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EFFECTS OF DRILLING VARIABLES ON BURR PROPERTIES

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EFFECTS OF DRILLING VARIABLES ON BURR PROPERTIES

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

An investigation utilizing 303Se stainless steel, 17-4PH stainless steel, 1018 steel, and 6061-T6 aluminum was conducted to determine the influence of drilling variables in controlling burr size to minimize burr-removal cost and improve the quality and reliability of parts for small precision mechanisms. Burr thickness can be minimized by reducing feedrate and cutting velocity, and by using drills having high helix angles. High helix angles reduce burr thickness, length, and radius, while most other variables reduce only one of these properties. Radial-lip drills minimize burrs from 303Se stainless steel when large numbers of holes are drilled; this material stretches 10 percent before drill-breakthrough. Entrance burrs can be minimized by the use of subland drills at a greatly increased tool cost. Backup-rods used in cross-drilled holes may be difficult to remove and may scratch the hole walls.

WPC-dvh

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SUMMARY

Components of small precision mechanisms typically require nearly sharp, burr-free edges to assure their reliable operation. In the past, the removal of machining burrs with the assurance of part-edge sharpness 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 drill geometry and drilling techniques upon the size of the burrs produced. The thickness and length of both entrance and exit burrs produced from 303Se stainless steel, 17-4PH stainless steel, 1018 steel, and 6061-T6 aluminum were measured. An explanation of the manner in which drilling burrs form also was developed.

Subland drills minimized the size of entrance burrs, but their use increased the tool cost by 600 percent. With two exceptions, little change was noted in burr properties as additional holes were drilled. However, increasing the feedrate from 0.001 to 0.003 ipr (25.4 to 76.2 μm/rev) increased the thickness of both entrance and exit burrs by 40 percent. A similar increase in burr thickness and the radius on the backside of the burr occurred when the cutting velocity was increased from 50 to 100 sfpm (255 to 510 mm/s).

The radial-lip and the four-facet-point drills produced equivalent results except when a large number of holes (exceeding 150) were drilled in 303Se stainless steel. In the latter case, the radial-lip drill produced noticeably smaller burrs. In 303Se stainless steel, the material below the drill point was found to stretch by at least 10 percent before the drill broke through the bottom surface.

Burr height was found to increase with increased drill diameter, but high helix angles of 37-1/2 degrees were found to reduce burr height by 50 percent and burr thickness by 20 percent.

While the use of a backup-rod was found to minimize the size of the burrs produced in cross-hole drilling, the burrs which formed on the rod tended to lock it in the hole, and they scratched the walls of the hole when the rod was removed.

The information obtained from this study will be combined with that obtained from similar tests of other machining operations to determine optimum machining conditions for minimizing the cost of deburring and other related fabrication expenses.

DISCUSSION

SCOPE AND PURPOSE

This study was made to determine the manner in which conventional drilling practices influence the size of burrs. Specifically, it sought to determine how drill-point geometry, feedrate, workpiece material, workpiece thickness, and the use of backup material affect burr thickness and length.

PRIOR WORK

This report is the second in-depth study of drilling burrs by personnel of the Bendix Kansas City Division. In the first report,[1] the effects of drill-point geometry, feedrate, and workpiece thickness were evaluated for four materials. Previous studies, less extensive, have also been reported at Bendix.[2,3]

In related investigations, burrs produced by ballizing, reaming, end-milling, side-milling, and grinding have been described,[4-8] and general theories of burr formation have been developed.[9-11] Some experimental work has been reported by other agencies on drilling burrs,[12-19] stamping burrs,[20-26] and burrs formed from electrical-discharge machining.[27]

ACTIVITY

All conventional machining operations produce some burrs, the size of which depend upon the tool-geometries used, the speeds and feedrates, and the properties of the workpiece material. The cost of removing the burrs is proportional to the burr size. When miniature precision parts are involved, the close tolerances, minute part size, and large burr size often may cause the burr-removal cost to approach the cost of machining the parts.

To minimize these fabrication costs, the manner in which deburring costs vary with burr size and the influence of machining conditions upon burr size must be analyzed. A series of tests therefore have been initiated to provide data on burr properties as a function of machining conditions. The complete series of tests will include most of the common machining operations.

This study consists of five sets of tests. In the first set, two drill-point geometries were evaluated in four materials for two drill diameters at two surface velocities. In the second set of tests, subland drills were used to determine whether a light counterboring action would eliminate noticeable burrs on the entrance-side of the holes. The third set consisted of a drill-life evaluation of three drill-point geometries in three workpiece materials. The use of removable, consumable backup material for cross-hole drilling was evaluated in the fourth set of tests. Material deflection below the drill point was studied in the fifth set.

Effects of Helix Angle, Diameter, Velocity, Point Geometry, and Workpiece Material

The initial tests in this study were designed to determine the manner in which drill helix angle, diameter, point geometry, and surface velocity affected the burr size for four workpiece materials. However, because of repeated cases of drill breakage in 17-4PH (H900) stainless steel, results for only the following three materials are described: 303Se stainless steel (R_C34); 1018 steel (R_B99); and 6061-T6 aluminum (R_B54). Except for aluminum, the specimens consisted of 0.127-inch-thick (3.175 mm) discs, each 0.500 inch (12.7 mm) in diameter. The thickness of the aluminum specimens was 0.188 inch (4.78 mm). Drilling was performed on a Hardinge HLV lathe using power feed and a flood coolant. Five specimens were machined at each of the 48 conditions evaluated.

The test conditions used in this study are indicated in Table 1. All radial-lip drills were ground by the Radial Lip Machine Company (Lake Bluff, Illinois).

The four-facet drills were off-the-shelf, screw-machine-length, high-speed-steel drills (List Numbers 957 and 967, Cleveland Twist Drill, Cleveland, Ohio) with a 128-degree, printed-circuit-board four-facet point added. The feedrate was maintained constant at 0.001 ipr (25.4 μm/rev). The height, thickness, and radius on the back surface of each burr were measured at both the drill-entrance and drill-exit sides of each hole (Figure 1). The data obtained are shown in Table A-1 of the Appendix.

An analysis-of-variance (ANOVA) indicated that each of the factors studied affected at least two of the six properties measured (Table 2). However, considering only the exit burr, which is much larger than the entrance burr, only the helix angle and the drill diameter played major roles in determining the burr properties. As indicated by the large number of interactions, there are unique combinations of variables which show significantly different results than would have been predicted from the averaged data.

Table 1. Drilling Conditions Used in the Study

Condition	Level 1	2	3
A Helix Angle	High--(37-1/2°)	Normal--(27-1/2°)	
B Drill Diameter (Inch)*	0.250	0.125	
C Surface Velocity (SFPM)**	100	50	
D Drill-Point Type	Radial Lip	Four-Facet	
E Material	1018 Steel	303Se SST	6061-T6 Al

*0.001 inch = 25.4 μm.
**100 sfpm = 510 mm/s.

Burr Height

Although the entrance-burr height decreased slightly with increased cutting velocity (Figure 2), the exit-burr height was unaffected by the cutting velocity. (Unless otherwise indicated, the results shown are averages for the three different materials used in the study.) Entrance burrs were only 0.0014 inch (35.6 μm) high, while typical exit burrs were 0.0056 inch (142.2 μm) high (Table 3). Exit burrs from 303Se stainless steel were slightly higher than those from 1018 steel (Figure 3). High helix angles reduced noticeably the height of both entrance and exit burrs (Figure 4). The exit-burr height was directly proportional to the drill diameter (Figure 5). Results from the radial-lip drill were similar to those from the conventional drill (Table 2).

Burr Thickness

The 37-1/2-degree helix angle resulted in noticeably thinner burrs than were produced by the standard 27-1/2-degree helix angle (Figure 6). Increasing the surface velocity increased the burr thickness (Figure 7). The exit burrs tended to be 30 percent thicker than the entrance burrs (Figures 6, 7, and Table 3). The radial-lip drill point did not produce thinner burrs than did the four-facet point (Figure 8). In this study, the thinnest burrs occurred from 303Se stainless steel (Figure 9), although the difference was not great.

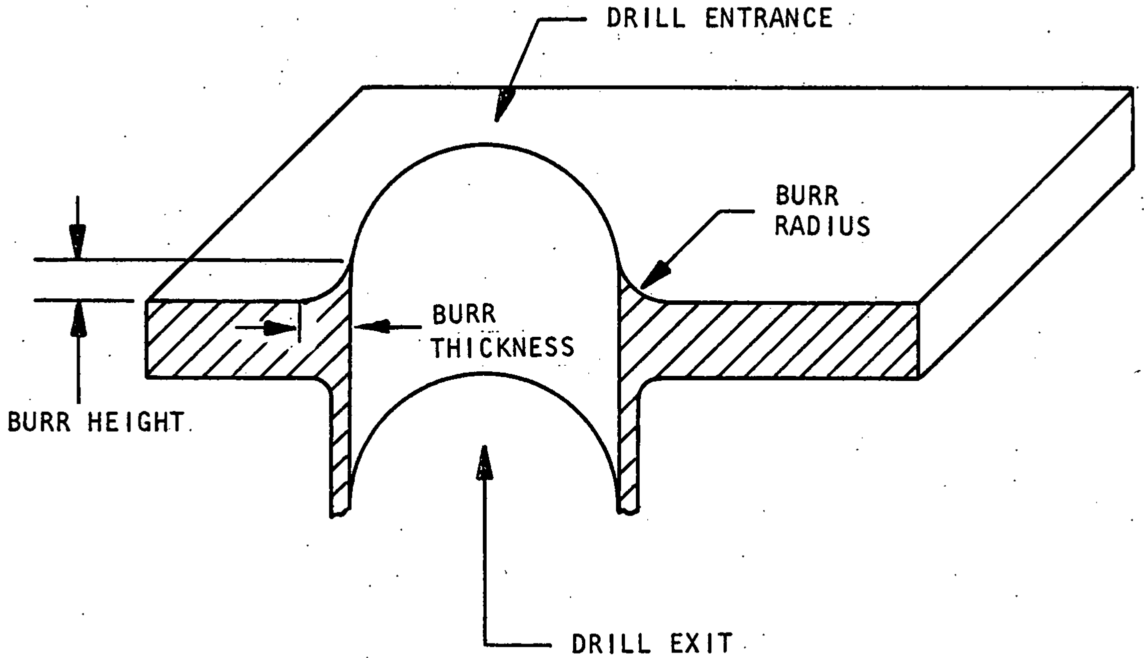

Figure 1. Definition of Burr Properties

Burr Radius

The burr radius decreased with an increase in the helix angle (Figure 10). The exit-burr radius increased slightly with an increase in the drill diameter (Figure 11). Increasing the cutting velocity also increased the burr radius (Figure 12). The radial-lip drill produced a larger entrance-burr radius than did the four-facet point (Figure 13). The smaller radii occurred in burrs from 303Se stainless steel, and the larger in burrs from 6061-T6 aluminum (Figure 14).

