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**BURRS PRODUCED BY SIDE-MILLING
CUTTERS**

November 1975

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BURRS PRODUCED BY SIDE-MILLING CUTTERS

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

Small precision mechanisms, such as timers, switches, and actuators, must have burr-free, sharp-edged parts to operate well. By controlling the size of burrs produced in milling operations, burr removal costs can be lowered, and the repeatability of the edges can be improved. This study indicated that slower feedrates generally resulted in thinner burrs. The eight different burrs, produced by a side-milling cutter in a single cut, all respond differently to changes in cutting conditions. Cutters having a non-zero helix angle produce longer and thicker burrs than those with a zero helix angle. Radial depth of cut did not influence burr size. Full radius keyseat style cutters with Master Cut tooth geometry produced longer and thicker burrs than similar cutters with square tooth corners. Burrs in 17-4 PH stainless steel were much smaller than those in 303 Se stainless steel. A basic explanation of the formation of milling burrs is presented.

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SUMMARY

Component parts of small precision mechanisms have typically required near-sharp edges to assure reliable component operation. A burr-free condition is also needed to minimize possible jamming of the mechanism by burrs breaking off 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 sizes; small burrs are more easily removed.

This study was initiated to determine how side-milling cutter geometry and machining conditions affect the size of burrs produced. The thickness, length, and hardness of burrs produced on all eight edges of side-milled slots in 303Se stainless steel were measured. Some work was also performed on 17-4 PH stainless steel. The formation of side-milling burrs is also explained.

There is a distinct difference in the properties of the burrs produced at the eight different edges in a side-milling slotting operation. Increasing the helix angle of the cutter produced either thicker and larger burrs or produced no change; it was totally dependent on which of the eight edges was studied. Lowering the feedrate in general reduced burr thickness. In half of the cases it also reduced burr length. A full radius Master Cut keyseat style cutter produced grossly larger burrs than a similar cutter with conventional square corners.

Burrs in 17-4 PH stainless steel are considerably smaller than those in 303 Se stainless steel. In general, burr length appears to be a direct function of workpiece elongation while burr thickness is strongly influenced by strain hardening.

DISCUSSION

SCOPE AND PURPOSE

The objective of this study was to determine how side-milling parameters influence burr size. Specifically this study sought to determine how helix angle, radial depth of cut, feedrate, and cutter shape affect burr length, thickness, and hardness.

PRIOR WORK

No previous work has been published on the subject of side-milling burrs. A brief analysis of burr lengths produced by side milling has been reported by the author elsewhere.¹

Related studies on reaming, ball broaching, and drilling burrs have been published by Bendix.^{2,4} Some general theories of burr formation have also been reported.^{5,6}

ACTIVITY

All conventional machining operations produce some burrs. The size of these burrs depends on the tool geometries used, the speeds and feeds, and the workpiece material properties. The cost of removing the burrs is proportional to 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. Machining conditions affect burr size and burr size affects deburring costs. A series of tests have been initiated to provide data on burr properties as a function of common machining conditions.

In the current study, conceptual models of burr formation in side milling were developed, and two tests were performed. In the first test, slots were produced in 303 Se stainless steel with conventional side-milling cutters. In the second, miniature keyseat style cutters having Master Cut tooth geometry were studied. In this second study both standard geometry and a full radius cutter were used.

The Formation of Side-Milling Burrs*

Side-milling burrs occur by these three** basic plastic flow mechanisms:

- Lateral flow (Poisson burr),
- Chip roll over (roll over burr), and
- Material tearing (tear burr).

When a slotting cutter enters the workpiece, the principal cutting edge can generate a small burr on this edge depending on the sharpness of the cutting edge, workpiece material, tooth load, and tooth rake angle. Two possibilities exist. In the first case the cutting edge acts as a hemicylinder indenting the workpiece (Figure 1). Under some conditions this hemicylinder action will cause the material to flow in the opposite direction of tooth motion. Because the material flow is not in the same direction as the applied force, this formation has been labeled a Poisson entrance burr. In the second case the tooth acts as a punch and tends to produce a die-roll on the workpiece rather than a burr. As will be discussed later both cases occur with nearly equal frequency.

When a cutting edge exits from the backside of the workpiece, a roll-over burr forms. In this case the burr is actually a chip (or series of chips) that bends away from the path of the cutter rather than shearing off (Figure 2). The length of this burr (b_L) is equal to the depth (d) of the slot (Figure 3). In many instances, however, this burr is partially broken off in handling and thus is notably shorter.

The most common burr is formed by material flow followed by tearing. As seen in Figure 4 this burr forms as the chip is separated from the workpiece. As a cutter tooth forms a chip, material at the side of the chip yields because of a plastic hinge effect or because of direct shear forces (Figure 5). With continued yielding, the chip tears away from the workpiece. For shallow depths of

*The term burr is used to indicate the presence at an edge of material which was not there prior to a machining operation. This material sometimes appears as a short mound of material and sometimes as a long thin projection.

**In a sawing operation a cut-off burr will also form if the part is allowed to fall from the stock before the cut is completed. Because this type of burr can easily be prevented in most cases by clamping both the stock and the workpiece, it is not covered in this paper.

