9	
122114	181	11, 0	14, 0	9, 0	15, 39	5, 0	22, 22		
122121	29	22, 74	23, 39	55, 37	36, 61	14, 13	32, 32		
122122	72	2, 18	13, 27	22, 13	15, 56	8, 9	48, 48		
122123	129	17, 31	37, 17	35, 45	15, 38	0, 0	31, 31		
122124	172	10, 10	80, 21	72, 37	35, 51	0, 0	18, 18		
122211	30	23, 7	20, 20	52, 2	38, 19	0, 5	10, 10		
122212	85	56, 63	10, 37	78, 75	43, 56	10, 0	73, 73		
122213	130	22, 19	16, 5	11, 25	14, 39	0, 0	16, 16		
122214	185	17, 5	53, 14	41, 46	19, 48	0, 0	14, 14		
122221	35	10, 25	11, 23	16, 28	28, 46	3, 0	53, 53		
122222	71	9, 36	13, 35	28, 27	5, 11	0, 0	19, 19		
122223	140	16, 17	17, 32	5, 48	32, 48	0, 58	23, 23		
122224	171	15, 18	14, 25	86, 44	36, 54	0, 0	45, 45		
211111	13	8, 64		38, 27		14, 0		4, 11	
211112	64	11, 28		21, 52		12, 23		29, 44	
211113	113	6, 5		11, 37		0, 0		22, 3	
211114	164	18, 22		21, 30		3, 33		10, 10	
211121	6	10, 17		38, 1		7, 19		13, 35	
211122	56	9, 10		17, 33		11, 12		14, 14	
211123	106	12, 25		32, 43		0, 0		31, 31	
211124	156	24, 35		46, 48		0, 0		31, 37	
211211	5	0, 0		25, 14		0, 26		2, 12	
211212	59	4, 25		14, 50		3, 0		10, 32	
211213	105	4, 0		10, 0		0, 0		21, 40	
211214	159	4, 0		40, 31		0, 0		4, 0	
211221	16	12, 20		36, 37		0, 0		16, 24	
211222	60	9, 14		20, 37		0, 0		8, 22	
211223	116	11, 28		46, 40		0, 0		36, 34	
211224	160	16, 68		31, 42		20, 0		27, 62	
212111	28	69, 8	44, 51	44, 30	19, 40	17, 50	96, 96		
212112	82	16, 50	11, 25	18, 22	19, 0	0, 0	21, 21		
212113	128	7, 4	10, 16	14, 19	10, 21	0, 20	29, 29		
212114	182	27, 8	29, 23	22, 14	20, 19	0, 0	19, 19		
212121	25	14, 33	20, 32	15, 19	0, 0	13, 34	50, 50		
212122	75	36, 41	21, 39	38, 35	10, 10	11, 21	57, 57		
212123	125	29, 35	20, 33	50, 48	34, 56	12, 96	38, 38		
212124	175	22, 50	18, 36	41, 72	43, 56	10, 0	15, 15		
212211	22	5, 27	0, 8	1, 18	3, 0	6, 3	7, 7		
212212	84	13, 31	28, 42	41, 56	53, 104	0, 50	33, 33		
212213	136	8, 0	6, 7	14, 23	15, 53	13, 55	14, 14		
212214	184	15, 42	17, 27	42, 0	17, 16	0, 0	36, 36		
212221	27	12, 23	10, 18	22, 28	23, 28	0, 39	16, 16		
212222	76	8, 14	7, 26	32, 36	9, 38	5, 0	22, 22		
212223	127	12, 23	17, 28	41, 59	30, 39	20, 61	29, 29		
212224	176	19, 33	23, 62	129, 53	40, 58	0, 0	92, 92		
221111	9	6, 30		61, 48		15, 24		22, 12	
221112	62	11, 14		20, 50		19, 29		49, 78	
221113	109	10, 10		35, 22		0, 0		0, 8	
221114	162	8, 3		4, 0		0, 0		8, 10	
221121	3	8, 23		18, 25		10, -0		15, 22	
221122	51	18, 28		22, 30		17, 5		14, 25	
221123	103	11, 23		37, 35		0, 0		36, 40	