Effects of Specific Variable Combinations

As shown in Figure 15, the conventional helix angle on a 0.25-inch (6.35 mm) drill resulted in much higher burrs than did the other combinations. The high helix angle combined with the four-facet drill point produced thinner burrs than the other combinations (Figure 16). The exit-burr height and radius were the least when the small-diameter four-facet drill points were used (Figure 17). The burr height from the aluminum specimen was not as velocity-dependent as it was from the other materials (Figure 18).

Table 2. Analysis-Of-Variance Summary of Significant Effects

	Significant Effects					
	Entrance Burr			Exit Burr		
Conditions*	Thick-ness	Length	Radius	Thick-ness	Length	Radius
A	***	***		**	****	****
B					***	***
C	****	***	**	**		
D	**		**			
E	***	***	**			
AB					***	***
AC	****	***	***			
AD	**			**		
AE	**	**				
BC						
BD					**	**
BE						
CD						
CE	**	***		**	**	**
DE	**	***	**			
ABC	***		**			
ABD				**	**	**
ABE	**					

Table 2 Continued. Analysis-Of-Variance Summary of Significant Effects

	Significant Effects					
	Entrance Burr			Exit Burr		
Conditions*	Thick-ness	Length	Radius	Thick-ness	Length	Radius
ACD				**		
ACE	**		***		***	***
ADE						
BCD	***		***	**		
BCE		**				
BDE					**	**
CDE		***				

*Conditions indicated by letters are identified in Table 1.
**Significant effect at 95-percent confidence level.
***Significant effect at 99-percent confidence level.
****Significant effect at a confidence level exceeding 99 percent.

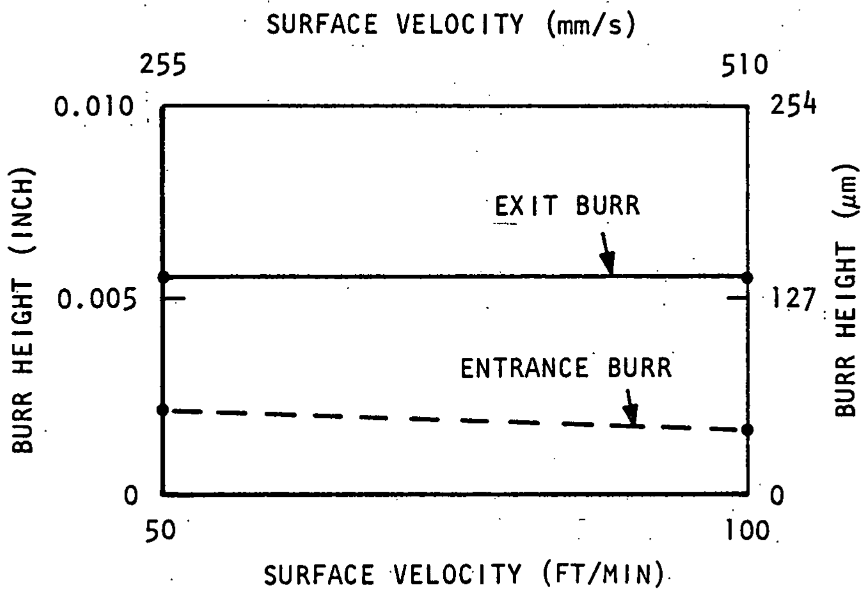

Figure 2. Effect of Surface Velocity on Burr Height

Effects of Feedrate, Spindle Speed, and Workpiece Material With Subland Drills

In the second study, subland drills (List Number 1401, Mohawk Tools Inc., Montpelier, Ohio) were used to determine whether the transitional area from the small to the large diameter of the drill would provide the hole with a burr-free entrance-side. Ideally, the transitional area should remove any burr which is formed when the small diameter of the drill enters the workpiece. In essence, this type of tool can be an integral drilling-deburring tool; however, it does not affect the burr on the exit-side of the hole.

When in operation, the subland drill is lowered until the transitional area just touches the entrance-surface of the workpiece. In practice, a very shallow counterbore must be produced to assure the removal of the entrance burr (Figures 19 and 20). Although a second burr is produced at the diameter of the counterbore, it is very small and easy to remove.

As shown in Table 4, the subland drill minimized the entrance-burr size for all materials, although the burr produced at the counterbore was approximately the same size as the original entrance burr. The counterbore burr probably could be virtually eliminated by utilizing a transition angle that is slightly greater than 90 degrees; this tool then would not produce a distinct edge if it were stopped before the large cutting diameter entered the

Table 3. Average Measurements of Burr Properties

Burr Property*	Entrance Burr	Exit Burr
Height (Inch)**	0.0014	0.0056
Thickness (Inch)	0.0023	0.0030
Radius (Inch)	0.0019	0.0021

*Values were obtained from the average of four materials.
**0.0001 inch = 2.54 μm.

workpiece (Figure 21). The point geometry of the subland drill produced significantly larger exit burrs than did the four-facet point. This also could be prevented by grinding a four-facet point on the subland drill.

In addition to determining the effect of the subland-drill design upon burrs, the effects of feedrate, spindle speed, and workpiece material also were evaluated. The machining variables studied are shown in Table 5; the data obtained are shown in Table A-2 of the Appendix. The analysis-of-variance is presented in Table 6. As indicated, no factor affected all properties. The thickness of both the entrance and exit burrs was affected by each of the three variables studied. The most noticeable trends are shown in Figures 22 through 24. As indicated in Figures 22 and 23, the burr thickness increased as the feedrate and spindle speed were increased. The entrance-burr length also increased slightly as the spindle speed was increased. Typically, burrs from 303Se stainless steel were thicker than those from the other materials (Figure 24).

Effect of Drill Wear

The third test under this project investigated the effect of drill wear on the properties of the burrs. The materials and the 0.125-inch-diameter (3.175 mm) drills used in the previous tests were used in this test. Eight-facet drills also were used, in addition to the other 0.125-inch-diameter drills. (Eight-facet drills are four-facet drills with another chamfer added at the drill corners.[1])

Text continued on page 23.