Figure 1. Cutting Edge Produces Burr as it Enters Workpiece

Figure 2. Chip Deformation Modes at End of Cut

Figure 3. Location of Roll-Over Burr

Figure 4. Separation of Initial Side-Milling Chip

BENDING MODE FAILURE

SHEARING MODE FAILURE

Figure 5. Tear Burr Failure Modes

cut (tooth load) the burr is produced primarily by bending. As the depth of cut becomes larger, the shearing mode becomes more dominant.

When cutters have inadequate clearance or when they become worn, they can rub against previously cut edges (and burrs). The forces and temperatures produced by this rubbing can greatly increase the thickness of the burr produced and thus can become the prominent mechanism for determining burr properties. This is particularly true of materials having high coefficients of expansion and low thermal conductivities. The 300 series-stainless steels fall into this category.

Implications of Burr Formation

In a typical slotting operation involving a side-milling cutter and through slots, burrs are produced on eight different edges (Figure 6). If the cutter has a helix angle, the burrs on each of these edges will have properties different from burrs on the other edges. This is a highly significant observation, because in a single operation and without changing any variable, eight different burrs with widely varying properties can form.

Actually the burrs on any one edge vary considerably. Burr length will vary somewhat along the entire edge. Burr thickness will vary considerably from the root of the burr to the tip of the burr as will burr hardness. To further confuse the situation, the burrs on six of the edges are produced by many different teeth thus the burr is a periodic series of burrs rather than a continuous burr (Figures 7 and 8).

Although climb cutting produces burrs by the same basic mechanisms as conventional cutting, two noteworthy changes occur. First, an exit burr is produced on the side that a cutter first approaches (Figure 7). In this case the longest burrs occur on the leading surface of the part. Second, the thickest part of a chip produced by a climb cut occurs at the initial engagement of the cutter tooth; the thinnest part occurs when the cutter exits from the workpiece. Thus for the same feed and speed, the climb cut is taking a smaller cut than the conventional cut when it exits from the workpiece. This significantly changes the burr properties.

Test Results

Standard Cutters

Two tests were performed to obtain quantitative information on the magnitude of burrs produced by side milling. In the first test 303 Se stainless steel was machined using the conditions shown in Table 1. The length of burrs produced was measured at

Text continued on page 18.

Figure 6. Burrs Produced in Side Milling (Conventional Cut)

Figure 7. Climb Cut Entrance Burr

Figure 8. Periodic Nature of Side-Milling Burr

Table 1. Side-Milling Test Conditions

Cut*	Helix Angle (Degrees)	Depth of cut		Feed		Feedrate	
		(inch)	(mm)	(IPR/T)	(μ m/R/T)	(IPM)	(mm/sec)
1	0	0.125	3.18	0.002	50.8	3.5	1.482
2	0	0.125	3.18	0.00057	14.5	1.0	0.423
3	0	0.375	9.52	0.002	50.8	3.5	1.482
4	0	0.375	9.52	0.00057	14.5	1.0	0.423
5	10	0.375	9.52	0.002	50.8	3.5	1.482
6	10	0.375	9.52	0.00057	14.5	1.0	0.423
7	10	0.125	3.18	0.002	50.8	3.5	1.482
8	10	0.125	3.18	0.00057	14.5	1.0	0.423

*Using 4 inch (101.6 mm) diameter, 1/2 inch (12.7 mm) wide HSS side-milling cutters with 18 teeth at 98 RPM and a conventional cut. The cutter with a 10 degree Helix was a staggered tooth cutter. A highly sulfurized cutting oil was used for this test. Only one specimen was produced at each combination.

three points along each edge. Specimens were then cross sectioned to obtain burr thickness and hardness information.* The results of the measurements are presented in Appendix Tables A-1 through A-3.

An analysis of variance (ANOVA) was performed for each burr.** The results of this analysis are summarized in Table 2. As seen there, Burr 1 was influenced by the helix angle but not by depth of cut or feedrate. Burr 2, however, was influenced by depth of cut and feedrate but not helix angle. One unique combination of helix angle, depth of cut, and feedrate (Burr 3) produced a noticeably different burr length. Burr 4 was affected by helix angle as was Burr 5. The length of Burr 6 was affected by feedrate as was Burr 7. The length of Burr 7 was also affected by helix angle and certain combinations of helix angle and feedrate. Burr 8, the entrance burr, was affected by all variables.

The cavity produced by each cutter is significant. A standard cutter having zero helix angle should produce identical burrs on Edges 1 and 2 because of symmetry (Figure 9). This would also be true of the Edge pairs, 3, 4, 6, and 7. This is not true of staggered tooth cutters. Staggered tooth cutters leave a narrow band of metal on one side of the cut for the next tooth to remove (Figure 10). One tooth leaves the metal on one side of the slot, the next tooth leaves it on the opposite side. The length of the cavity produced by each tooth is the same as the feedrate per tooth, although along one edge each tooth will remove some metal for twice this length. If dial indicators are used to measure burr length it would be difficult to position the indicator by hand so that the point of measurement on Edge 2 is exactly opposite that on Edge 1.† Yet, this point of measurement is required to get a true microscopic understanding of the effect of the staggered tooth cutter.

*Burr thickness was measured at the surface of the workpiece (root of the burr) from metallurgical mounts. This provides the maximum thickness of the burr.

