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BURRS PRODUCED BY GRINDING

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BURRS PRODUCED BY GRINDING

BDX-613-1372, UNCLASSIFIED Topical Report, Published August 1976

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

An investigation was conducted to determine the influence of variables in controlling the size and repeatability of grinding burrs to minimize burr-removal costs and improve the quality and reliability of parts for small precision mechanisms. Each of the three different types of burrs produced by surface-grinding a rectangular block responds differently to changes in cutting conditions. Reducing the downfeed rate generally produces shorter burrs. Although the size of the abrasive grain affected the thickness of one of the burrs, thickness was relatively unaffected by the variables studied. The thickest burrs occurred on low-carbon steel.

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SUMMARY

Components of small precision mechanisms typically require nearly sharp edges to assure their reliable operation. A burr-free condition is also needed to assure that burrs will not break loose and jam the mechanism. In the past, the reliable removal of machining burrs and the assurance of part-edge sharpness requirements have dictated that deburring be done only by hand. This method is inherently time-consuming and operator-variable.

Small burrs are easily removed by many deburring processes. Because the repeatability of burr removal and the time required for removal are directly related to burr size, this study was initiated to determine the influence of grinding conditions upon the size of the burrs produced. The thickness and length of burrs produced on all four edges of surface-ground specimens of 303Se stainless steel, 17-4PH stainless steel, and 1018 steel were measured. An explanation of the manner in which grinding burrs form also was developed.

In general, a measurable difference was found in the properties of the burrs produced on three of the four edges during a surface-grinding operation. Increasing the downfeed rate generally produced longer burrs. One notable exception was the burr formed on the edge from which the grinding wheel entered the workpiece for a conventional cut pass; none of the variables studied changed the size of this burr. Burr length also was proportional to the number of passes made for a downfeed rate of 0.001 inch/pass (25.4 μm/pass).

A grain size of 46 produced much thicker burrs on 1018 steel than did a 120-grain size. Wheel hardness had no noticeable effect on burr properties.

Typically, the burrs produced were 0.0025 inch (63.5 μm) long and 0.002 inch (50.8 μm) thick, or less. A burr of this size is readily removable by most deburring processes.

DISCUSSION

SCOPE AND PURPOSE

This study was undertaken to determine the influence of grinding parameters upon burr size. Specifically, it sought to determine how wheel hardness, grain size, downfeed rate, and the number-of-passes affect the burr length and thickness.

PRIOR WORK

Although no previous work on grinding burrs has been published by Bendix Kansas City, a brief analysis of burr lengths produced by grinding has been reported by the author elsewhere.[1] Related studies on reaming, ball-broaching, drilling, and side-milling burrs have been published by Bendix.[2-5] General theories concerning the formation of burrs also have been reported.[6,7]

ACTIVITY

All conventional machining operations produce burrs. The size of the burrs depends upon the tool geometries used, the speeds and feeds, and the properties of the workpiece material.

The cost of burr removal is proportional to the burr size. In many instances, because of close tolerances, minute part size, and large burr size, the burr-removal cost for precision miniature parts may approach the machining cost. To minimize these fabrication costs, the influence of machining conditions upon burr size, and the influence of burr size upon burr-removal cost must be analyzed. A series of tests therefore have been initiated to provide data on burr properties as a function of machining conditions. These tests will include most common machining operations.

In this study of grinding burrs, conceptual models of burr formation were developed, and tests were performed. These tests utilized three workpiece materials, two downfeeds, two number-of-pass values, two grain sizes, and two values of wheel hardness.

Grinding-Burr Formation

Grinding burrs form by two basic mechanisms--a lateral flow of material (Poisson burr) and chip roll-over (roll-over burr). Although the basic cutting phenomenon in grinding often has been considered to be similar to that of hundreds of minute milling-cutter teeth, there are many significant differences. These differences, in turn, produce burrs that are significantly different in properties than those that would be expected from burrs produced by minute milling cutters.

The following grinding factors are significant in the formation of burrs:

- The abrasive grains have a large negative rake angle;
- The random placement of grains results in overlapping cuts; and
- The grinding temperatures are twice those produced by most cutting processes.

Each abrasive grain on the surface of a grinding wheel produces a chip. Because of the grain's roughly spherical shape, it cuts with an effectively negative rake angle (Figure 1). This angle, which approaches -30 degrees, requires much greater force than does the positive rake angle of a conventional cutting tool. To illustrate the magnitude of the difference, consider Merchant's equation[8] for the principal cutting force.

$$F_c = tb\sigma_s\left[\tan\left(\frac{C + \gamma - \alpha}{2}\right) + \cot\left(\frac{C - \gamma + \alpha}{2}\right)\right], \qquad (1)$$

where

σ_s = shear strength of the workpiece,

α = rake angle of the tool,

γ = friction angle = $\tan^{-1}\lambda$,

t = depth of cut,

b = width of cut,

C = material machining constant (92 for 303Se stainless steel),

λ = coefficient of friction (0.8 for 303Se stainless steel), and

ϕ_s = shear angle = $\frac{C - \gamma + \alpha}{2}$.

For a positive rake angle of 15 degrees and a workpiece of 303Se stainless steel, the value of the term in the brackets becomes 1.586. For the same conditions, a negative rake angle of 30 degrees results in a value of 11.393 for the term in the brackets. This sevenfold increase in the cutting force increases

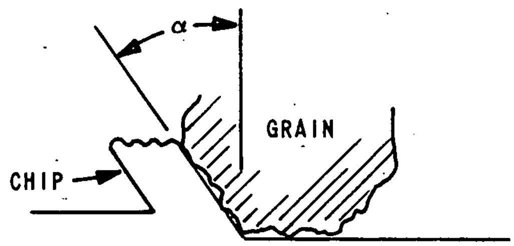

Figure 1. Effective Rake Angle of an Abrasive Grain

the plastic stresses at the sides of the cut which, in turn, produce a larger burr. In other words, a microscopic cutting tool would concentrate the cutting action within a very small area; an abrasive grain, however, increases the width of the zone in which work is performed on the part. Essentially, it produces large bulk stresses which, in turn, increase the burr size.

The Poisson Burr

A burr is formed on both sides of an abrasive grain as it cuts the workpiece (Figure 2). The formation of the burr is the result of the lateral forces which occur in any material having a Poisson ratio greater than zero. The spherical shape of the grain also produces lateral forces all around the leading half of the grain's periphery (Figure 3). Conceptually, the burr that is formed is similar to the ridge which occurs when a marble is pushed through loose dirt. In the case of the abrasive grain, the grain also produces a chip as it ploughs through the workpiece.

The magnitude of the burr produced by an individual grain appears to be a function of the following variables:

- Strain hardenability of the workpiece;
- Size of the grain;
- Wheel speed;
- Table speed;
- Downfeed; and
- Grain "sharpness."