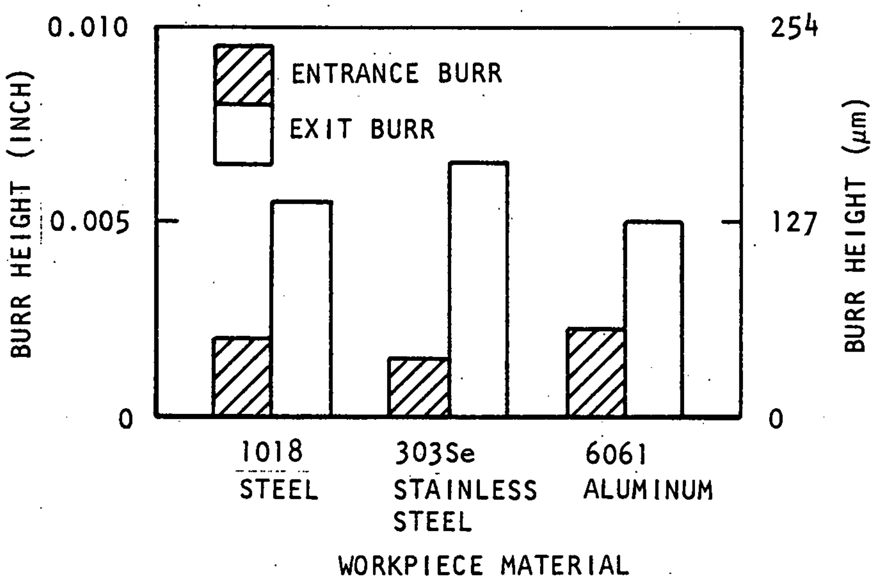

Figure 3. Effect of Workpiece Material on Burr Height

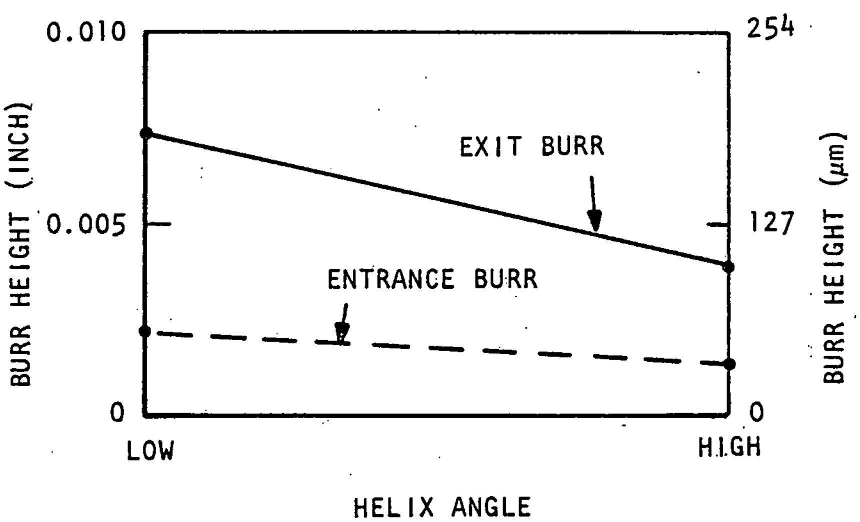

Figure 4. Effect of Helix Angle on Burr Height

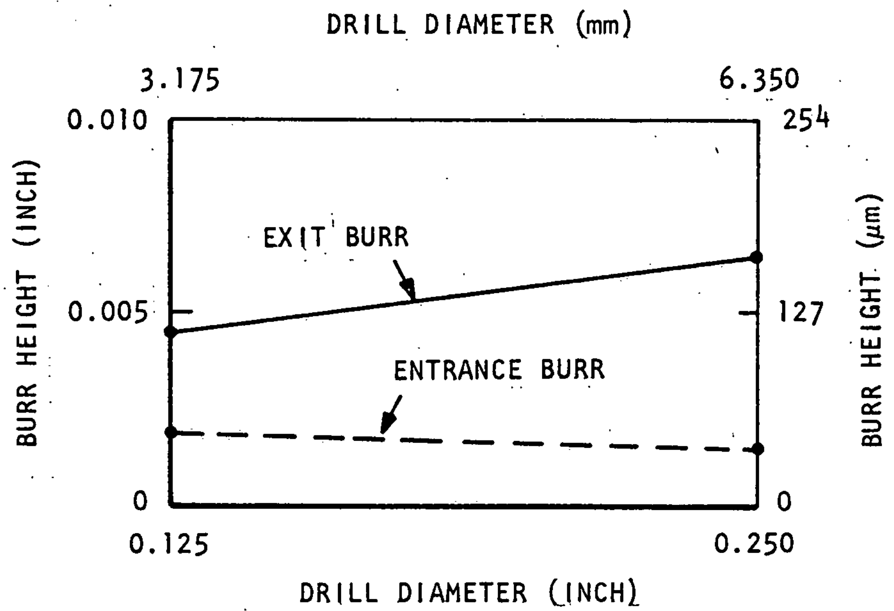

Figure 5. Effect of Drill Diameter on Burr Height

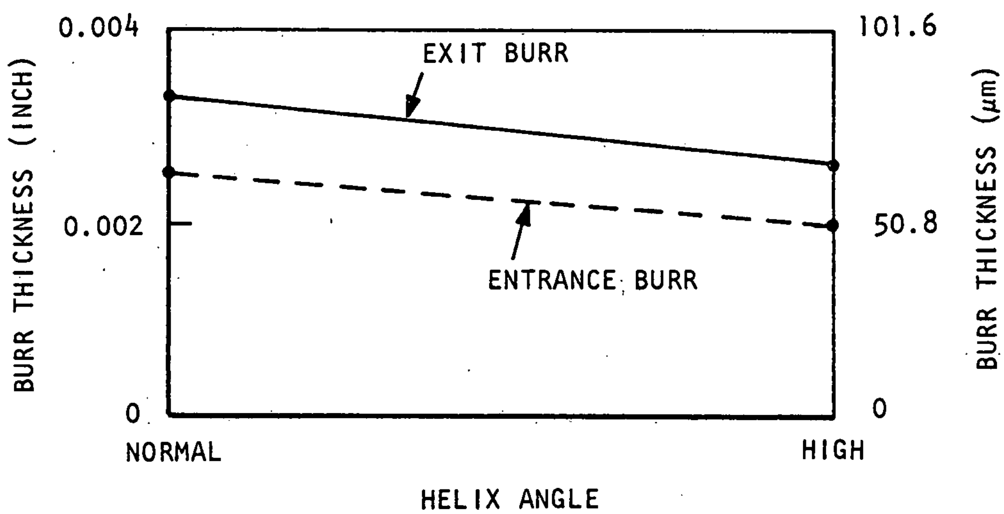

Figure 6. Effect of Helix Angle on Burr Thickness

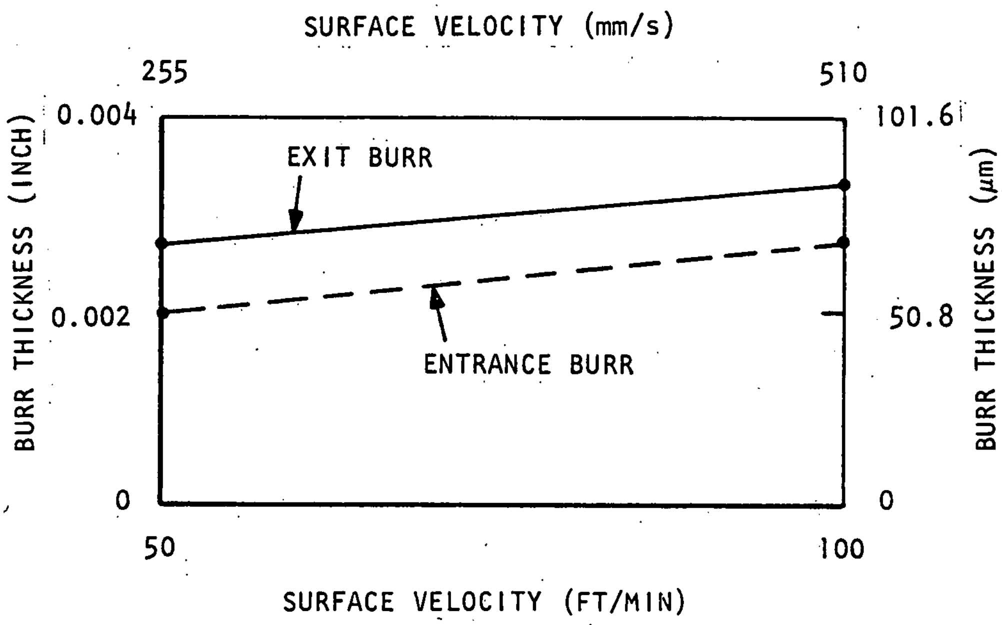

Figure 7. Effect of Surface Velocity on Burr Thickness

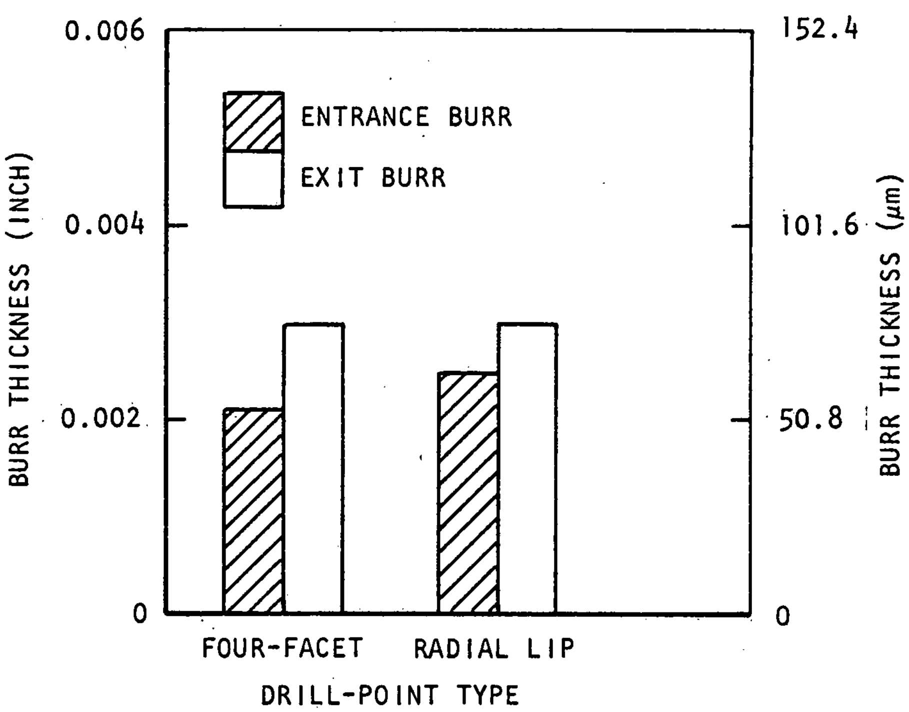

Figure 8. Effect of Drill-Point Geometry on Burr Thickness

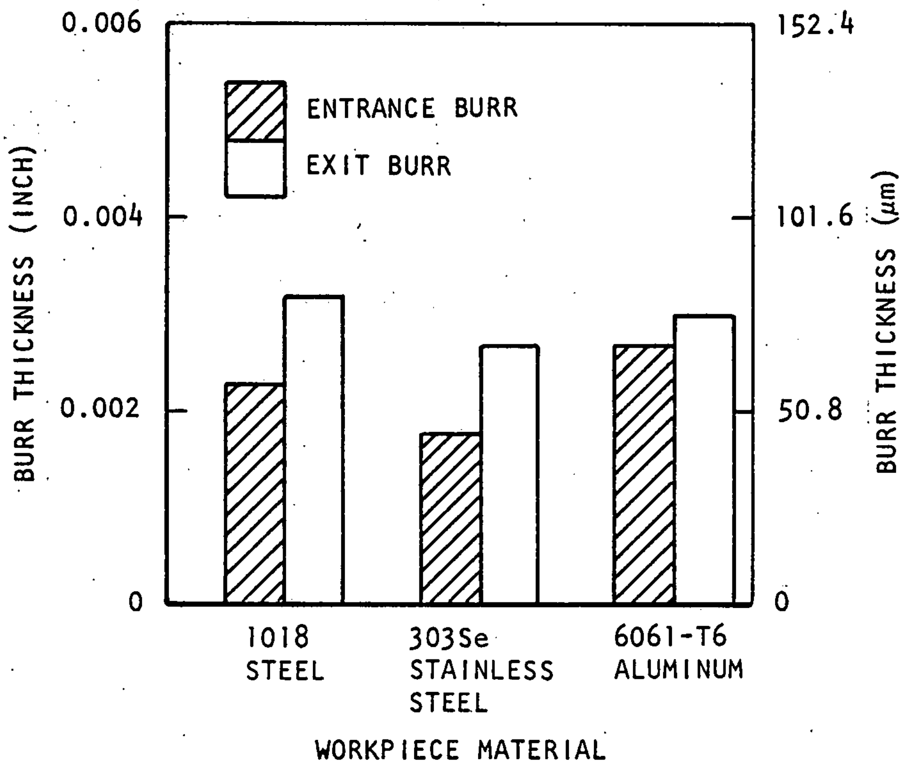

Figure 9. Effect of Workpiece Material on Burr Thickness

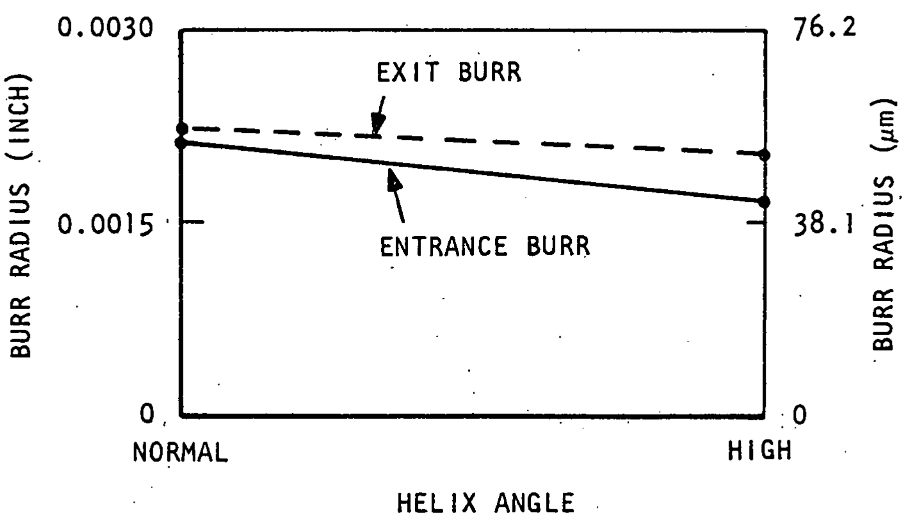

Figure 10. Effect of Helix Angle on Burr Radius

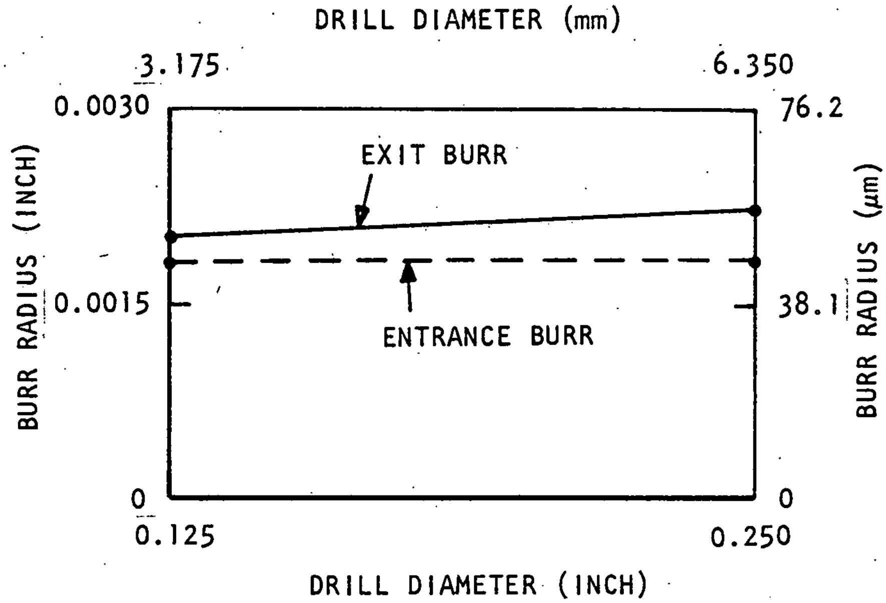

Figure 11. Effect of Drill Diameter on Burr Radius

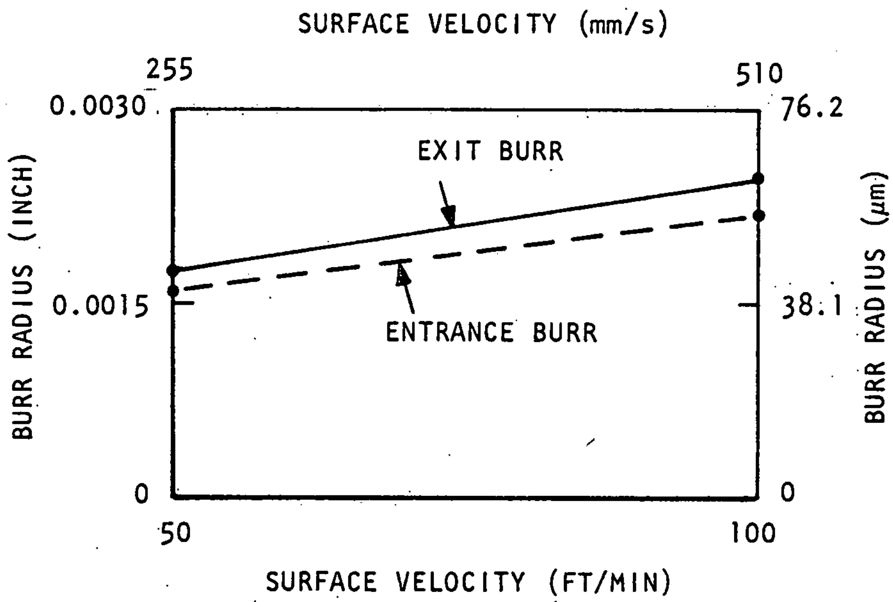

Figure 12. Effect of Surface Velocity on Burr Radius

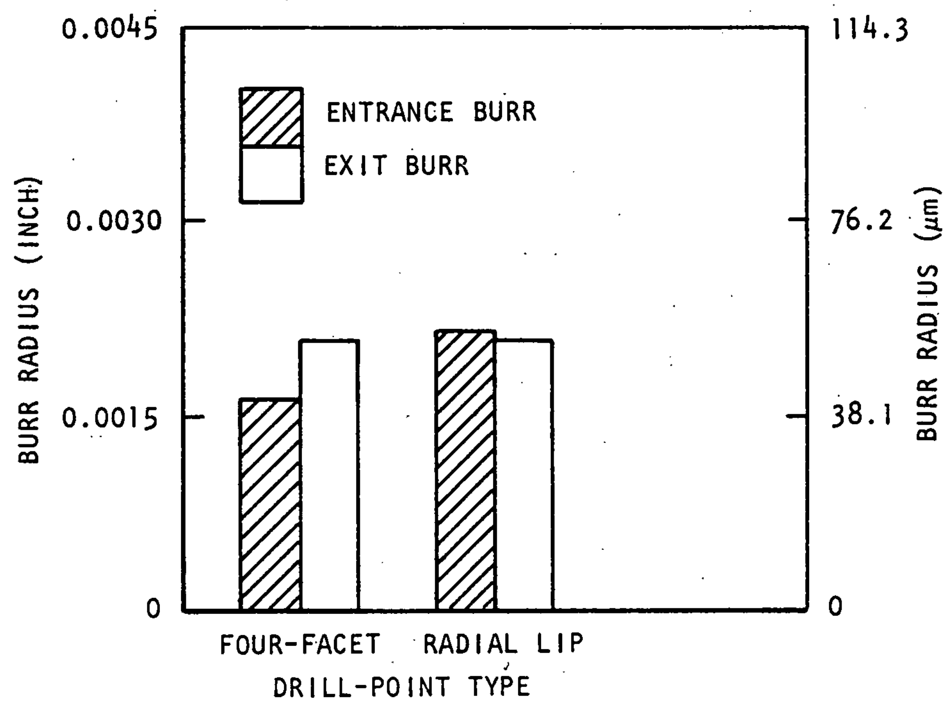

Figure 13. Effect of Drill-Point Geometry on Burr Radius

To duplicate typical production practice, the speeds were varied with each material. Table 7 indicates the drilling conditions that were used. The holes were drilled with an N/C machining center, using a water-soluble flood coolant. All were through holes in a 1/4-inch-thick (6.35 mm) bar which had been ground to eliminate mill scale and surface residues. No backup material was used to minimize the burr size.

Both the entrance and exit burrs were measured from metallurgical mounts. Four readings were taken of each burr; the data obtained are shown in Table A-3 of the Appendix. Prior to measuring the length, the loose burr fragments were removed by wiping a hand over them. Thus the burr lengths shown represent only the burrs which would be significant in deburring efforts.

Only one of the drill-workpiece combinations studied exhibited any noticeable wear tendency: the entrance-burr height increased with the number of holes drilled when the radial-lip drill was used, but the entrance-burr thickness decreased as the number of holes increased for the same drilling combination (Figure 25--Data are shown in Table A-3 of the Appendix; data for the first 46 holes have been previously published[1]).