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TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES
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Table A-2 Continued. Effect of Machining Conditions on Burr Thickness

CODE NO.	CUT NO.	EDGE NUMBER						
		1	2	3	5	6	7	9
221124	151	21, 36		50, 49		0, 0		34, 35
221211	11	37, 9		19, 12		0, 0		0, 15
221212	54	11, 6		54, 26		0, 0		10, 43
221213	111	5, 10		19, 19		0, 0		14, 14
221214	154	41, 28		10, 0		0, 0		16, 34
221221	12	11, 22		54, 13		0, 15		14, 23
221222	63	16, 30		32, 31		0, 15		15, 32
221223	112	11, 14		33, 89		0, 0		21, 65
221224	163	18, 16		53, 69		0, 0		30, 39
222111	33	12, 20	10, 17	15, 26	20, 30	4, 0	21, 21	
222112	74	11, 11	8, 15	10, 17	8, 19	7, 0	12, 12	
222113	133	10, 40	20, 17	12, 0	12, 13	0, 0	15, 15	
222114	174	12, 0	19, 0	11, 12	18, 45	0, 0	11, 11	
222121	34	23, 36	3, 0	26, 30	32, 22	10, 24	18, 18	
222122	77	30, 34	8, 27	13, 37	34, 28	16, 40	36, 36	
222123	134	10, 36	25, 34	55, 39	33, 35	0, 0	49, 49	
222124	177	13, 20	26, 38	73, 111	36, 66	0, 0	22, 22	
222211	26	10, 18	13, 16	34, 36	46, 13	14, 4	36, 36	
222212	86	6, 19	7, 9	8, 29	35, 57	15, 0	18, 18	
222213	126	4, 0	10, 21	21, 23	23, 34	0, 0	40, 40	
222214	186	6, 0	7, 0	9, 25	10, 49	0, 0	37, 37	
222221	24	8, 21	11, -0	15, 34	35, 0	7, 16	15, 15	
222222	79	19, 20	12, 22	52, 30	36, 44	0, 0	27, 27	
222223	138	14, 25	11, 30	35, 78	52, 51	0, 52	59, 59	
222224	179	17, 25	30, 23	65, 62	54, 64	0, 24	65, 65	

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TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES

**CODE NUMBERS ARE IDENTIFIED IN TABLE 4 IN THE MAIN BODY OF THIS REPORT

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Table A-3. Burr Radius Measurements From End Milling

CODE NO.	SAMPLE NO.		EDGE NUMBER				
		1	2	3	5	7	9
111111	14	15.10		15.05			5.03
111112	57	12.12		6.02			5.22
111113	114	14.02		54.0			3.02
111114	157	4.03		14.14			2.10
111121	2	27.21		14.03			11.10
111122	52	10.15		16.50			87.10
111123	102	9.02		13.33			9.07
111124	152	20.07		14.24			15.10
111211	7	14.08		13.12			9.40
111212	65	8.10		13.02			8.10
111213	107	7.0		10.10			0.0
111214	165	0.10		13.37			100.02
111221	15	18.17		7.44			2.15
111222	66	21.27		26.18			0.16
111223	115	10.49		23.17			7.17
111224	166	18.21		19.0			0.29
112111	36	3.02	9.20	7.0	2.03	10.33	
112112	73	13.14	12.18	7.11	6.25	9.20	
112113	139	7.02	6.05	0.0	0.0	7.03	
112114	173	0.08	13.19	17.15	12.04	8.0	
112121	32	5.12	11.55	10.17	32.12	20.07	
112122	80	19.53	22.26	9.56	23.42	16.12	
112123	132	5.0	9.13	13.10	17.12	21.11	
112124	180	9.02	4.03	18.20	45.32	13.45	
112211	31	17.0	0.02	15.13	26.07	2.12	
112212	83	6.13	9.08	21.18	8.19	17.21	
112213	131	3.05	7.04	7.27	0.23	3.20	
112214	183	32.28	12.10	22.20	26.53	2.0	
112221	21	7.71	10.21	99.10	11.25	8.08	
112222	78	32.38	17.31	32.16	32.31	15.15	
112223	135	10.09	13.10	8.31	21.24	14.0	
112224	178	22.11	13.17	8.13	12.16	98.0	
121111	1	3.23		9.03			9.25
121112	55	8.10		10.15			8.12
121113	101	0.04		0.07			0.0
121114	155	0.19		100.17			15.09
121121	4	10.15		11.04			7.10
121122	53	18.17		10.02			20.16
121123	104	9.04		11.32			6.09
121124	153	20.17		9.11			12.10
121211	10	10.32		1.10			6.39
121212	61	24.19		14.41			0.15
121213	110	0.02		10.07			0.0
121214	161	0.16		3.10			2.02
121221	8	19.23		13.05			20.17
121222	58	25.22		14.18			44.75
121223	108	9.08		19.05			6.12