By analogy with the Poisson burrs formed during drilling[4] and milling[5] operations, the thickness and length of the burrs are

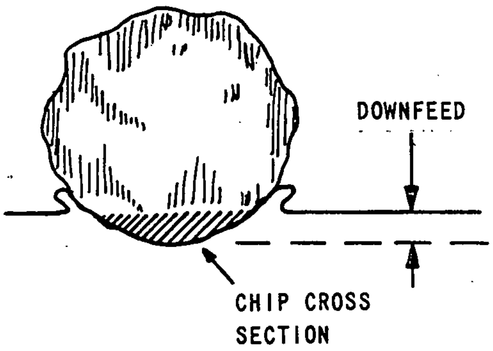

Figure 2. Poisson Burr Formed by Abrasive Grain

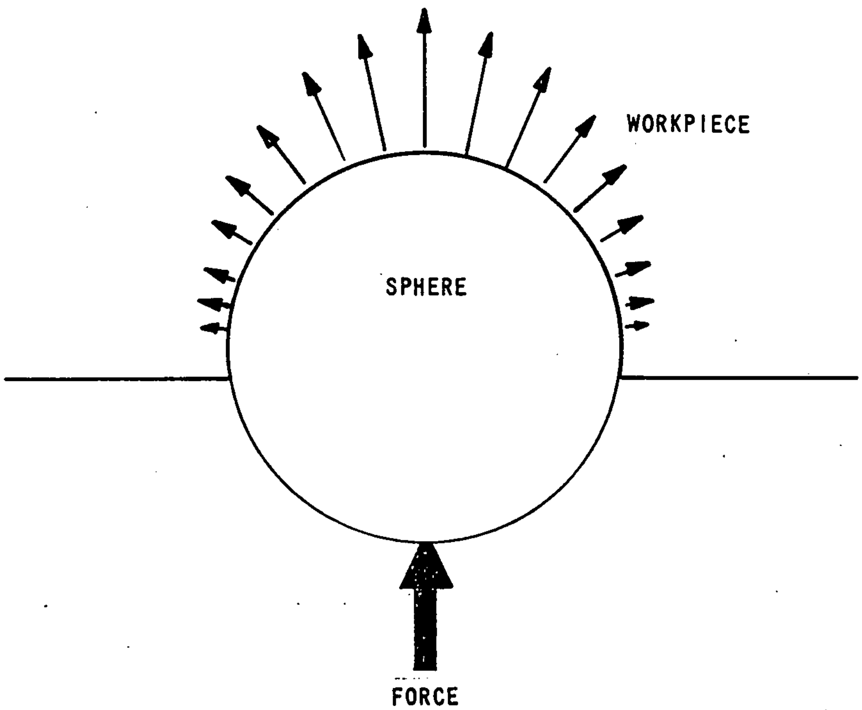

Figure 3. Distribution of Force Between a Sphere and a Solid Body Due to a Force Applied to the Sphere

a function of the strain-hardening exponent of the workpiece material. Because the force produced by a grain is proportional to downfeed, grain size, and sharpness, the assumption would be made that these factors also directly affect the burr size. The combination of wheel speed and downfeed affect the cutting velocity; the velocity is directly proportional to the cutting strain-rate which, in turn, influences the cutting stresses. Most materials exhibit less elongation and distortion as the strain-rate increases, and hence they should produce shorter burrs.

Up to this point, only the burr produced by an individual grain has been considered; however, the burr left on the finished workpiece is the net result of the action of hundreds of grains. Because of the random spacing of the grains, the burr produced by one grain will be partially cut off by a succeeding grain (Figure 4).

Ignoring the effect of cross feed, Figures 5 and 6 show that a grain near either Edge 1 or 2 will force material to move laterally over the edge of the workpiece. Because the wheel is turning, an individual grain is in contact with the workpiece for only a short distance. Lai and Shaw[9] indicate that this length of contact (Figure 7) can be expressed by the following equation.

$$L = \sqrt{Dd}, \qquad (2)$$

where

L = length of contact,

D = grinding-wheel diameter, and

d = depth-of-cut (downfeed).

For an 8-inch-diameter (203.2 mm) wheel and a 0.001-inch (25.4 μm) depth-of-cut, L is 0.089 inch (2.26 mm). Thus each grain produces a burr for a distance of 0.089 inch, or less. By the nature of the process, part of the burr produced by the first grain is removed by the second grain as it makes a chip.

Assuming that only one grain cuts at a specific point during a single revolution of the wheel, the feedrate per tooth can be expressed by Equation 3.