**To simplify discussion burrs are identified as Burr 1, 2, and so forth corresponding to the edge on which they occur (Figure 6). Because one of the burr-thickness specimen was not available for measurements, it was not possible to perform an ANOVA on burr thickness or hardness.

†As noted in Table 1 this per tooth feedrates used in this study only varied from 0.00057 to 0.002 inch per revolution (14.5 to 50.8 μm per revolution per tooth).

Table 2. ANOVA Results for Side Milling (Burr Length Data)

Code	Variation Source	Variance Ratio at Burr Location Number							
		1	2	3	4	5	6	7	8
A	Helix Angle	5.62*			10.6*	9.2*		5.0*	12.1*
B	Depth of Cut	3.05	5.62*	2.98					10.4*
C	Feedrate		5.62*			3.62	10.0*	4.18*	6.0*
AB	Interaction								14.0*
AC	Interaction							5.0*	43.3*
BC	Interaction								18.2*
ABC	Interaction			5.5*	2.38	2.32		5.9*	34.0*
	Error Mean Square	0.43	0.91	17.31	8.76	9747.0	0.06	0.04	0.025
*Indicates significance at the 95 percent confidence level. Blanks and numbers without asterisks indicate that variable did not affect burr length.

Figure 9. Typical Side-Milling Cutters

Figure 10. Cavities Produced by Staggered Tooth Side Milling Cutter

A macroscopic approach was used in this test to provide average properties that would have more meaning from a production standpoint. No attempt was made to take measurements at points exactly opposite those of the other edge. By using this approach and by making multiple measurements, the staggered tooth cutter can be treated as a symmetrical cutter differing only in helix angle from the standard cutter.

Because of the symmetry of the cutter geometries used in this test, the properties and the ANOVA of burrs 1 and 2 should be identical.* Unfortunately, the ANOVA indicated that different variables were significant for each of these burrs. Because no physical reason for these differences is obvious, the data for both burrs was pooled to determine the significant variables for these identical burrs. A similar test was performed for Burrs 3, 4, 6, and 7 because they should also be identical pairs in this test.

Table 3 has recorded that the length of burrs at positions 1 and 2 were affected by feedrate. One combination of depth of cut and helix angle also was noticeably different. The helix angle affected the length of burrs 3, 4; feedrate did not. Feedrate influenced the results at Edges 6 and 7.

One major observation of note in Tables 2 and 3 is that not all burrs are affected by the same variables. Thus changing variables to minimize the length of one burr might not affect the length of any other burr. Thus there is no simple way (other than using sharp cutters) to minimize all burrs produced by one cut. For this particular study, however, a lower helix angle and a slower feedrate reduced the length of many burrs (Figure 11).

Because one set of the burr thickness and hardness measurements could not be completed, it is not possible to draw many firm conclusions about these properties. Typically, however, burr hardness varied from Knoop 340 to 360 (approximately Rc 33 to 35). This is roughly 5 Rc points higher than the hardness of the parent material.

*Note that the conventional side-milling cutters that have helix angles will have one burr formed by the leading edge of the tooth and one by the trailing edge. The properties of these burrs should be different. In contrast a staggered tooth cutter will only produce burrs with leading edges (Figure 9).

Table 3. ANOVA Results for Side Milling (Pooled Burr Length Data)

Code	Source of Variation	Variance Ratio		
		1,2	3,4	6,7
A	Helix Angle	0.360	6.646*	2.863
B	Depth of Cut	2.126	0.189	0.192
C	Feedrate	5.049*	0.267	13.672***
AB	Interaction	8.206**	3.699	0.192
AC	Interaction	2.884	2.941	2.455
BC	Interaction	0.360	0.764	3.303
ABC	Interaction	0.000	0.332	0.192
*Indicates significance at the 95 percent level **Indicates significance at the 99 percent level ***Indicates significance at a level higher than 99 percent				

Burr thickness values varied widely. The thickest burrs tended to occur on Edges 1 through 4 (Table 4), and Edges 6, 7 and 8 had places where burr thickness was zero. In general, however, some burrs existed along all these edges. Edge 8 had some surprisingly thick burrs (up to 0.0052 inch - 132.1 μ m).

It appears that increasing feedrate results in thicker burrs along Edges 1 and 2 (Figure 12). The 10 degree helix cutter appears to have produced thicker burrs on Edges 3 and 4 than did the cutter with zero helix. The same appears to be true for burrs on Edges 6 and 7.

In reviewing the data as a whole, the following items appear most significant.

- Depth of cut did not greatly influence burr length (cuts were relatively shallow).
- The ten degree helix angle on the staggered tooth cutter produced longer or thicker burrs on some edges than did the conventional zero helix cutter.
- Feedrate effects appear to be fairly small for burr length, but faster feedrate appear to produce thicker burrs at some locations.