*ALL VALUES SHOWN ARE IN 0.0001 INCH UNITS.

0.0001 INCH EQUALS 2.54 MICROMETERS.

TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES.

** CODE NUMBERS ARE IDENTIFIED IN TABLE 1 IN THE MAIN TEXT OF THIS REPORT.

Table A-3 Continued. Burr Radius Measurements From End Milling

CODE	SAMPLE	EDGE NUMBER					
NO.	NO.	1	2	3	5	7	9
121224	158	13.10		13.16			6.10
122111	23	16.34	14.17	25.35	24.09	13.12	
122112	81	2.04	9.46	11.26	27.16	12.47	
122113	137	2.02	10.02	0.26	3.05	7.28	
122114	181	15.0	0.0	9.0	17.18	6.02	
122121	29	13.21	15.25	10.30	14.21	19.23	
122122	72	0.21	20.09	15.16	5.13	7.10	
122123	129	6.03	11.10	15.23	7.06	11.29	
122124	172	0.02	13.12	11.08	29.40	14.17	
122211	30	6.03	4.08	0.80	0.16	6.08	
122212	85	36.38	4.20	26.45	99.30	15.25	
122213	130	2.03	5.05	0.19	19.26	14.14	
122214	185	10.13	5.02	6.04	0.20	11.10	
122221	35	8.12	7.08	30.12	7.16	27.09	
122222	71	13.26	15.11	10.07	0.02	11.29	
122223	140	28.10	13.58	17.47	18.16	17.39	
122224	171	24.05	15.11	20.20	26.14	21.10	
211111	13	25.27		13.10			11.02
211112	64	13.32		37.09			12.22
211113	113	0.0		3.16			0.0
211114	164	9.18		17.12			100.0
211121	6	11.15		11.12			12.16
211122	56	10.0		13.11			10.08
211123	106	9.02		19.02			12.0
211124	156	6.11		15.14			23.05
211211	5	0.0		7.03			0.40
211212	59	0.0		20.23			13.15
211213	105	0.0		0.0			42.13
211214	159	0.0		13.11			4.0
211221	16	8.03		8.13			17.12
211222	60	16.03		8.06			10.15
211223	116	9.07		43.0			27.02
211224	160	100.19		21.16			16.03
212111	28	13.03	25.24	99.14	99.48	8.11	
212112	82	7.99	4.22	10.18	14.0	25.05	
212113	128	7.02	0.0	22.20	16.13	19.21	
212114	182	100.02	5.14	16.08	9.06	10.04	
212121	25	18.13	8.10	13.29	25.0	9.12	
212122	75	25.22	16.27	10.12	0.05	36.42	
212123	125	14.10	13.12	13.11	9.15	13.10	
212124	175	33.35	12.14	20.29	8.16	9.20	
212211	22	0.50	0.03	20.20	2.0	6.09	
212212	84	13.22	8.13	22.43	41.39	20.11	
212213	136	12.0	15.06	12.14	9.34	13.04	
212214	184	16.31	18.10	100.0	20.12	33.49	
212221	27	7.17	11.11	10.17	2.05	9.08	
212222	76	9.02	7.22	12.11	36.78	11.27	

*ALL VALUES SHOWN ARE IN 0.0001 INCH UNITS.