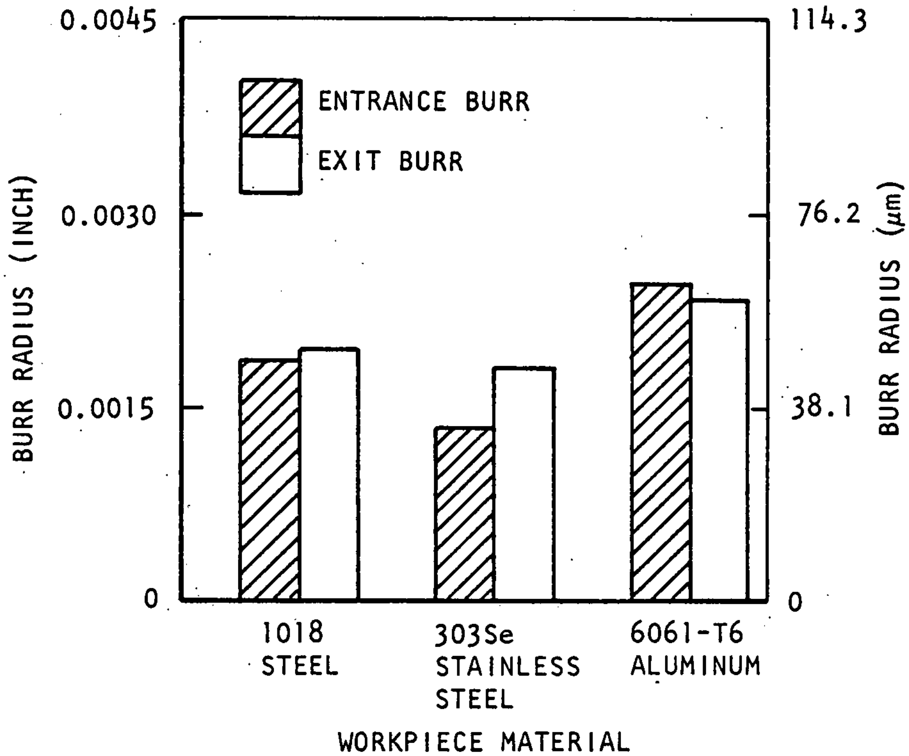

Figure 14. Effect of Workpiece Material on Burr Radius

Except for the burrs produced by the four-facet drill from 303Se stainless steel, no changes in the exit burrs were evident (Figure 26). The four-facet drill appeared to wear rapidly after 125 holes; however, the data were insufficient to determine whether this was a real trend.

Because significant trends were not apparent, except for the combinations just described, the means and standard deviations (σ) were calculated to provide comparative data. For these calculations, the data used were from Holes 51 through 184. As shown in Figures 27 through 30, the radial-lip drill produced significantly smaller burrs than did the four-facet drill in 303Se stainless steel. Little or no difference was observed in burrs from the other two materials. The burrs produced by this drill in 303Se stainless steel were more uniform (had a small standard deviation) than those produced by the four-facet drill.

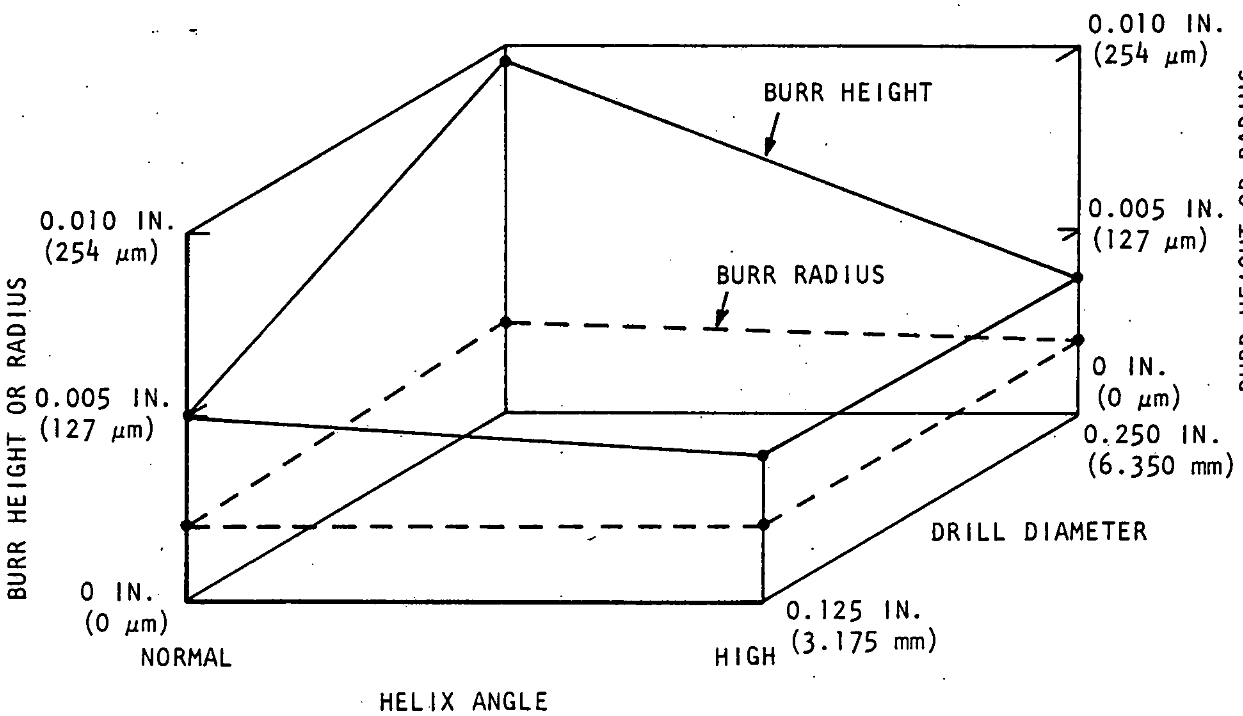

Figure 15. Effect of Helix Angle and Drill Diameter on Exit-Burr Height and Radius

Burr Minimization in Cross-Hole Drilling

In the fourth study, an attempt was made to minimize the size of burrs which form when the drill breaks through into another drilled hole. In this test, the first hole drilled in the workpiece was plugged with a removable rod (Figure 31). Both the workpiece and the rod were of 303Se stainless steel. The rod served as sacrificial backup material to minimize the formation of a large burr.

The use of the consumable rod resulted in shorter burrs being produced at the intersection of the holes; obviously, the long, ragged portion of the burrs could not form. Because the intersection of the holes is a three-dimensional surface, accurate measurements of the differences in burr thickness were impossible to obtain; however, under a magnification of 80X, the burrs produced with the backup-rod in place appeared to be thinner than those produced without the rod by 50 percent.

When the cross-hole was the same diameter as the initial hole, improvement in the burr size occurred without use of the backup-rod because the drill diameter just touched the sides of the first drilled hole at two places (Figure 32). At these points there was no open area for a burr to form; a burr did form, however, on the remaining portions of the hole intersection.

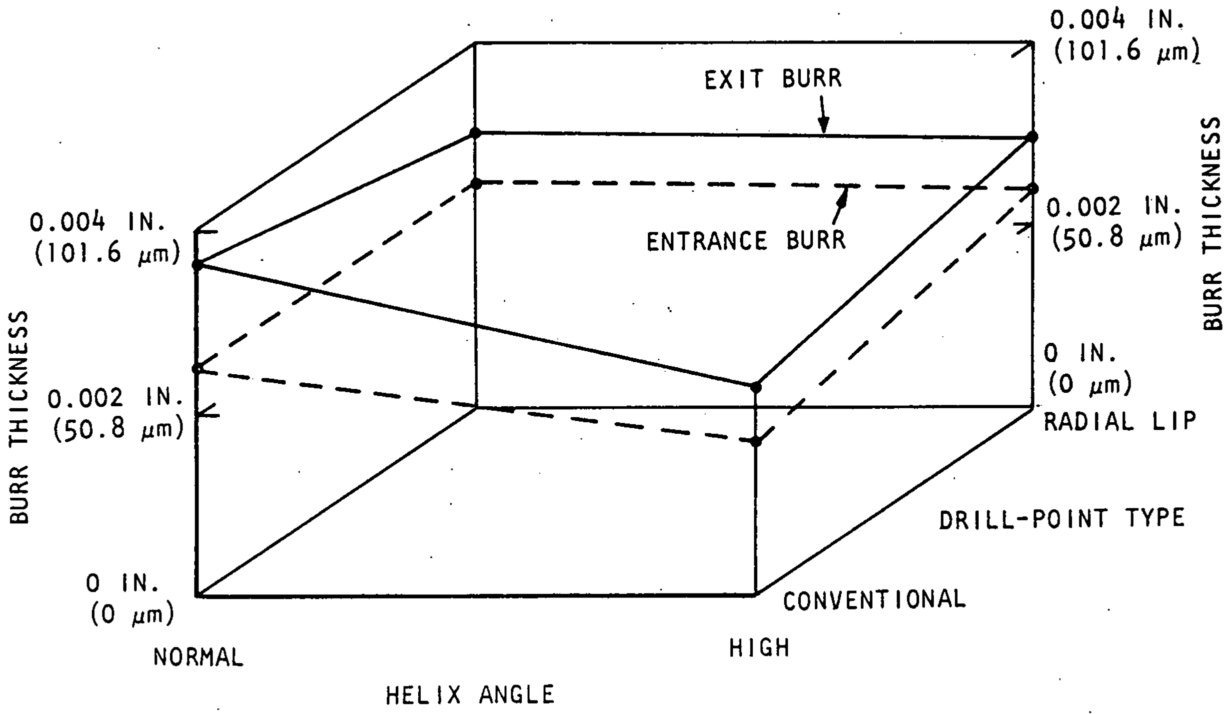

Figure 16. Effect of Helix Angle and Drill-Point Type on Burr Thickness

The following observations were recorded from this study. When the cross-hole is close to the same size as the first hole drilled, the backup-rod, if used, will be cut in half. Because the slight burr which forms is sufficient to hold both halves of the rod in the workpiece, the rod cannot be used when the first hole is blind since there is no way of removing the bottom portion of the rod from the part. If the rod used is longer than the depth of the hole, the top portion can be removed. In the case of through holes, of course, both pieces of the rod can be knocked out of the part.