Figure 11. Effects of Machining Conditions on Side-Milling Burrs

Table 4. Typical Properties of Side-Milling Burrs in 303 Se Stainless Steel

Burr Property	Burr Location							
	1	2	3	4	5	6	7	8
Length (inch) *	0.0028	0.0020	0.0140	0.0073	0.0600	0.0001	0.0004	0.0002
Thickness (inch)	0.0017	0.0017	0.0021	0.0011	0.0010	0.0015	0.0001	0.0001
Hardness (Knopp)	360	345	350	350	350	350	350	350
*0.001 inch equals 25.4 μ m

Figure 12. Effect of Machining Conditions on Thickness of Side-Milling Burrs

Miniature Keyseat Cutters

In the second test a full radius convex keyseat style cutter was compared to a standard keyseat style cutter (Figure 13). Identical cutters were not available for this test but an attempt was made to use cutters with similar properties. Table 5 indicates the basic geometry of each cutter.

FULL RADIUS CUTTER

STANDARD CUTTER

Figure 13. Geometry of Miniature Keyseat Style Cutters

Table 5. Cutter and Burr Properties

Geometry	Cutter	
	Full Radius*	Standard Cutter*
Diameter (Inch) (mm)	1.125 (28.575)	0.850 (21.590)
Number of Teeth	60	40
Cutter Width (Inch) (mm)	0.063 (1.600)	0.080 (2.032)
Typical Burr Properties Produced in 303 Se SS		
Thickness (Inch) (μ m)	0.001 to 0.003 (25.4 to 76.2)	0.0003 maximum (7.62)
Length (Inch) (mm)	0.005 to 0.100 (0.127 to 2.540)	0.002 maximum (0.051)
*25° helix angle; C2 carbide, Metal Removal Company medium mastercut		

The objectives of this test was to determine how cutter shape and feedrate affected burr properties. Both climb and conventional cuts were taken with the full radius cutter in 303 Se stainless steel. In this test the leading edge of the teeth from Edges 2 and 4 exits before the trailing edges, 1 and 3 (Figure 14). In climb cutting the cutter actually starts cutting at Edges 3, 4, and 5, rather than Edges 6, 7, and 8.*

One particularly noteworthy observation of this study is the length of burr produced by the full radius cutter.** Burrs up to 0.100 inch (2.54 mm) long were found on some edges after conventional milling (Figure 15). This is almost twice the cutter width. In a climb-milling operation the maximum burr

*Figure 7 illustrates that Edges 6, 7, and 8 occur on the side of the workpiece which is nearest the cutter as it approaches the workpiece in a conventional cut. In a climb cut the cutter approaches the side on which Burrs 3, 4, and 5 occur.

**Measurement data of these burrs are presented in appendix Table A-4.

Figure 14. Identification of Burr Locations and Type of Cut

length was 0.030 inch (0.76 mm) (Figure 16). The extraordinary length of the conventional milling burrs on Edges 3 and 4 indicates that the chip stretched to nearly twice its initial size before tearing and forming a burr.

The second noteworthy item of this data is the extremely short length of the burr on Edge 7, the edge where the leading tooth enters. Edge 7 has a consistently shorter burr than the burr produced by the trailing side of the tooth (Edge 6). The burr on Edge 3 is also consistently larger than that on Edge 4. The same is true of burr thickness (Figures 17 and 18). Edges 7 and 4 had thinner burrs than Edges 6 and 3 (Figures 17 and 18). With one exception, climb milling produced thinner burrs than those produced by conventional milling.

Lowering feedrates below 0.00004 inch (1.02 μm) per revolution per tooth (IPRT) tended to increase the size of most burrs (probably the result of thermal expansion of the workpiece and consequent rubbing of the cutter).

Figure 15. Effect of Feedrate on Burr Length, Conventional Cut

Burr hardness tended to decrease after feedrate exceeded 0.00006 IPRT ($1.52 \mu\text{m}$)/rev/tooth) (Figure 19 and 20).* In this study burr hardness approached Knoop 600 (equivalent to Rc 54). This extreme hardness (the parent material was Rc 30) can only be the result of extreme work hardening. Published data on 303 Se indicates that in the fully cold worked condition this material only has a hardness of Rc 47.

*Burr hardness could not be measured on some edges because of specimen mounting.

Figure 16. Effect of Feedrate on Burr Length, Climb Cut

To obtain some information on the influence of workpiece material on burr size 17-4 PH stainless steel specimen were also machined with both cutters.*

With only one exception from both materials, the burr properties produced by the standard cutter were significantly smaller than those produced by the full-radius cutter (Figures 21 and 22). Burrs produced in 303 Se also tended to be much bigger than those produced in 17-4 PH stainless steel. This apparently is a direct result of the inability of 17-4 PH to elongate and its relatively low strain hardening exponent.

Implications of Tests and Theory

These tests provide an initial understanding of burrs produced by side milling. Although a great amount of additional study is required before a complete picture of burr properties can be presented, several significant observations appear.

*In the H900 condition this material has a Rockwell C hardness of 44.

Figure 17. Effect of Feedrate on Burr Thickness, Conventional Cut

- Burrs can form on the surface in which the cutter enters the workpiece.
- The burrs produced on each edge of a cut can vary significantly in thickness and length from those on other edges.
- Burr hardness when measured at the root of the burr is noticeably harder than the workpiece but does not vary greatly between burrs on the same workpiece.
- Burr length and thickness vary along each edge because many teeth are involved in producing these burrs.
- The helix angle (axial rake) affects burr properties.
- Feedrate influences are generally minor although above a certain limit, increasing feedrate increases burr thickness. The very low per tooth feedrate required by small cutters with master-cut teeth appear to greatly increase burr hardness.
- The square-cornered master-cut cutter produced longer but thinner burrs than those from the conventional cutter. Because

Figure 18. Effect of Feedrate on Burr Thickness, Climb Cut

of the many teeth on the master-cut cutter for equal cutter diameters, this cutter will have a higher metal removal rate than the conventional cutter. Because they also produce thinner burrs, they should be used whenever possible.