0.0001 INCH EQUALS 2.54 MICROMETERS.

TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES.

** CODE NUMBERS ARE IDENTIFIED IN TABLE 1 IN THE MAIN TEXT OF THIS REPORT.

Table A-3 Continued. Burr Radius Measurements From End Milling

CODE NO.	SAMPLE NO.	EDGE NUMBER					
		1	2	3	5	7	9
212223	127	16.07	16.25	25.22	20.03	18.18	
212224	176	18.08	20.50	25.04	12.10	14.16	
221111	9	12.18		19.14			8.17
221112	62	7.04		13.20			5.40
221113	109	2.04		0.05			0.0
221114	162	0.0		0.0			10.0
221121	3	9.12		0.02			12.10
221122	51	15.16		22.17			27.18
221123	103	13.02		11.04			11.08
221124	151	9.12		13.12			8.08
221211	11	0.04		3.04			0.50
221212	54	9.02		7.03			20.18
221213	111	0.25		11.07			0.12
221214	154	10.10		0.0			0.42
221221	12	7.14		6.23			19.22
221222	63	10.20		9.16			20.30
221223	112	7.02		42.62			5.10
221224	163	11.0		12.10			3.15
222111	33	7.15	7.12	11.26	7.17	11.11	
222112	74	3.04	5.09	6.10	8.18	12.20	
222113	133	0.10	9.07	14.0	0.0	10.08	
222114	174	16.0	0.0	0.03	22.32	19.21	
222121	34	14.24	0.0	0.09	19.04	13.13	
222122	77	22.28	12.24	28.30	10.12	23.27	
222123	134	5.23	16.13	11.13	18.11	24.19	
222124	177	20.05	24.27	14.28	21.26	13.05	
222211	26	12.10	6.11	28.21	29.06	4.10	
222212	86	2.20	2.03	11.27	23.36	14.23	
222213	126	12.0	16.02	28.08	39.34	25.21	
222214	186	0.0	0.0	3.30	14.35	32.10	
222221	24	5.15	9.11	17.27	26.0	13.17	
222222	79	2.13	8.13	18.18	26.23	24.27	
222223	138	3.02	7.20	21.17	20.18	34.10	
222224	179	33.13	26.11	25.21	34.23	5.15	

*ALL VALUES SHOWN ARE IN 0.0001 INCH UNITS.

0.0001 INCH EQUALS 2.54 MICROMETERS.

TWO MEASUREMENTS WERE MADE AT EACH COMBINATION OF VARIABLES.

** CODE NUMBERS ARE IDENTIFIED IN TABLE 1 IN THE MAIN TEXT OF THIS REPORT.

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Table A-4. Burr Height By End Milling