$$f = F/rpm, \qquad (3)$$

where

f = feedrate per tooth (or feedrate per revolution),

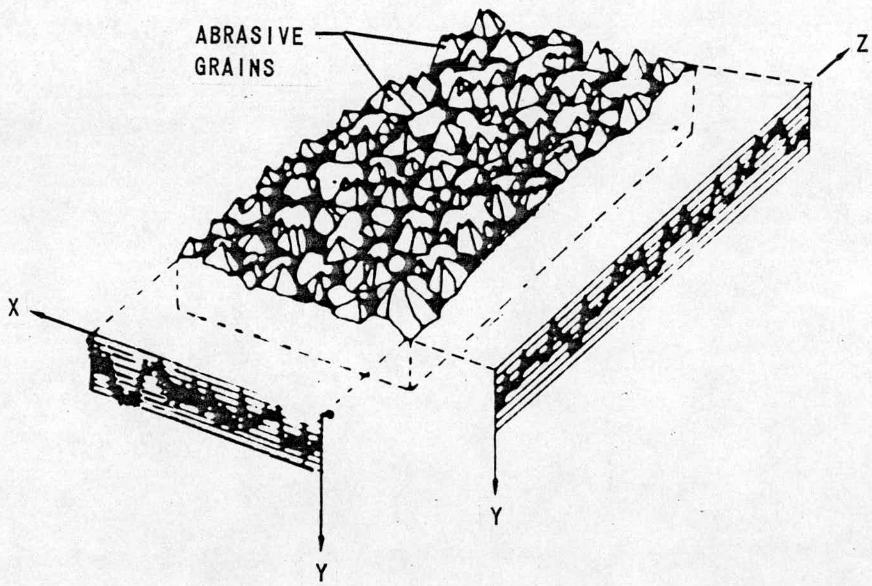

Figure 4. Cutting Surface of a Grinding Wheel

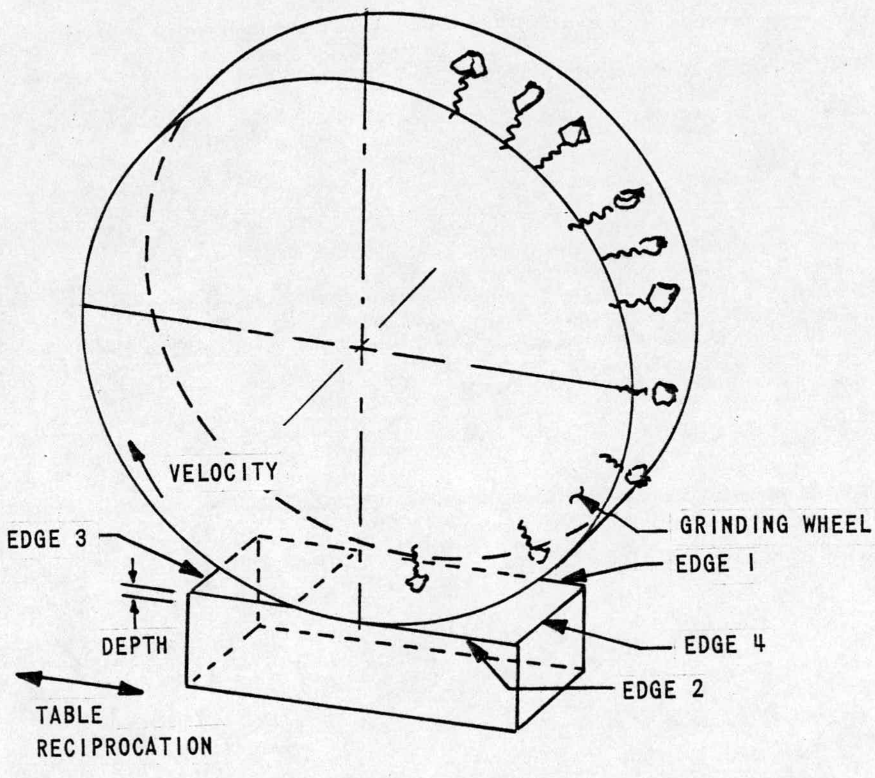

Figure 5. Identification of Workpiece Edges at Which Burrs Form

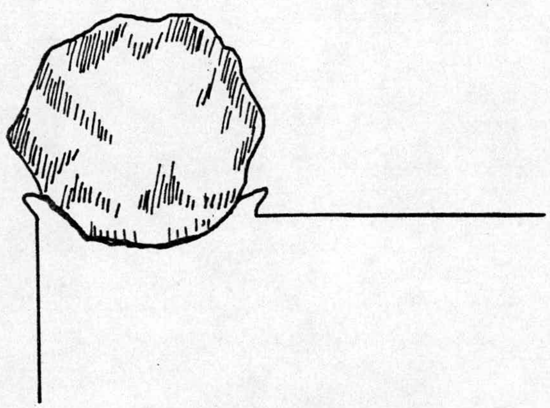

Figure 6. Grain Cutting Near Edge of Part (Motion is away from observer.)

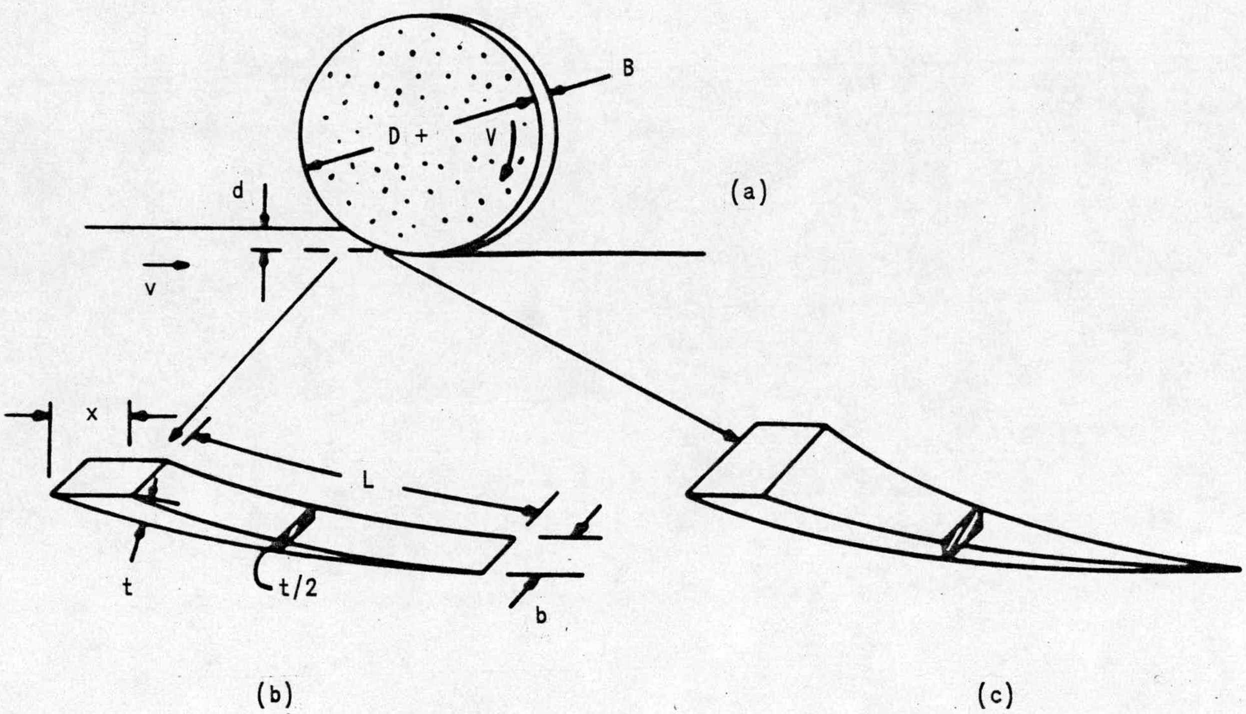

Figure 7. Chips Produced by Surface Grinding: (a) Schematic View of Process, (b) Idealized Chip Used to Insure Volume Continuity, and (c) Shape of Undeformed Chip (From Lai and Shaw[9])

F = longitudinal table feedrate, and

rpm = spindle speed.

For a longitudinal table feedrate of 50 ft/min (0.0254 m/s) and a spindle speed of 3450 rpm, f = 0.0145 inch (368 μm). Thus in grinding a 2-inch-long (50.8 mm) specimen, a single grain would make 138 separate cuts. This alone would produce a burr having constantly varying properties.

Because of the random spacing of the grains, one grain will be positioned slightly to the left of the grain shown in Figure 4, and another will be positioned slightly to the right. This alternating random spacing tends to push the burr produced by the first grain farther over the edge. At some points, however, the grains will be positioned in such a manner that they will cut off the burr formed by a preceding grain. Thus a close examination of a workpiece edge having a grinding burr should reveal a noticeable burr attached at intermittent intervals (Figure 8).

Materials which become noticeably work-hardened may exhibit a continuous burr attachment, rather than the intermittent attachment common to other materials. The work-hardening effect tends to swell the material to such an extent that the grains cannot entirely remove the swell.

The Roll-Over Burr

When abrasive grains exit over Edge 3 (Figure 5) of the workpiece, they produce a roll-over burr. This burr consists of a grinding chip which bent out of the grain's path rather than become severed from the material. Because the grain also pushes metal ahead of it, some of the roll-over burr consists of swelled metal as well as unsevered chips (Figure 9).