In applications where the bottom of the hole-intersection need not be clear, the captured portion of the rod can remain in the hole. However, since the remaining portion of the rod might rotate, and since the drilled portion of the rod does not have a flat surface, a projection may result to block any flow or motion through the cross-hole.

Despite a noticeable change in the burr properties of parts having cross-hole intersections, only a slight saving occurs in the deburring cost when the parts are deburred manually. Deburring of the hole intersections so that 0.005-inch-maximum (127 µm) edge breaks were maintained required 12 minutes per part when the backup-rod was used, and 10 minutes per part when it was not used.

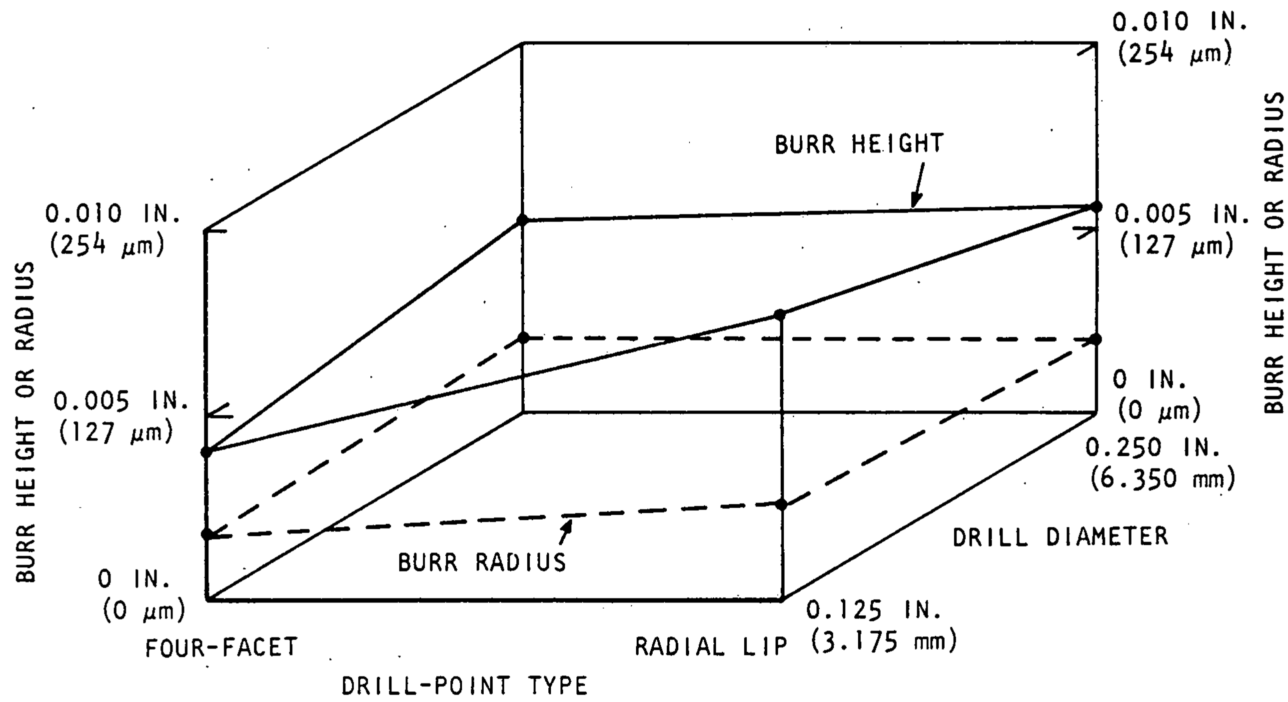

Figure 17. Effect of Drill Diameter and Drill-Point Type on Exit-Burr Height and Radius

The use of the backup-rod would have a more significant effect if electrochemical or extrude hone deburring were used, since both of these processes are sensitive to long, flexible burrs. In the first process, the long burrs increase the chance of electrical short circuits and consequent part damage. In the second process, the long burrs fold over flush with the hole walls and thus slow the deburring operation.

The Formation of Burrs at Drill-Breakthrough

The formation of drill-exit burrs was briefly studied by cross-sectioning workpiece samples as the drill began to exit from the bottom of the workpiece. The workpiece materials studied included 303Se and 17-4PH stainless steel, 1018 steel, and 6061-T6 aluminum in the disc form used in the first test previously described. A high-speed-steel drill, 0.125 inch (3.175 mm) in diameter (List Number 967, Cleveland Twist Drill Co., Cleveland, Ohio), was used at a speed of 1200 rpm and a feedrate of 03.6 ipm (1.53 mm/s) in all materials except the 17-4PH stainless steel. For the latter material, a speed of 750 rpm and a feed of 1.2 ipm (0.51 mm/s) were used.

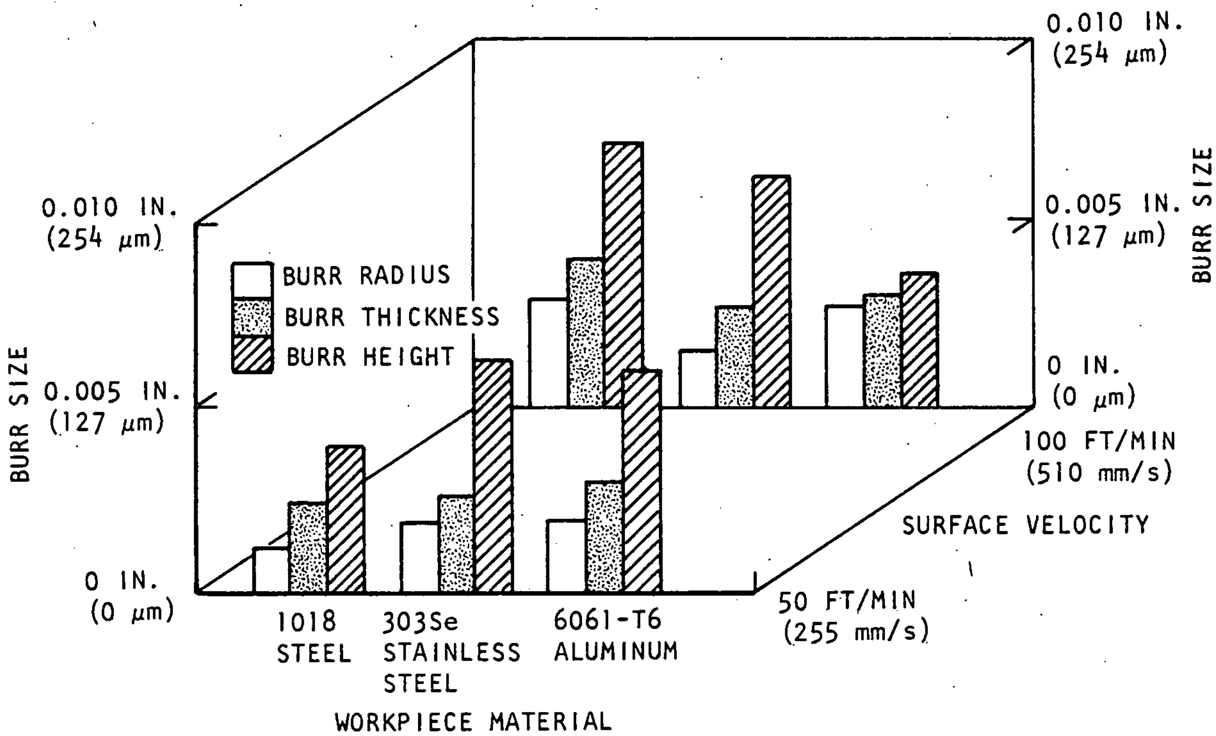

Figure 18. Effect of Workpiece Material and Surface Velocity on Exit-Burr Height, Radius, and Thickness

As previously described,[1] the material below the drill point stretches and is pushed outward as the drill exits from the workpiece (Figure 33). The closer the drill point approaches the backside of the material, the greater the material deflects (Figures 34 through 36). The thickness of the material below the drill point decreases in a nonlinear fashion as the drill advances. Figures 37 and 38 show material deformation below the drill point, and the discontinuity of the metal shown in Figure 39 evidences a rapid tearing of the 17-4PH stainless steel. The data obtained during this portion of the study are shown in Table A-4 of the Appendix.

The Appearance of Drill-Exit Burrs

Drill-exit burrs can assume many shapes. The following descriptions and referenced figures illustrate the basic forms:

- Very short and uniform (Figure 40);
- Very long and uniform (Figures 41 and 42);

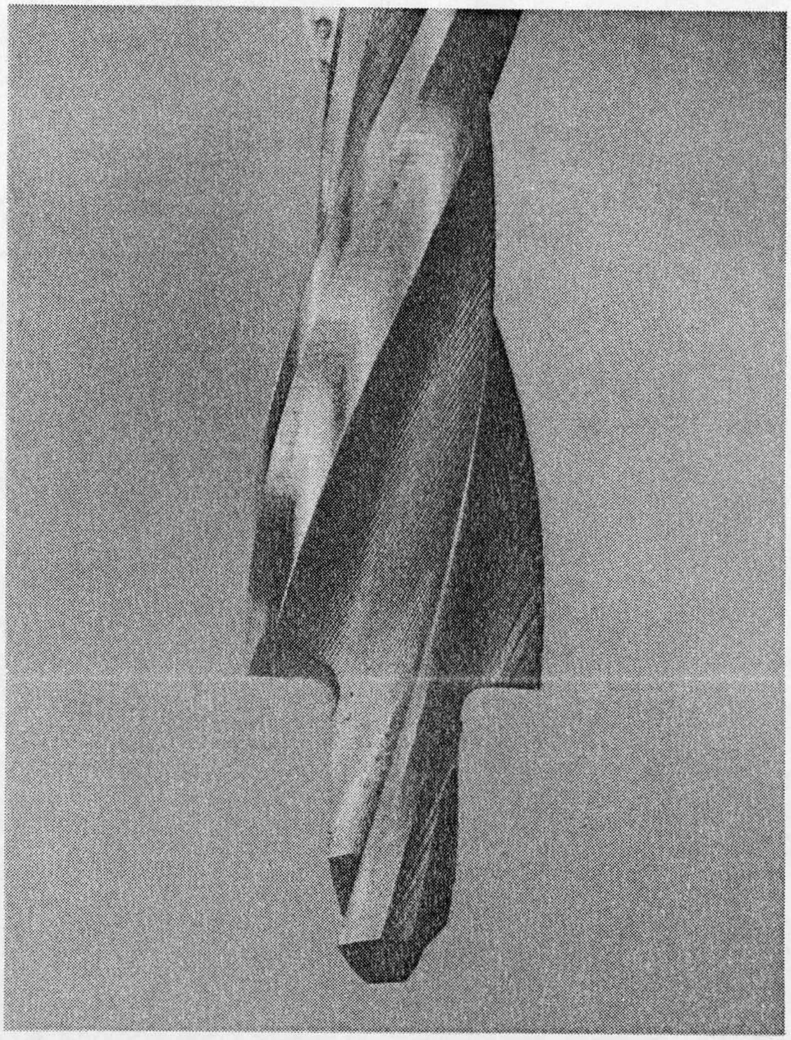

Figure 19. Subland Drill Point

- Extremely ragged (Figures 43 and 44); and
- Short, with a cap of metal (Figure 45).