- Full radius cutters appear to produce much thicker and longer burrs than do standard cutters.

The smallest burrs on the workpiece typically occur where the teeth enter the workpiece (Edge 8). Although there is no theory to predict the size of the burrs, an analogy has previously been discussed that indicates that burr length can be inversely related to the strain hardening exponent of the workpiece and that burr thickness can be directly proportional to this exponent (Figure 23).

The exit tear burrs (Burrs 3 and 4) are noticeably longer than the tear burrs on Edges 1 and 2. The latter tend to be thicker than those on Edges 3 and 4. Although a conceptual model of tear burr formation has previously been advanced^{1,5} and summarized in this report, no equations have been developed that would predict the size of these burrs. There are two logical assumptions

Figure 19. Burr Hardness as a Function of Feedrate, Conventional Cut

based on the results of these tests and a similar study of burrs produced by drilling.⁴

- Tear burr length is controlled by the ability of the workpiece to stretch.
- Burr thickness is probably influenced more by strain hardening than any other single property.

On a conventional cutter with zero helix angle, the corners of the teeth initiate chip separation from the workpiece. They provide a high stress concentration which accelerates shearing along the sides of the teeth. Thus tearing of the chip from the

Figure 20. Burr Hardness as a Function of Feedrate, Climb Cut

workpiece only involves a very narrow band of material on either side of the tooth edge. The stretching of this narrow band of material will produce only a relatively short burr.

When a full-radius cutter is used, this high stress concentration is absent. As a result greater forces are required to separate the chip from the workpiece. This in turn widens the zone around the edges of the teeth where metal stretching takes place. On a very narrow, full-radius cutter this zone can cover the entire width of the cut. In essence the cutter is acting as a punch.

If a material does not stretch, then no burrs can form (witness cast iron and glass). The more materials stretch, the longer the burrs. As has been shown, 303 Se stainless steel formed noticeably

Figure 21. Effect of Cutter Geometry and Workpiece Material on Burr Lengths

longer burrs than 17-4 PH stainless steel which has lower ultimate elongation.

That burr thickness is more greatly affected by strain hardening than affected by other properties is more intuitive than in the case of burr length. Studies of depressions made by spherical indenters⁷⁻⁹ indicate that, in nonstrain-hardening materials, a hump of material forms around the contour of the ball. This hump is similar to the crater produced by meteorites (the lip of the crater extends above the original surface). In strain-hardening materials, however, a shorter but wider hump forms at some distance from the edge of the ball (Figure 24). Similar results have been shown to exist for wedge-shaped indenters.

Essentially this phenomena indicates that the areas nearest the loading are work-hardened and that it is easier to deform metal further away from the loading than to deform the metal in the immediate vicinity.

Figure 22. Effect of Cutter Geometry and Workpiece Material on Burr Thickness

Representative values of strain hardening exponents and ultimate elongation for several materials are presented in Table 6. As seen there, 17-4 PH stainless steel in the H900 condition has less than half of the elongation of 303 Se. Consequently the 17-4 PH stainless specimen should exhibit shorter burrs. As shown in Figure 21 this does in fact happen. If burr thickness increases with strain hardening exponent, then 17-4 PH specimen should produce thin burrs while 303 Se and 304 stainless steel specimen should produce thicker burrs. This has been shown to be the case by the data from this test (Figure 22).

An analytical analysis of roll-over burrs^{1, 5} indicates that roll-over burr thickness should be

$$b_t = \left[2 F_c + \sqrt{4 F_c^2 - \frac{2b \sigma_o \epsilon_f t \theta F_c}{(n+1) \tan \phi_s}} \right] \left[\frac{(n+1)}{b \sigma_o \theta \epsilon_f^n} \right] \quad (1)$$

Figure 23. Effect of Strain Hardening Exponent on Ridging Burr Formation (From Reference 1)

where

b_t = burr thickness in inches

F_c = cutting force (lb)

b = width of cut (inches)

σ_o = material stress at a true strain of 1.0 (psi)

ϵ_f = true strain at fracture

n = strain hardening exponent

t = uncut chip thickness (inches)

Figure 24. Material Displacement Using Spherical Indentors (For highly worked metals [non strain hardenable], the flow of metal around the indenter produces "piling up" [left]. For annealed metals, the displacement of metal occurs at regions at a small distance from the indenter so that "sinking in" occurs. [From Reference 1])

Table 6. Typical Workpiece Properties

Material	Elongation at Failure Percent	True Strain at Failure	Strain Hardening Exponent
303 Se SS annealed*	40	1.16	0.51
304 SS annealed**	60	1.3	0.45
17-4 PH SS (H900)***	14	0.5	0.17-0.26
430***annealed			0.225
SAE 4130 annealed†			0.118
1018 steel annealed*	30-40	1.05	0.25
*From Datsko ¹¹ **From Kalpakjian ¹² ***From Mulkey ¹³ †From Baumeister ¹⁴			

θ = tooth rake angle + $\pi/2$ (radians)

ϕ = shear angle produced by cutter in workpiece (radians).