With each downfeed movement, the roll-over burr lengthens. As shown in Figure 7, an abrasive grain produces a definite chip which separates from the workpiece when the wheel approaches the end of the cut. The last few grains, however, do not produce a loose chip.* Potential Chips 1, 2, and 3 shown in Figure 10

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*Throughout this report, the discussion assumes a conventional cut. A similar effect occurs for climb cutting, but in that case the "entrance" burr actually occurs at the point where the wheel exits from the edge (Figure 7). The results of milling tests indicate that burrs from climb milling are somewhat smaller than those from conventional milling. In one cycle of table reciprocation during surface grinding, one conventional pass is followed by a climb cut. The properties of the resultant burr therefore are caused by a combination of both types of cut.

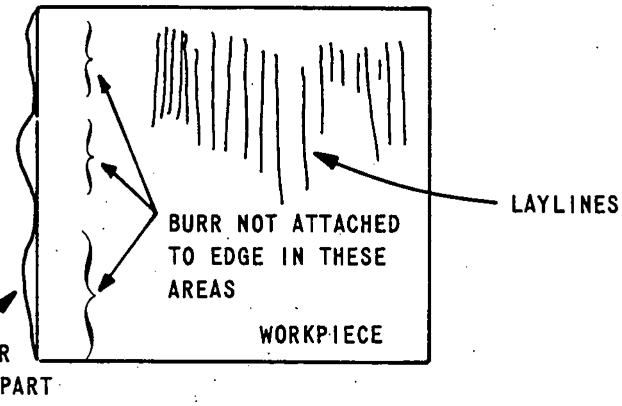

Figure 8. Intermittent Attachment of Burr to Edge of Part

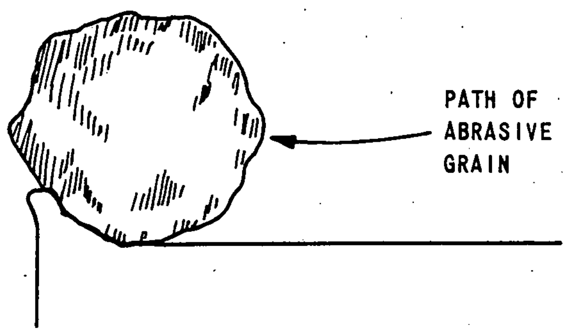

Figure 9. Formation of Roll-Over Burr as Grain Exits From Back Edge of Workpiece

will separate from the workpiece; Potential Chip 4 will not form. Because material can be pushed out of the grain's path easier than a chip can be formed, the grain will not cut. Instead, it will push material out of the way. This material, which normally would become a chip, lengthens the burr just as peeling a banana produces a longer peel. Each succeeding downfeed thus lengthens the roll-over burr by an amount approximately equal to the downfeed. By analogy, a similar phenomenon occurs where the Poisson burrs form at the sides of the part.

The Entrance Burr

A burr also forms on the edge at which the grinding wheel enters the workpiece (Edge 4 in Figure 5). This entrance burr consists

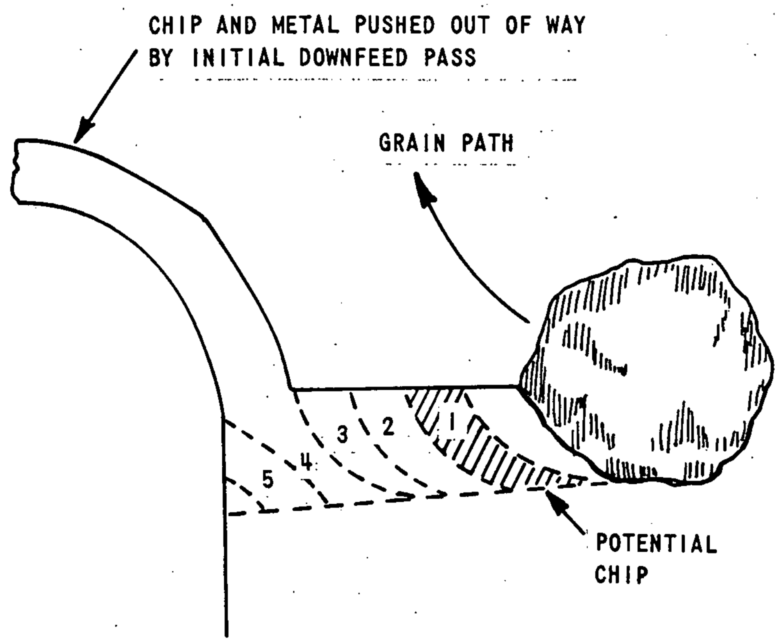

Figure 10. Grain Paths and Material Flow Near End of Cut

of material which has flowed opposite to the direction of the grain motion (Figure 11), and it is similar to the ridge which forms around the indentation made by a Brinell hardness tester. With conventional cutting tools, this burr may or may not form, depending upon the shape of the tool and the properties of the workpiece material. Because of the high forces involved and the spherical shape of the abrasive grains, entrance burrs likely will form on most workpieces.

Based on Brinell hardness results, a lip of material has been shown to form when the material has a low strain-hardening exponent (Figures 12 and 13).[10,11] As shown in Figure 13, the flow of highly worked (non-strain-hardenable) metals produces a "piling up" around the indenter. For annealed metals, the displacement of metal occurs a short distance from the indenter so that a "sinking in" is produced. Materials having high strain-hardening exponents therefore cause a bulge, but not a sharp burr. Assuming a constancy of volume, this bulge will be wide but short; in the previous case, the burr will be long and narrow. With a high strain-hardening exponent, the bulge probably will be so short that it will be difficult to detect. This entrance burr is essentially one form of a Poisson burr.