CUT NO.	CODE NUMBER	EDGE LOCATION								
		1	2	3	4	5	6	7	8	9
14	111111	167		190		26	18		20	46
57	111112	79		251		36			9	26
114	111113	189		444		28	3		12	21
157	111114	83		289		19				27
2	111121	172		788		130	18		25	97
52	111122	135		338		45	32		170	21
102	111123	115		316		68			5	45
152	111124	185		525		50			17	81
7	111211	24		521		57			11	22
65	111212	97		292		34	12		18	58
107	111213	21		207		24	12		8	14
165	111214	13		341		19			3	14
15	111221	118		386		18	12		14	78
66	111222	91		735		36	12		12	60
115	111223	161		173		47			15	8
166	111224	140		246		33	2		11	50
36	112111	21	230	67	167	110	34	34	412	
73	112112	91	567	29	25	26		400	20	
139	112113	20	46	21	9	19		168	14	
173	112114	1343	821	27	14	23	5	154	10	
32	112121	18	256	1774	998	218	19	538	33	
80	112122	1617	602	1800	709	389	19	112	79	
132	112123	368	392	1885	37	271	43	373	44	
180	112124	536	237	1270	219	1483	105	68	68	
31	112211	12	15	2777	12	114	3	32	35	
83	112212	118	28	1961	28	84	56	122	16	
131	112213	42	17	24	18	51		43	15	
183	112214	14	111	11		72		58	15	
21	112221	37	62	1926	43	134	28	80	24	
78	112222	660	840	810	868	33	17	73	31	
132	112223	139	290	1180	24	212	47	495	40	
178	112224	703	727	1905	71	194		69	43	
1	121111	47		274		10			16	131
55	121112	35		223		24	29		5	17
101	121113	17		164		15			3	3
155	121114	64		187		12	2		5	36
4	121121	267		325		7	14		20	31
53	121122	187		314		89	37		14	171
104	121123	161		294		38	10			114
153	121124	211		672		42	3		14	383
10	121211	97		192		9	5		13	24
61	121212	16		515		37			14	57
110	121213	54		220		18			11	11
161	121214	15		26		18	2		8	7
8	121221	132		221		148	5		26	154
58	121222	62		292		114	195		49	29
108	121223	137		322		48				55
158	121224	99		510		43	9		14	139
23	122111	105	32	1531	148	91	7	96	12	
81	122112	667	128	2223	941	87	37	494	39	
137	122113	16	62	1688		91		350	15	

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
BURRS WERE MEASURED OPTICALLY PRIOR TO CROSS SECTIONING

Table A-4 Continued. Burr Height By End Milling

CUT NO.	CODE NUMBER	EDGE LOCATION									
181	122114	80	57	1719	5	26		208	94		
29	122121	155	146	1598	46	75	12	310	26		
72	122122	484	843	1871	299	431	5	292	62		
129	122123	69	35	1911	235	111	137	454	50		
172	122124	252	136	2358	413	135		146	42		
30	122211	18	12	1974	10	129	10	41	51		
85	122212	290	51	2215	50	171	17	165	52		
130	122213	20	40	1593	46			20	161		
185	122214	48	378	1780		84		33	33		
35	122221	116	105	331	11	93	16	86	24		
71	122222	112	148	2208	40	104		136	45		
140	122223	88	148	2387	152	44		320	110		
171	122224	150	231	2069	106	178	26	236	34		
13	211111	2		481		40	11		14	12	
64	211112	59		609		50	16		12	30	
113	211113	147		575		11	16		3	5	
164	211114	12		414		11				25	
6	211121	43		659		77	46		16	83	
56	211122	106		365		30	16		24	23	
106	211123	244		609		60			7	41	
156	211124	24		284		38	9		9	73	
5	211211	3		487		9	11		6	7	
59	211212	17		53		157	3		19	11	
105	211213	14		471		22				5	
159	211214	22		591		29	3			14	
16	211221	50		565		77	7		7	25	
60	211222	29		50		88	10		52	19	
116	211223	215		790		23			3	59	
160	211224	167		362		38			13	70	
28	212111	1556	1580	40	35	111	82	788	13		
82	212112	39	22	2735	18	109	6	600	19		
128	212113	137	147	17	10	17	4	224	9		
182	212114	32	19	9		38		699	11		
25	212121	327	330	44	30	60	18	647	18		
75	212122	1301	171	2868	588	230	37	1152	21		
125	212123	365	272	1268	801	58	38		491		
175	212124	622	837	857	440	834		73	33		
22	212211	12	18	34	7	54	3	58	3		
84	212212	67	164	2938	45	266	2	402	77		
136	212213	42	113	150	73	11		11	107		
184	212214	52	304	2764		98	10	82	22		
27	212221	50	24	2292	27	93	40	101	18		
76	212222	96	128	266	39	88	10	17	506		
127	212223	156	232	1313	115	824	30	53	192		
176	212224	661	797	2721	49	573		240	27		
9	221111	50		381		54	21		13	31	
62	221112	127		409		67	12		12	83	
109	221113	44		300		31	2			17	
162	221114	11		21		14	15		9	11	
3	221121	61		387		54			16	36	
51	221122	175		358		9	16		10	31	
151	221124	394		356		63	11		14	127	