Thus roll-over burr thickness is defined as a function of workpiece properties and cutting conditions. To use this equation, it is necessary to know these parameters as the cutter breaks

through the back side. Because the chip thickness constantly varies in a milling cut and because it is not feasible to predict what the exact thickness will be at breakthrough, additional assumptions must be made to use the equations. Cutting forces can be estimated from any of a large number of equations developed for turning operations.

For 303 Se stainless steel one can extrapolate Vilenski and Shaw's force data¹⁵ for a 3/8 inch (9.5 mm) wide plunge cut with a 10-degree rake angle tool. At 100 surface feet per minute (5.08 mm/sec) and 0.002 IPR/t (50.8 $\mu\text{m}/\text{rev}/\text{tooth}$) the principal cutting force was 200 pounds (90.8 Kg). Assuming $\epsilon_f = 1.16$, $n = 0.5$, $b = 0.0375$ inch, $t = 0.002$ inch (50.8 μm), $\sigma_o = 205,000$ PSI (143.5 kg/mm²), $F_c = 200$ lb., $\theta = 1.745$ radians (100°) and $\phi = 31.8$,* the predicted burr thickness would be 0.0052 inch (157.5 μm). As indicated in Table 4 a typical thickness is 0.0010 inch (25.4 μm) while one burr was 0.002 inch (50.8 μm) thick. Thus the model over-predicts burr size by a factor of 6 or less. Although this is a significant over prediction, the mathematical model is useful in indicating the role of each variable.

It should be noted that roll-over burr thickness is proportional to the factor $(n + 1)$, where n is the strain-hardening exponent. For a perfectly plastic material, n is zero. A value for n of 0.5 increases the factor in the second bracket by 50 percent, and the total product by something less than this. This adds support to the assumption that tear burr thickness is also a function of strain hardening.

Another notable aspect of Equation 1 is that anything that increases the cutting force will also increase the thickness of the roll-over burr. This is consistent with the production observation that dull tools (increased cutting forces) produce bigger burrs than sharp tools.

The hardness of burrs is directly proportional to the amount of straining in the burrs.¹ The maximum theoretical possible hardness in 303 Se is in the order of Brinnell 500. As seen in Figures 17 and 18, actual hardnesses of Brinnell 627 (Knoop 700) were observed from the key seat cutters, hardnesses of Brinnell 330 (Knoop 360) were observed from the large cutters. This difference is the impact that rubbing has on burr properties.

*Calculated from Merchant's formula and data for 303 Se SS.¹⁶

Implications on Burr Removal

Although the purpose of this study was to determine how machining conditions affect the burrs produced by side milling, the underlying reason for the study was to find conditions to minimize burr properties. By minimizing the size of burrs the deburring costs would be minimized. Under most conditions this also lowers the total fabrication cost of the part.

As previously indicated, eight different burrs can be produced by a single cut. Because each burr has properties significantly different from the other burrs, the deburring process will affect each burr differently. For example, vibratory deburring can remove a 0.001 inch (25.4 μm) thick burr and produce a 0.002 inch (50.8 μm) radius in one hour. An edge such as Edge 8 with a very small burr will obviously have a radius larger than 0.002 inch (50.8 μm) after deburring, and the edges having a 0.002 inch (50.8 μm) thick burr will not be completely deburred at this time. This can be a significant problem when parts must be completely burr free, and workpiece tolerances of 0.001 inch (25.4 μm) or less must be maintained. The problem becomes more acute when workpiece designs necessitate that edge radii must not be larger than 0.002 or 0.003 inch (50.8 or 76.2 μm).

As a rule of thumb, the maximum burr thicknesses that can be removed by vibratory deburring and related processes from stainless steel (wristwatch size) components is 0.002 inch (50.8 μm). This assumes that stock losses of 0.0005 inch (12.7 μm) from the exterior of the part can be tolerated. The data from these tests indicate that most side-milling burrs are 0.002 inch (50.8 μm) or thinner.

For conventional side-milling cutters, burr thicknesses can be minimized by reducing the feedrate and by using a 0° helix angle. Feedrate did not affect burr thickness when master cut style cutters were used (except when feedrates were slower than 0.00006 IPR/t (1.52 $\mu\text{m}/\text{rev}/\text{tooth}$). Full radius cutters should not be used unless absolutely necessary on materials that elongate noticeably. These cutters produce thicker as well as much longer burrs than do square edged cutters.

For 303 Se stainless steel, lowering the feedrate from 0.002 to 0.00057 IPRT (50.8 to 14.5 μm) reduced some burr thicknesses by a factor of 2.0. In this range of feeds, burr thicknesses can be expressed approximately by the equations given in Table 7.

Table 7. Equations for Burr Thickness

Burr Location	Equation for Burr Thickness*
1 and 2	$b_t = 0.00024 + 1.3549f$
3 and 4	$b_t = 0.00097 + 0.7517f$
6 and 7	$b_t = 0.0001 + 0.361f$
*Assumes 0° helix and conventional cut b_t = burr thickness (inch) f = feedrate in ipr/t	

When burr lengths exceed 0.050 inch, loose abrasive deburring processes tend topeen these until they lie flush with the surface. These burrs are then very difficult to remove by any process. As previously indicated, the length of the burrs were only slightly affected by feedrate. The only physically significant change which reduced burr length was to use a standard cutter rather than a full-radius cutter.