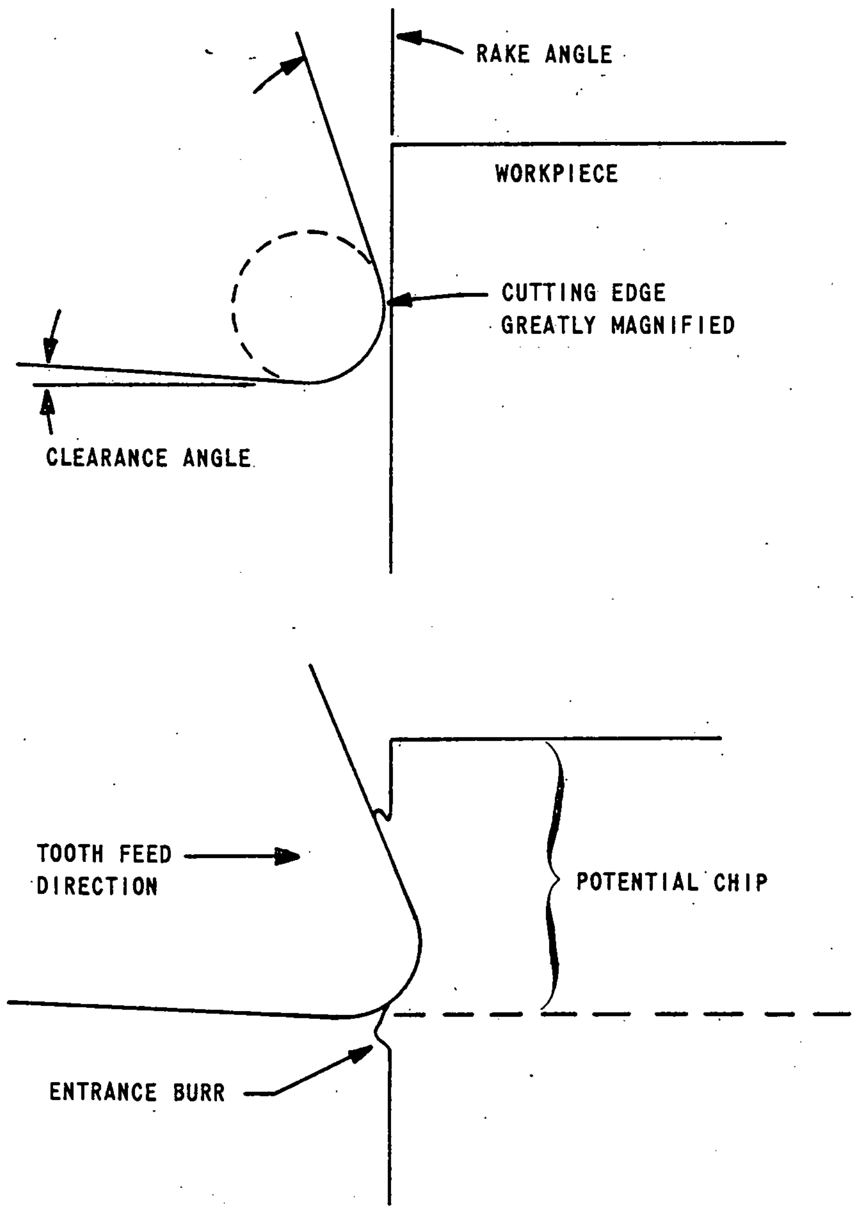

Figure 11. Cutting Edge Producing Indentation as It Enters Workpiece

Significant Variables

From the previous discussion, it can be seen that the size of burrs produced by grinding will increase whenever the cutting forces increase without a corresponding increase in the amount of material removed. Thus "dull" grains will increase the magnitude of the Poisson burr, the roll-over burr, and the entrance burr.

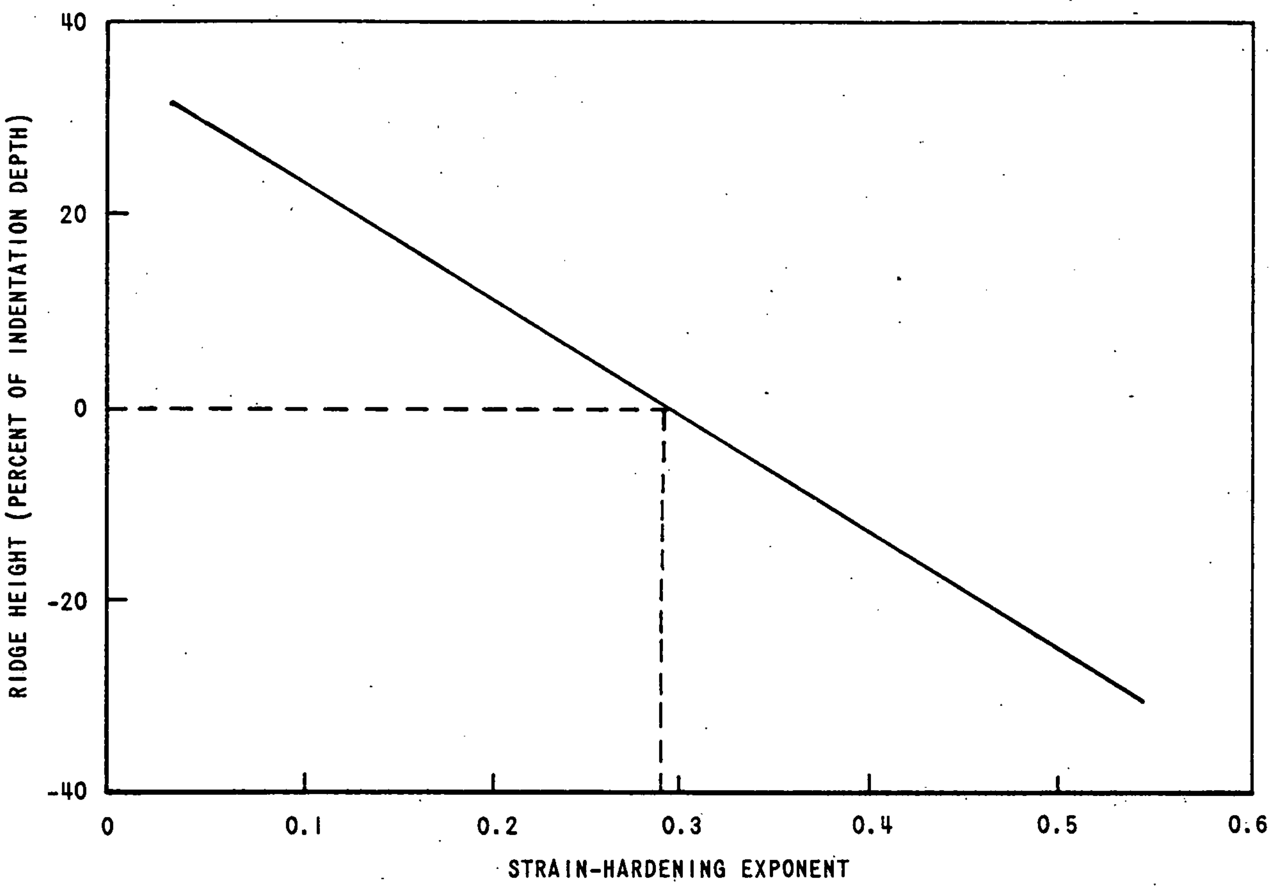

Figure 12. Effect of Strain-Hardening Exponent on Ridging-Burr Formation (Data From O'Neill[11])

Figure 13. Material Displacement, Using Spherical Indenters (non-strain-hardenable metal left and annealed metal right)

High wheel speeds should minimize burr size since they increase the strain rate and thus effectively reduce the plasticity of the material.

Increasing the downfeed and the grain size increases the cutting forces. While cutting stresses, and not forces, determine burr size, the unique shape of the abrasive grains allows the use of forces as indicators of burr size. Larger grains should widen the area of plasticity-deformed material and, as a result, they should produce thicker burrs. Increasing the table speed also increases the strain rate and thereby minimizes burr size. (There is a critical velocity for each workpiece material which must be exceeded before this effect becomes noticeable.)

High strain-hardening exponents increase the thickness of both entrance and roll-over burrs and decrease the height of entrance burrs. Their effect on roll-over burr properties is linear.[6,7]

Burr length is a function of workpiece ductility, but the function is not necessarily linear. With the employment of appropriate grinding practice, brittle materials should not form long grinding burrs.