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
BURRS WERE MEASURED OPTICALLY PRIOR TO CROSS SECTIONING

Table A-4 Continued. Burr Height By End Milling

CUT NO.	CODE NUMBER	EDGE LOCATION							
103	221124	216		320	56	5		3	98
11	221211	5		353	56			13	15
54	221212	19		385	68	3		5	19
111	221213	12		521	28				11
154	221214	11		550	36	2		3	13
12	221221	52		621	38	5		8	46
63	221222	61		366	53	3		9	26
112	221223	140		564	45			3	92
163	221224	165		496	55	11		10	71
33	222111	25	27	2824	101	50	14	187	37
74	222112	44	26	60	3	57	12	303	16
133	222113	75	54	13		22		242	17
174	222114	20	58	27	10	44		162	21
34	222121	519	357	3324	38	167	14	495	20
77	222122	497	117	2467	78	182	23	370	46
134	222123	258	443	2920	10	142	5	734	133
177	222124	738	797	2915	1462	184		234	43
26	222211	16	16	2304	16	125	11	31	6
86	222212	42	43	2978	47	93	7	216	37
126	222213	30	30	52		49		151	20
186	222214	141	126	2609		42		266	12
24	222221	53	44	2448	39	133	14	57	18
79	222222	47	49	2631	5	103		133	32
138	222223	312	202	2953	20	114	10	685	60
179	222224	879	609	2811	56	223	29	199	70

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
BURRS WERE MEASURED OPTICALLY PRIOR TO CROSS SECTIONING

Table A-5. Effect of Length of Cut on Burr Properties in
303 Se Stainless Steel

SAMPLE TOTAL CUT		BURR HEIGHT*		BURR THICKNESS*		BURR RADIUS*			
NO.	LENGTH(INCH)	INDICATOR	MOUNT	EDGE NUMBER					
		1	2	1	2	1	2		
1	6	386	180	26	32	13	21	9	8
2	12	54	97	17	30	7	7	6	4
3	18	138	172	8	21	20	11	7	0
4	24	126	168	78	39	18	8	2	13
5	30	186	271	31	65	21	11	12	45
6	36	70	142	39	7	22	8	25	20
7	42	97	217	75	30	31	8	7	32
8	48	47	88	67	90	46	9	7	39
9	54	42	138	49	123	8	10	1	12
10	60	119	122	95	36	31	12	8	27
11	66	138	114	58	18	29	12	5	10
12	72	103	80	53	31	42	11	9	32
13	78	70	273	61	27	43	19	10	26
14	84	95	296	69	44	39	15	9	30
15	90			12	7	12	9	9	6
16	95.5	188	202	147	33	48	20	40	4
17	101	118	125	54	86	19	18	10	18
18	106.5	162	150	56	63	28	7		
19	112	48	136	66	38	29	7	5	9
20	117.5	72	208	51	60	20	15	4	12
21	123	98	101	75	0	49	0	0	17
22	128.5	91	318	29	51	12	18	2	8
23	134	114	148	24	53	19	15	2	10
24	139.5	71	106	122	55	53	8	10	39
25	145	157	171	82	13	55	19	23	47
26	150.5	43	123	67	0	24	0	0	18
27	156	306	213	50	33	40	16	8	23
28	161.5	96	201	32	57	32	29	0	12
29	167	300	350	170	41	25	19	3	9
30	172.5	85	114	43	28	41	8	5	53
31	177.5	152	542	28	38	11	47	50	5
32	182.5	75	121	55	40	14	9	0	10
33	187.5	272	185	61	43	63	27		
34	192.5	156	133	54	26	95	18	11	100
35	197.5	274	343	17	15	18	29	25	13
36	202.5	54	162	99	0	20	0	0	13
37	207.5	84	170	62	56	62	14	6	57
38	212.5	118	430	83	72	75	10	0	43
39	217.5	282	119	34	28	18	13	2	5
40	222.5	78	242	123	0	37	0	0	60
41	227.5	52	205	92	0	37	0	0	24
42	232.5	224	189	55	0	58	0	0	64
43	237.5	4	183	70	9	67	32	7	98
44	242.5	148	203	49	0	24	0	0	72
45	247.5	208	431	53	6	16	18	4	3
46	252	184	219	110	31	41	13	3	29
47	256.5	164	230	78	4	12	15	0	11
48	261	210	89	30	12	30	28	22	25