In most cases, Burr 5 readily breaks off in handling, and only a 0.010 inch (0.254 mm) burr remains on the part. When the burr is not this brittle, it too will bend flush with the nearest surface. At this time available data cannot indicate which machining conditions produce an easily broken off portion of the burr.

ACCOMPLISHMENTS

The effects of feedrates, radial depth of cut, and cutter geometry have been evaluated for side-milling cutters in 303 Se and 17-4 PH stainless steel. A model of burr formation has been presented. These results will allow manufacturing engineers to select the technique that provides the smallest and easiest burrs to remove.

FUTURE WORK

No additional work is planned on the subject of side-milling burrs. Additional tests on end milling, turning, grinding, and drilling will be performed as part of the total effort of the project. Additional burr prevention and deburring tests will also be performed.

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¹⁶M. Eugene Merchant, "Metal Cutting Research," *Machining — Theory and Practice*. Cleveland: American Society of Metals, 1950, pp 11-16.

¹⁵D. Vilenski and M. C. Shaw, "The Importance of Workpiece Softening on Machinability," *Annals of the C.I.R.P.* Vol. 18, 1970, pp 623-631.

¹⁶M. Eugene Merchant, "Metal Cutting Research," *Machining — Theory and Practice*. Cleveland: American Society of Metals, 1950, pp 11-16.

Appendix

BURR PROPERTY MEASUREMENTS

Table A-1. Measured Burr Lengths by Side-Milling With
303 Se Workpiece

Burr Location				
Sequence	1	2	3	4
1	44,25,25	55,32,22	70,80,60	22,17,12
2	25,22,24	25,34,24	60,36,39	31,30,48
3	25,30,25	18,55,38	50,56,50	55,59,52
4	25,21,27	19,16,17	70,170,70	50,30,110
5	27,40,40	30,40,40	70,60,50	180,120,40
6	32,47,33	27,32,29	90,80,50	50,60,60
7	29,27,29	17,18,25	110,60,250	70,70,80
8	36,20,34	16,19,21	70,70,70	100,80,80
Sequence	5	6	7	8
1	25,19,15	3,1,2	6,3,4	15,15,11
2	57,46,43	4,6,3	8,7,3	1,2,1
3	2,2,4	1,0,4	3,1,1	6,1,1
4	250,250,270	5,10,3	7,11,4	5,2,3
5	600,630,590	5,2,1	1,1,3	1,0,2
6	3000,3200,3150	1,10,5	3,1,7	5,5,4
7	600,650,550	0,2,0	5,4,4	3,1,3
8	859,900,900	5,3,4	2,3,1	3,5,4
Values shown are burr length in 0.0001 inch (2.54 μ m). Three readings were taken of each burr. Measurements were made by dial indicators.				

Table A-2. Measured Thickness of Side-Milling Burrs

Burr Location								
Cut*	1	2	3	4	5	6	7	8
1	-----Specimen was lost-----							
2	10,12	5,11	14,10	12,7	7,5	1,0	1,0	1,0
3	22,21	39,36	18,26	8,16	0,0	24,0	0,0	0,0
4	6,16	10,11	19,15	11,19	19,12	0,0	0,15	0,0
5	17,17	37,30	26,47	22,17	7,0	21,0	34,0	18,0
6	11,26	17,15	21,26	23,26	4,15	15,19	11,12	16,0
7	32,19	9,24	16,7	11,10	10,18	0,13	0,0	0,0
8	19,14	15,16	29,17	22,34	12,14	11,17	0,7	0,0
*Values shown are thicknesses in 0.0001 inch increments 0.001 inch equals 25.4 microns								

Table A-3. Measured Hardness of Side-Milling Burrs

Burr Location								
Cut*	1	2	3	4	5	6	7	8
1	-----Specimen was lost-----							
2	360	376	370	355	360	400	374	350
3	368	368	368	360	350	340	360	360
4	322	340	325	325	330	329	334	322
5	362	326	351	334	368		366	341
6	342	345	348	340	340	360	355	350
7	355	335	336	336	340	342	343	340
8	366	343	368	351	365	362	365	334
*Values shown are Knoop hardness numbers. A 100 gram load was used. The nominal hardness of the workpiece is Knoop 305. Knoop 322 is approximately Rockwell C32.								