While the preceding discussion has explained the underlying nature of burr formation, the actual mechanism is more complex. Mohun,[12] for example, notes that the temperature of tungsten at the wheel-workpiece interface can approach 6500°F (3593°C). For most materials, the interface temperature approaches or exceeds the melting point of the workpiece. Although these temperatures occur only in front of the wheel for a depth of only a few ten-thousandths of an inch below the surface of the workpiece, they are high enough to significantly change the mechanical properties of the workpiece in the zone of chip formation. For this reason, burrs can be found on such normally brittle materials as cast iron or tungsten.

Bond-strength variations, grain friability, the frequency of dressing, and the type of grain material also affect the burrs formed. A comprehensive analytical determination of grinding-burr properties would require the use of complex statistical equations to define the microprofile of the wheel, the cutting action, and the constantly changing conditions of the wheel. Such equations have not as yet been applied to this subject.

Experimental Results

A brief study was performed to determine the magnitude of the influence of typical grinding variables on the burrs produced. Three workpiece materials, two downfeeds, four grinding-wheel compositions, and two number-of-downfeed-pass increments were used in the investigation. The materials studied included 17-4PH stainless steel, 303Se stainless steel, and 1018 steel. A total of 48 combinations was evaluated; the magnitude of the variables used is shown in Table 1. Both burr thickness and length were measured at each edge indicated in Figure 5. The workpiece samples were 1-inch (25.4 mm) square and 1/2-inch (12.7 mm) thick. A water-soluble coolant was used on all specimens. The measurements that were made are tabulated in the Appendix.

An analysis-of-variance (ANOVA) of the test results indicates that downfeed and the number-of-passes affected the burr length, but the wheel composition did not. The wheel composition, as referred to in this report, implies a combination of grain size and wheel hardness. The wheel-hardness values used in the study were as close to one another as was practical. All wheels utilized aluminum-oxide abrasive, were 7 inches (177.8 mm) in diameter, and rotated at 3450 rpm.

In general, the workpiece material did not influence the length of any of the burrs (Table 2), but there were some combinations in which the workpiece material did make a difference.

Burr thickness was generally independent of all the variables studied (Table 3). However, workpiece material and wheel construction did affect the thickness of burrs at Location 3.

The quantitative influence of the significant variables indicated in Tables 2 and 3 are illustrated in Figures 14 through 17. In all cases, a 0.0002-inch/pass (5.1 μm/pass) downfeed produced shorter or thinner burrs than did the 0.0010-inch/pass (25.4 μm/pass) downfeed, or it resulted in no difference. Burrs became longer at all edges except Edge 4 as the number of passes increased when a fast feedrate was used. The thickest burrs occurred on 1018 steel with the 46-grit abrasive grain (Figure 18). As shown in Table 4, the smallest burrs occurred on the entrance side (Edge 4) of the workpiece, and the longest and thickest occurred on the chip-roll-over side (Edge 3).

<u>Significance of Experimental Results</u>

Three different types of burrs are produced by grinding the top surface of flat specimens: the entrance burr; the Poisson burr; and the roll-over burr. These burrs differ from each other in thickness and length. Of the three, the entrance burr is the thinnest and the shortest. Statistically, test results indicate that the entrance burr is unaffected by downfeed, number-of-passes, grain size, wheel hardness, or workpiece material.

The length of the Poisson burrs which formed at the sides of the workpiece was found to be proportional to the downfeed. For fast

Table 1. Grinding Variables and Levels Used in Study

Level	Workpiece Material--Factor A	Grinding Wheel--Factor C	Variable Downfeed Per Pass--Factor B (Inch)	(μm)	Number of Passes--Factor D
1	17-PH SST	32A120J9VG	0.0002	5.08	1
2	303Se SST	38A46H8VBE	0.0010	25.4	10
3	1018 Steel	A120P4R30			
4		38A46M5VBE			

downfeeds, the length also was proportional to the number-of-passes taken, but it was not affected by either the wheel composition or workpiece material. With the exception of one of the 48 combinations studied, the burr thickness was found to be independent of the variables.

The length of the roll-over burr (formed where the wheel exits from the workpiece) was found to be proportional to the downfeed. In a few instances, the workpiece material and the number-of-passes affected the length of these burrs. The thickness of roll-over burrs from 1018 steel specimens was approximately twice that of burrs from other materials. Wheels having small grains produced thinner burrs than did the 46-grit wheels by a factor of 2.

In the discussion of burr formation, materials having high strain-hardening exponents were predicted to exhibit thicker entrance and roll-over burrs and shorter entrance burrs than materials having low strain-hardening exponents. This was *not* confirmed experimentally. One possible explanation for this discrepancy between theory and practice is that the temperatures and forces involved resulted in a plastic zone that was more pronounced than those encountered in conventional cutting operations. This would have the effect of producing greater uniformity for all workpiece-material properties in the thin layer that is responsible for the formation of burrs. As predicted, downfeed and grain size did influence the burr properties.

Experience indicates that burrs produced by grinding are relatively easy to remove by any deburring process. Previous studies indicate that any burr that is 0.002 inch (50.8 μm) in thickness, or less, can be readily removed by vibratory deburring,

Table 2. Analysis-Of-Variance Results for Burr Length

		Burr Location (Edge)			
Variable*		1	2	3	4
A	Workpiece Material	***	**	***	
B	Downfeed				
C	Wheel				
D	Number of Passes				
AB	Interaction	***		**	
AC	Interaction				
AD	Interaction				
BC	Interaction				
BD	Interaction	***		***	
CD	Interaction				

*Three-factor and higher-order interactions were pooled to form a residual mean square from which tests of significance were made.
**Significance at 95-percent level.
***Significance at 99-percent level.

provided that the burr is short. As indicated in Table 4, the burrs observed during this study fulfilled both requirements. As a result, grinding variables generally do not require any control beyond the employment of good grinding practice to produce burrs that are easy to remove. In special cases where control is desired, minimizing the downfeed will minimize the burr size.

ACCOMPLISHMENTS

The downfeed per pass has been shown to be the most significant variable in controlling the properties of burrs produced by grinding. Three different types of burrs are produced on the four sides of a surface-ground rectangular specimen. A basic explanation of how these burrs are produced by grinding has been developed.

Table 3. Analysis-Of-Variance Results for Burr Thickness

Variable*		Burr Location (Edge) 1	2	3	4
A	Workpiece Material			***	
B	Downfeed				
C	Wheel			**	
D	Number of Passes				
AB	Interaction				
AC	Interaction				
AD	Interaction				
BC	Interaction				
BD	Interaction		**		
CD	Interaction				

*Three-factor and higher-order interactions were pooled to form a residual mean square from which tests of significance were made.
**Significance at 95-percent level.
***Significance at 99-percent level.

FUTURE WORK

No additional study of the burrs produced by grinding is planned. Additional tests will be reported on the burrs produced by drilling, turning, and end-milling, and an analysis of economic trade-offs between the costs of machining and those of deburring will be made.