Combinations between these extremes also are produced. As previously indicated, a great amount of variability occurs from one hole to the next. Figure 46, for example, illustrates two burrs that were produced, one after the other, using a hand-fed drill press. On the part shown, one burr is twice the length of the other. Figure 47 illustrates an extruded burr formed by drilling and boring a 0.0938-inch (2.38 mm) hole in beryllium-copper. After a twenty-minute cycle in a Harperizer, the thick, uniform burr is still obvious. As illustrated by these photographs, burr-height measurements can be subject to a large amount of variability. The impact of this variability has been described elsewhere.[28]

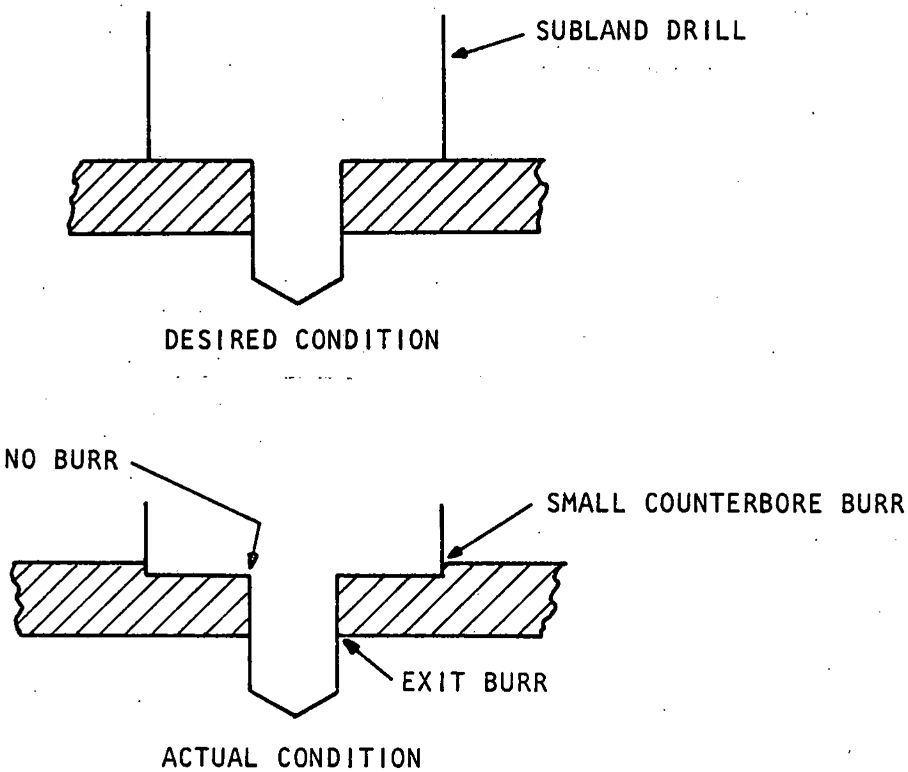

Figure 20. Desired and Actual Burr Conditions When Subland Drill Is Used

Analysis of Recently Published Reports

Since the first report[1] in this series was prepared, four other publications have appeared on the subject of burrs produced by drilling. In addition to these, at least two other individuals have initiated studies on the subject.

In the first of these recent reports,[18] the effect of coolants on burrs produced from stacks of different aerospace materials was evaluated. Burr height and thickness were monitored on both the entrance and exit sides of 0.5-inch-diameter (12.7 mm) holes. All drills used in the study were oil-hole drills. Conclusions were based on the results obtained from 520 measurements of burrs produced by drills and reamers in titanium, aluminum, and 4130 steel.

Table 4. Comparison of Burrs Produced by Subland Drills With Those Produced by Conventional Drills

			Typical Burr Properties*		
Material	Burr Type	Drill Type	Height (Inch)**	Thick-ness (Inch)	Radius (Inch)
1018 Steel	Entrance	4-Facet	0.0013	0.0014	0.0012
		Subland	0.0004	0.0009	0.0014
	Counterbore	Subland	0.0007	0.0020	0.0012
	Exit	4-Facet	0.0045	0.0020	0.0012
		Subland	0.0073	0.0033	0.0042
303Se SST	Entrance	4-Facet	0.0012	0.0021	0.0017
		Subland	0.0006	0.0010	0.0013
	Counterbore	Subland	0.0010	0.0018	0.0015
	Exit	4-Facet	0.0024	0.0025	0.0023
		Subland	0.0038	0.0045	0.0044
6061-T6 Al	Entrance	4-Facet	0.0018	0.0027	0.0026
		Subland	0.0008	0.0019	0.0022
	Counterbore	Subland	0.0015	0.0039	0.0035
	Exit	4-Facet	0.0038	0.0032	0.0022
		Subland	0.0144	0.0036	0.0020

*Feedrate = 0.001 ipr (25.4 μm/rev); surface velocity of the 0.140-inch-diameter (3.556 mm) subland drill was 27.5 ft/min (140 mm/s); surface velocity of the conventional drills was 50 ft/min (255 mm/s).
**0.001 inch = 25.4 μm.

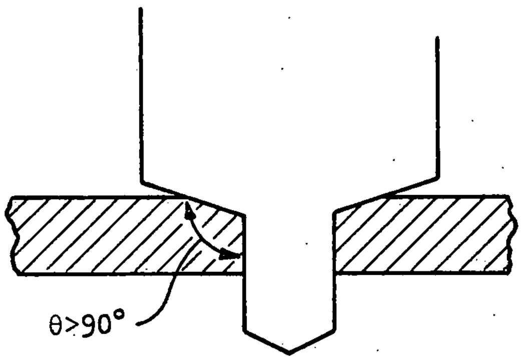

Figure 21. Subland-Drill Transition Angle to Minimize Counterbore Burr

In the study, one of ten coolant-application combinations was found to minimize the burr size. With this coolant, both the entrance and exit burrs from titanium tended to be approximately 0.003 inch (76.2 μm) in height and 0.010 inch (0.25 mm) in thickness. Burrs from 4130 steel were less than 0.001 inch (25.4 μm) high and from 0.002 to 0.005 inch (50.8 to 127.0 μm) thick.

The second recent report[19] is a continuation of the tests described in the previous reference. The tests, however, included the influence of speed, feed, and drill geometry, and the results were based on 2600 burr measurements.

In the study, high feedrates and speeds were found to have little effect on burr size. Burrs from 2024-T351 aluminum were much smaller than those from Ti-6Al-4V titanium, PH-13-8 stainless steel, or HP-9 Ni-4 Co steel. Holes drilled without the coolant were only slightly larger than those drilled using the coolant.

Drill-point geometry was found to have little effect on burr properties; tool sharpness was the most significant element in determining burr size. Exit burrs from reaming were higher than those from drilling. For many of the specimens, removing the drilling burrs lowered the fatigue strength of the sample.

In the third report[29] of Phillips' series, the burrs formed between two stacked plates were found to be much more consistent than those formed at either the entrance or the exit of holes in single plates.

Table 5. Drilling Conditions Used in Subland-Drill Experiments

Condition	Level 1	2	3
A Feedrate (IPR)*	0.001	0.003	
B Spindle Speed (RPM)	375	750	
C Material	303Se SST	1018 Steel	6061-T6 Al

*0.001 ipr = 25.4 μm/rev.

Hasegawa, Zaima, and Yuki's work[17] on drilling aluminum indicates that exit-burr thickness increases with the feedrate, decreases substantially with the helix angle, and is relatively unaffected by the lip-clearance angle. Burr thickness is a nonlinear function of the point angle; angles less than 75 degrees and greater than 150 degrees result in the thinnest burrs. The point angle at the corners of the drill rather than the angle at the chisel edge is more significant in determining the burr height. In the tests, burr thickness was not affected by the cutting speed. The use of carbon tetrachloride as a coolant resulted in burrs half the thickness of those produced using water-soluble oil.

Yuki's study[30] of burrs produced by drilling and through-hole boring of aluminum indicates that burr thickness decreases slightly with an increased end-relief angle and decreases dramatically with an increased back-rake angle. The equivalent side-cutting-edge-angle in boring affects exit-burr thickness in the form of a third-order equation; a 20-degree angle produces the thinnest burr. Burr thickness increases with an increased feedrate and depth-of-cut, decreases with the drill-point angle, and, in the case of boring-burrs, it decreases slightly as the cutting speed is increased.

The use of carbon tetrachloride as a coolant results in the thinnest burrs. When a drill is used to enlarge an existing hole, the burr thickness becomes a third-order function of the diameter of the initial hole. In boring, the thickness decreases with a decrease in the radial rake angle.