Table A-4. Effects of Machining Conditions on Burr Properties: 303 Se Workpiece Keyway Style Cutter

Specimen	Cutter	Spindle Speed (RPM)	Feed		Type of Cut	Nominal Properties			
						Burr Thickness (inch**)	Hardness (Knoop)***		Burr Length (inch)
			(IPM*)	(IPRT)			Burr	Parent Material	
1	Full Radius	207	1-1/16	0.000131	Climb	0.0015 0.0007 0.0013 0.0004	1 --- 2 512 3 372 4 454	254 $\sigma = 5$	0.0015 0.0013 0.006 0.002
2	Radius	207	1-1/16	0.000131	Conv.	0.0002 0 0.0025 0.0012	1 --- 2 --- 3 610 4 524	482 $\sigma = 1$	0.0015 0 0.060 0.030
3	Radius	307	1-1/16	0.000088	Climb	0.0014 0.0002 0.0015 0.0006	1 612 2 --- 3 512 4 414	290 $\sigma = 1$	0.010 0.003 0.012 0.009
4	Radius	207	1-1/16	0.000088	Conv.	0.0003 0 0.0025 0.0008	1 --- 2 --- 3 454 4 567	296 $\sigma = 0$	0.002 0 0.030 0.100
5	Radius	449	1-1/16	0.000060	Climb	0.0007 0 0.0010 0.0004	1 680 2 --- 3 --- 4 ---	268 $\sigma = 6$	0.027 0 0.008 0.003
6	Radius	449	1-1/16	0.000060	Conv.	0.0003 0.00025 0.0030 0.0015	1 --- 2 --- 3 560 4 528	304 $\sigma = 2$	0.003 0.002 0.080 0.050
7	Radius	538	1-1/16	0.000050	Climb	0.0011 0.0003 0.001 0.0003			0.018 0.005 0.012 0.004
8	Radius	538	1-1/16	0.000050	Conv.	0.0002 0 0.0025 0.001	1 --- 2 --- 3 434 4 424	256 $\sigma = 1$	0.0015 0 0.030 0.100
9	Radius	650	1-1/16	0.000042	Climb	0.00045 0.00045 0.00120 0.0002	1 567 2 --- 3 590 4 ---	290 $\sigma = 1$	0.013 0.002 0.013 0.006
10	Radius	650	1-1/16	0.000042	Conv.	0.0001 0 0.0024 0.0009	1 --- 2 --- 3 460 4 380	271 $\sigma = 7$	0.001 0 0.060 0.035
11	Radius	785	1-1/16	0.000034	Climb	0.0004 0.0002 0.0013 0.0003	1 661 2 --- 3 590 4 ---	258 $\sigma = 2$	0.028 0.007 0.008 0.008
12	Radius	785	1-1/16	0.000034	Conv.	0.0004 0.0002 0.0022 0.0014	1 543 2 --- 3 350 4 467	265	0.0025 0.002 0.040 0.012

*1.0 IPM equals 0.423 mm/s.
**0.0001 inch equals 2.54 μ m.

Table A-4 continued. Effects of Machining Conditions on Burr Properties: 303 Se Workpiece Keyway Style Cutter

Specimen	Cutter	Spindle Speed (RPM)	Feed		Type of Cut	Nominal Properties			
						Burr Thickness (inch**)	Hardness (Knoop)***		Burr Length (inch)
			(IPM*)	(IPRT)			Burr	Parent Material	
13	Radius	1150	1-1/16	0.000023	Climb	0.001 0 0.0019 0.0008	1 305 2 --- 3 323 4 ---	210 ---	0.014 0 0.028 0.008
14	Radius	1150	1-1/16	0.000023	Conv.	0.0002 0 0.0015 0.0005	1 --- 2 --- 3 454 4 372	271 σ = 7	0.0045 0 0.010 0.016
101	Standard	207	1-1/16	0.000131	Climb	0.0003 max	b	215	0.001 max
105	Standard	449	1-1/16	0.000060	Climb	0.0002 max	b	225	0.002 max
111	Standard	785	1-1/16	0.000034	Climb	0.0002 max	b	220	0.001 max
113	Standard	1150	1-1/16	0.000023	Climb	0.0001 max	b	220	0.001 max
2P a	Radial	207	1-1/16	0.000131	Conv.	0.0003 0 0.0030 0.0009	1 325 2 351 3 --- 4 ---	281 ---	0.003 0 0.030 0.070
1P	Radial	207	1-1/16	0.000131	Climb	0.0008 0.0004 0.0032 0.0011	1 --- 2 --- 3 308 4 ---	296	0.0023 0.0039 0.0431 0.0331
3P	Radial	307	1-1/16	0.000088	Climb	Not inspected			
13P	Radial	1150	1-1/16	0.000023	Climb	0.0015 0.0004 0.0014 0.0008	1 351 2 --- 3 --- 4 ---	281	0.0378 0.0131 0.0264 0.0217
14P	Radial	1150	1-1/16	0.000023	Conv.	0.0008 0.0008 0.0021 0.0009	1 --- 2 --- 3 305-351 4 ---	281-289	0.0032 0.0022 0.0368 0.0678
101P	Standard	207	1-1/16	0.0000131	Climb	0.0006 0.0009 0.0008 0.0005	1 --- 2 406 3 --- 4 ---	281	0.0020 0.0015 0.0010 0.0010
113P	Standard	1150	1-1/16	0.0000131	Climb	0.0005 0.0005 0.0004 0.0005	1 --- 2 375 3 --- 4 ---	285	0.0017 0.0014 0.0018 0.0013

*1.0 IPM equals 0.423 mm/s.

**0.0001 inch equals 2.54 μm.

***Hardness measurements are an average of 2 to 4 readings per specimen and imply standard deviation.

a P implies the specimen was made from 17-4 PH (H900) stainless steel. All other specimen were 303 Se ST.ST.

b Burr is too small to measure.

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