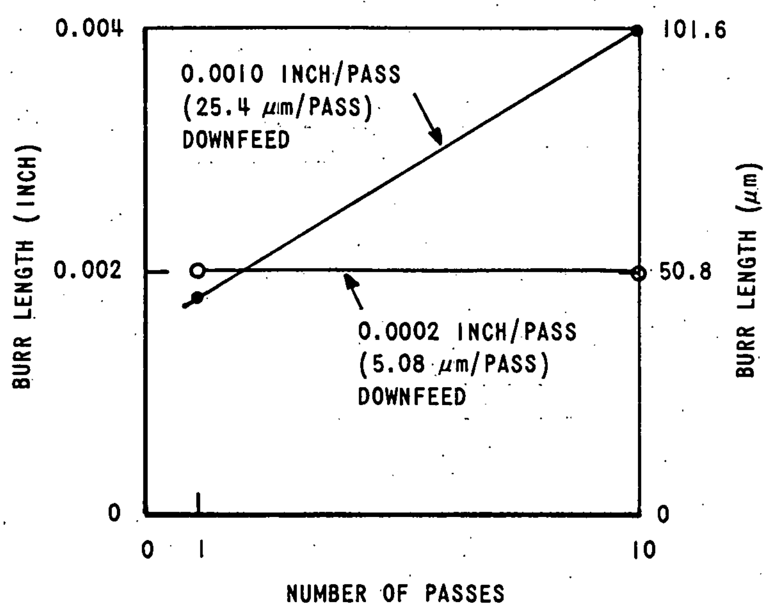

Figure 14. Influence of Number-Of-Passes on Burr Length at Location 1

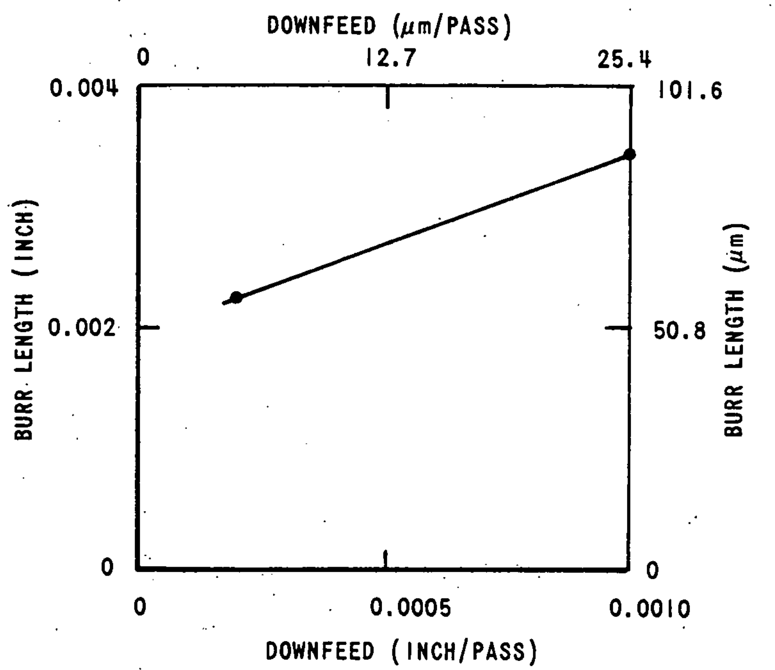

Figure 15. Influence of Downfeed on Burr Length at Location 2

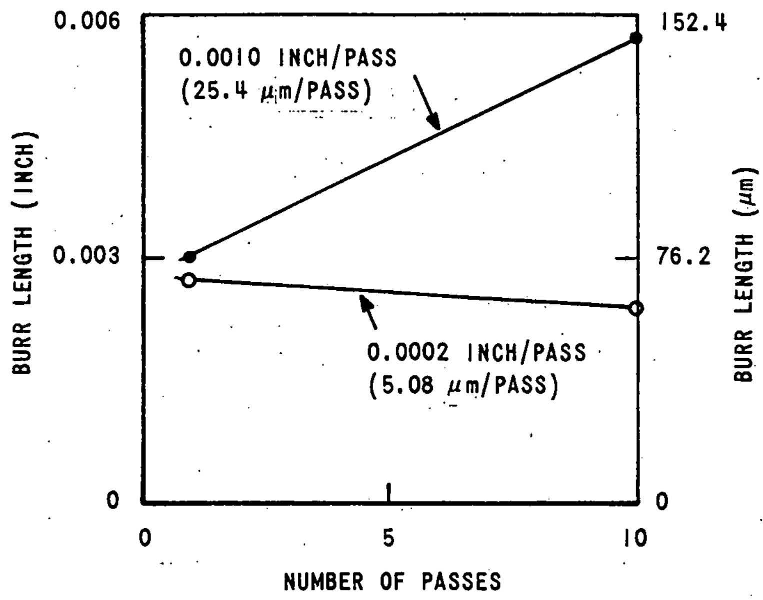

Figure 16. Influence of Number-Of-Passes on Burr Length at Location 3

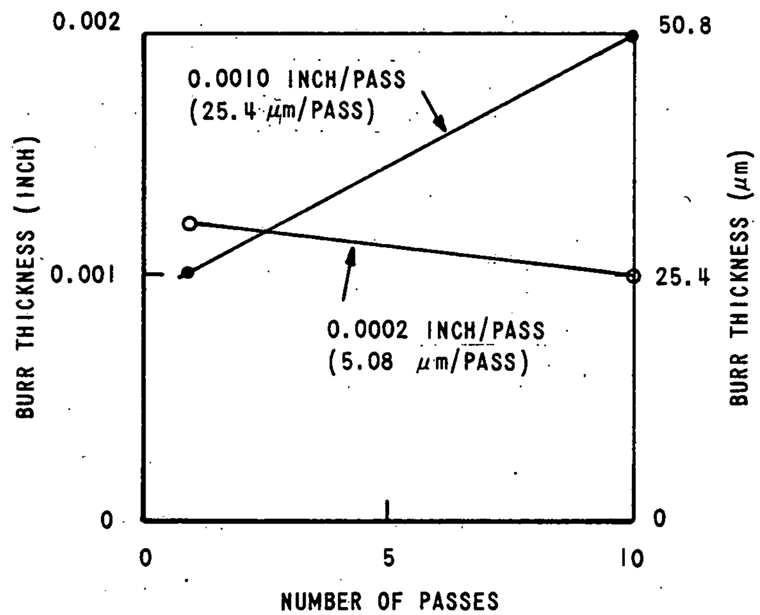

Figure 17. Influence of Number-Of-Passes on Burr Thickness at Location 2

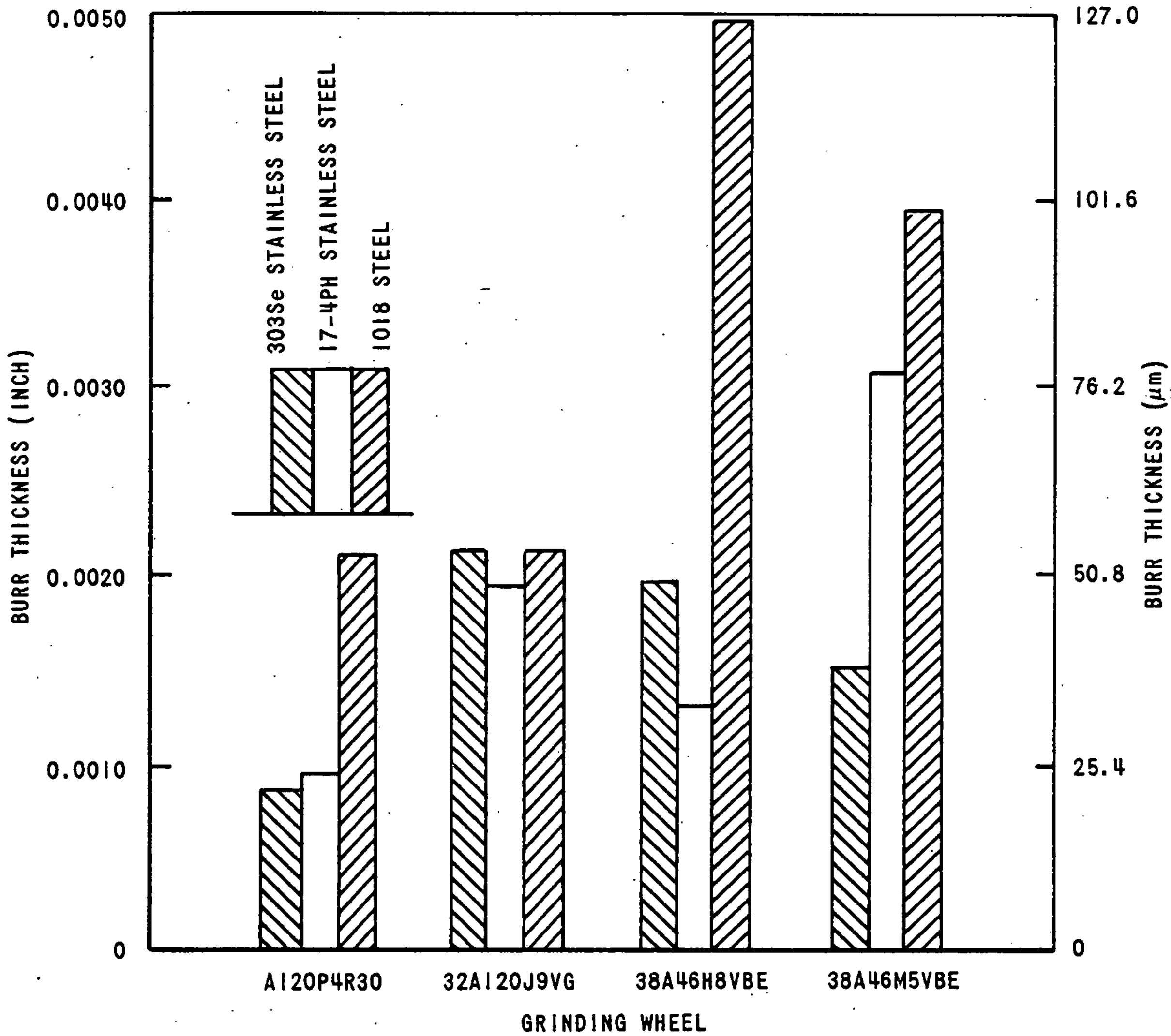

Figure 18. Burr Thickness at Location 3 as a Function of Grinding Wheel Used

Table 4. Typical Burr Sizes

Burr Location (Edge)	Burr Property			
	Length (Inch)	(μm)	Thickness (Inch)	(μm)
1	0.0025	63.5	0.0015	38.1
2	0.0028	71.1	0.0014	35.6
3	0.0034	86.4	0.0023	58.4
4	0.0018	45.7	0.0009	22.9

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Appendix

SIZES OF BURRS PRODUCED BY GRINDING

Table A-1. Burr Measurements

Factor and Level* ABCD	Sequence Number	Part Number	Burr Properties for Indicated Edge Locations: Length (0.0001 Inch)** 1	2	3	4	Thickness (0.0001 Inch) 1	2	3	4
1112	1	21	6	17	16	13	4	4	8	8
2211	2	1	14	8	6	21	8	10	15	7
3112	3	41	35	10	30	11	14	7	30	11
2212	4	2	51	81	26	8	12	16	41	11
3211	5	42	27	14	40	10	12	8	18	26
3111	6	43	23	20	20	14	13	6	6	3
1211	7	22	53	18	15	8	33	25	37	14
2111	8	3	24	27	44	19	18	22	18	17
1111	9	23	15	15	25	12	13	33	19	17
3212	10	44	41	35	75	19	30	40	32	9
1212	11	24	17	17	66	20	6	8	13	24
2112	12	4	21	11	7	11	26	7	11	5
3121	13	45	31	36	25	18	10	17	61	7