*ALL VALUES SHOWN ARE IN 0.0001 INCH UNITS.

0.0001 INCH EQUALS 2.54 MICROMETERS.

HEIGHT MEASUREMENTS IDENTIFIED AS MOUNT, AND ALL THICKNESS AND RADIUS MEASUREMENTS WERE MADE FROM METALLURGICAL MOUNTS SHOWING BURR CROSS SECTIONS. HEIGHT MEASUREMENTS IDENTIFIED AS INDICATOR WERE MADE BY MECHANICAL DIAL INDICATORS PRIOR TO PREPARATION OF METALLURGICAL MOUNTS.

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Appendix B

DESCRIPTION OF CUTTERS USED

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Appendix B

DESCRIPTION OF CUTTERS USED

EFFECTS OF MACHINING CONDITIONS STUDY

Bendix Tool Number 51103202

Special 0.25-inch-diameter, high-speed steel, 0.375-inch straight shank, right-hand spiral, right-hand cut, four-flute, two-flute, cutting to center, square end, double end, end mill; 0.625-inch-flute length, 3.375-inch overall length. No radius for steel.

Bendix Tool Number 51105213

0.375-inch-diameter cobalt, high-speed steel, 0.375-inch straight shank, right-hand spiral, right-hand cut, four-flute, two-flute cutting to center, square end, single end, end mill; 0.75-inch-flute length, 2.5-inch overall length. No radius for 17-4 PH stainless steel.

EFFECTS OF TOOL WEAR STUDY

Bendix Tool Number 51105222

See description for 51103202.

END-MILLING HIPERCO 50 STUDY

Bendix Tool Number 51101520

0.120 $\pm$ 0.001-inch-diameter, solid carbide (C-2) 0.625-inch straight shank, right-hand spiral, right-hand cut, four-flute, two-flute cutting to center, square end, single end, end mill; 0.375-inch-flute length, 1.5-inch overall length to cut.

EFFECT OF HELIX ANGLE STUDY

Bendix Tool Number 51103222

0.25-inch-diameter, solid carbide (C-6) 0.25-inch straight shank, right-hand cut, two straight flutes, square end cut to center, single end, end mill; 0.75-inch-flute length, 2.5-inch overall length. No radius for steel.

Bendix Tool Number 51103234

0.2650 $\pm$ 0.0005-inch-diameter, high-speed cobalt, 0.375-inch straight shank, right-hand spiral, right-hand cut, four-flute, center-cutting, single end, end mill; 0.625-inch-flute length, 2.4375-inch overall length. No radius for beryllium-copper.

Bendix Tool Number 51105206

0.375 + 0.000, - 0.002-inch-diameter, solid carbide, (C-2) 0.375-inch straight shank, left-hand spiral, right-hand cut, four-flute, square end, single end. end mill; 0.875-inch-flute length, 2.25-inch overall length. No radius for epoxy-glass.

NOTE: 1 inch = 25.4 mm.

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