1221	14	25	16	50	26	13	13	8	11	8
2221	15	5	11	11	16	15	6	7	20	7
1222	16	26	43	28	28	21	19	22	44	9
3122	17	46	13	12	23	24	9	22	52	8
2121	18	6	38	12	20	15	21	8	11	10
3222	19	47	67	78	76	4	15	27	43	4
3221	20	48	20	74	62	3	13	11	41	7
1122	21	27	13	14	15	12	35	10	10	8
1121	22	28	17	19	10	11	17	23	12	11
2122	23	7	24	83	70	25	10	16	6	9
2222	24	8	44	66	76	20	19	26	16	6
3232	25	49	49	32	51	33	11	11	22	6

Table A-1 Continued. Burr Measurements

Factor and Level* ABCD	Sequence Number	Part Number	Burr Properties for Indicated Edge Locations: Length (0.0001 Inch)** 1	2	3	4	Thickness (0.0001 Inch) 1	2	3	4
3132	26	50	24	21	33	28	8	4	17	23
2231	27	9	12	9	27	25	5	4	9	8
3131	28	51	12	14	8	6	12	6	19	11
1231	29	29	13	8	28	19	20	9	7	3
2131	30	10	9	41	46	9	7	5	4	7
2232	31	11	11	26	75	28	6	7	12	3
1232	32	30	46	12	16	25	13	5	6	6
3231	33	52	11	17	13	6	14	24	29	11
2132	34	12	26	14	26	12	10	9	13	7
1131	35	31	16	24	14	9	6	11	16	8
1132	36	32	14	11	5	16	13	8	9	5
1241	37	33	12	22	28	30	10	8	14	4
3142	38	53	29	11	24	3	9	11	50	4
1141	39	34	14	29	11	7	12	7	31	4
3141	40	54	11	11	81	88	11	12	20	5
2241	41	13	22	46	22	11	19	9	22	7
3241	42	55	20	19	55	10	24	10	17	10
3242	43	56	56	70	57	7	32	24	72	17
2142	44	14	28	21	13	15	15	16	12	11
1142	45	35	12	24	28	46	23	11	10	14
2242	46	15	29	41	73	36	19	41	16	14
2141	47	16	28	10	17	12	10	7	9	4
1242	48	36	44	43	76	32	28	20	72	4

*Factor and level codes are identified in Table 1.
**0.0001 inch = 2.54 μm.

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