Table 6. Analysis-Of-Variance Summary of Significant Effects for Subland Drills

Conditions*	Burr Type	Significant Effects Thickness	Length	Radius
A	Entrance	**		**
	Counterbore		**	
	Exit	****		
B	Entrance	**	**	
	Counterbore			
	Exit	**		
C	Entrance	***	***	***
	Counterbore		**	
	Exit	***		
AB	Entrance			
	Counterbore			
	Exit		**	
AC	Entrance			
	Counterbore			
	Exit			
BC	Entrance			
	Counterbore		**	
	Exit			
ABC	Entrance			
	Counterbore			
	Exit			

*Conditions indicated by letters are identified in Table 5.
**Significant effect at 95-percent confidence level.
***Significant effect at 99-percent confidence level.
****Significant effect at a confidence level exceeding 99 percent.

In another study[31] which was published in 1945 but just recently discovered, Okoshi and others noted that 60-degree point angles produced larger burrs than those produced by larger point angles. Burrs produced at a spindle speed of 10,000 rpm were smaller than those produced at a speed of 1120 rpm.

In addition to the test results just described, additional studies have developed a mathematical theory of drilling-burr formation with equations to provide a rationale for predicting burr size.[32,33]

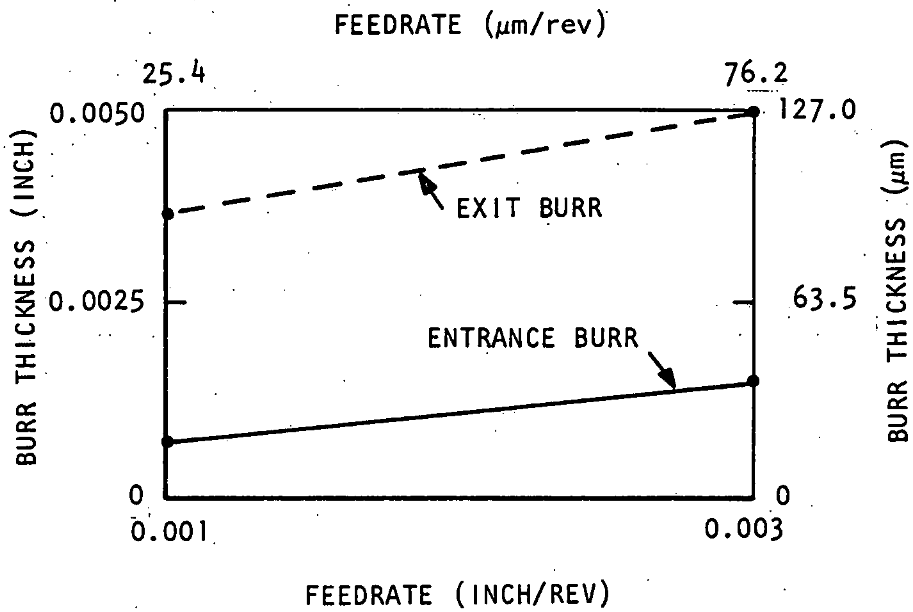

Figure 22. Effect of Subland-Drill Feedrate on Burr Thickness

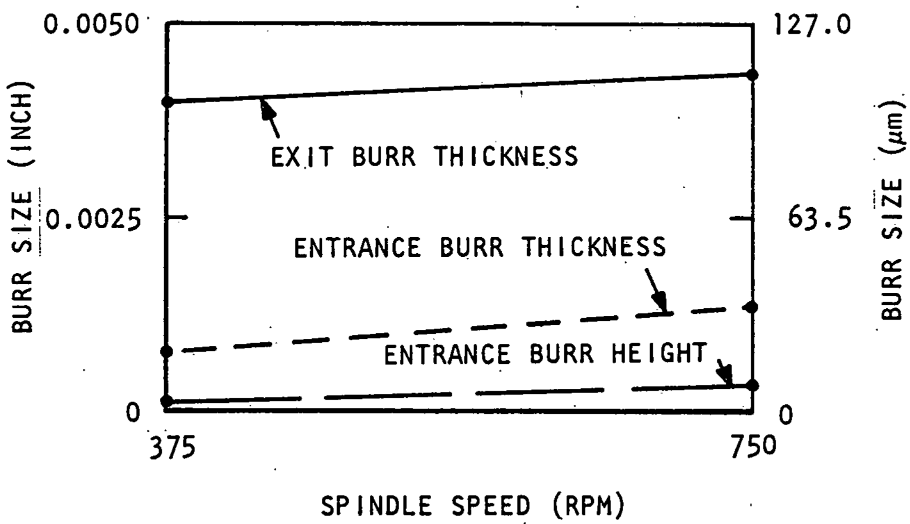

Figure 23. Effect of Subland-Drill Spindle Speed on Burr Size

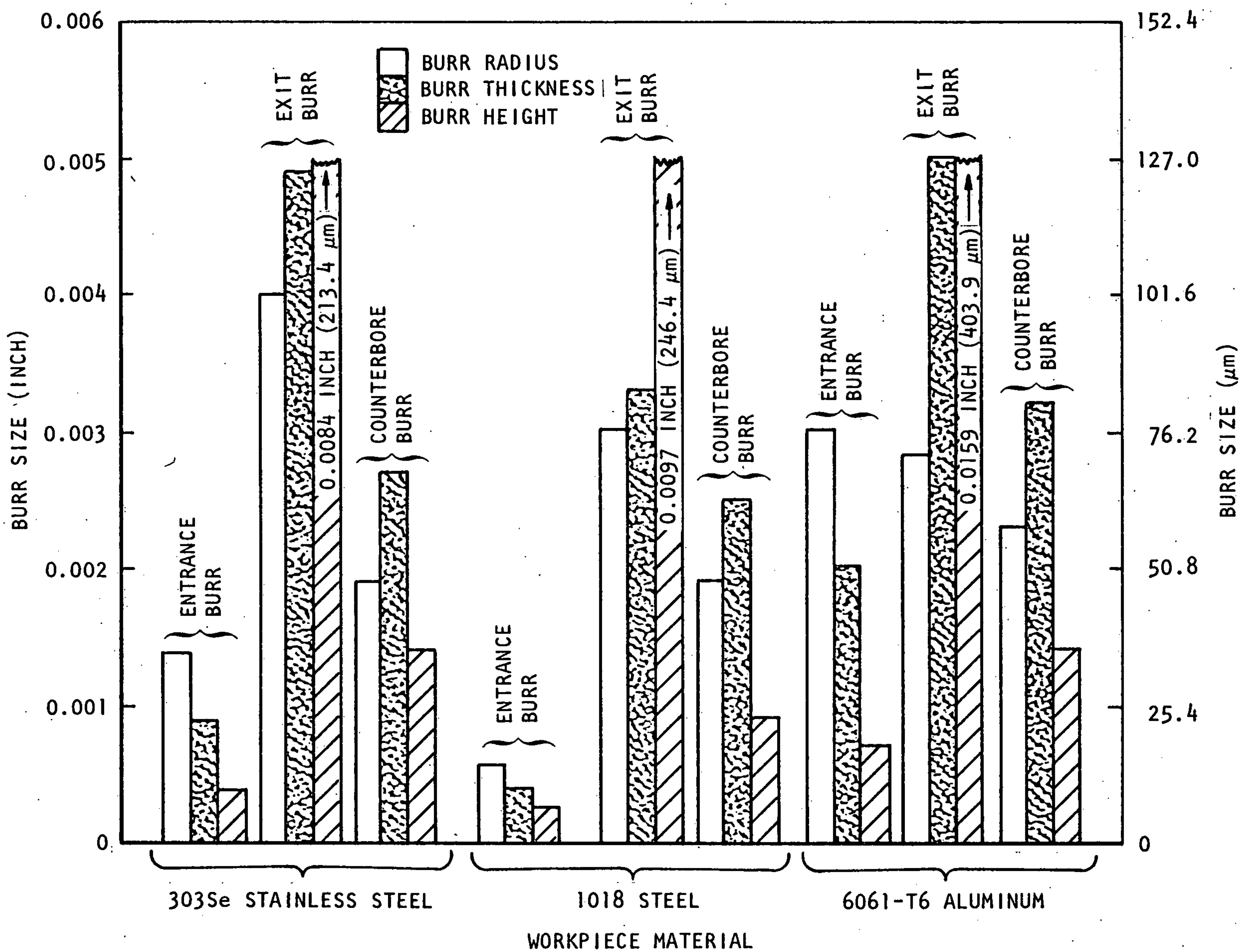

Figure 24. Effect of Workpiece Material on Subland-Drill Burr Size

Table 7. Drilling Conditions Used in Drill-Wear Study

Workpiece Material	Spindle Speed* (RPM)
1018 Steel (R_B90)	2000
303Se Stainless Steel (R_C33)	3000
6061-T6 Aluminum (R_B55)	4000

*All feedrates for this test were maintained at 0.003 ipr (76 μm/rev).

Production Implications

From the studies described in this report, the following conclusions have been drawn concerning the utilization of these results in the production of parts.

Material Influences

- Exit burrs from 303Se stainless steel are typically higher than those from 1018 steel.
- Exit burrs from 6061-T6 aluminum are typically shorter than those from either 1018 steel or 303Se stainless steel.
- Burrs from 17-4PH stainless steel tend to be smaller than those from other steels.

Speed and Feedrate Influences

- Increasing the surface velocity of drills from 50 to 100 sfpm (255 to 510 mm/s) results in a 40-percent increase in the thickness of both entrance and exit burrs.
- The radii of both entrance and exit burrs increase by 40 percent as the surface velocity doubles.
- Increasing the feedrate from 0.001 to 0.003 ipr (25.4 to 76.2 μm/rev) increases the entrance- and exit-burr thickness by 40 percent.

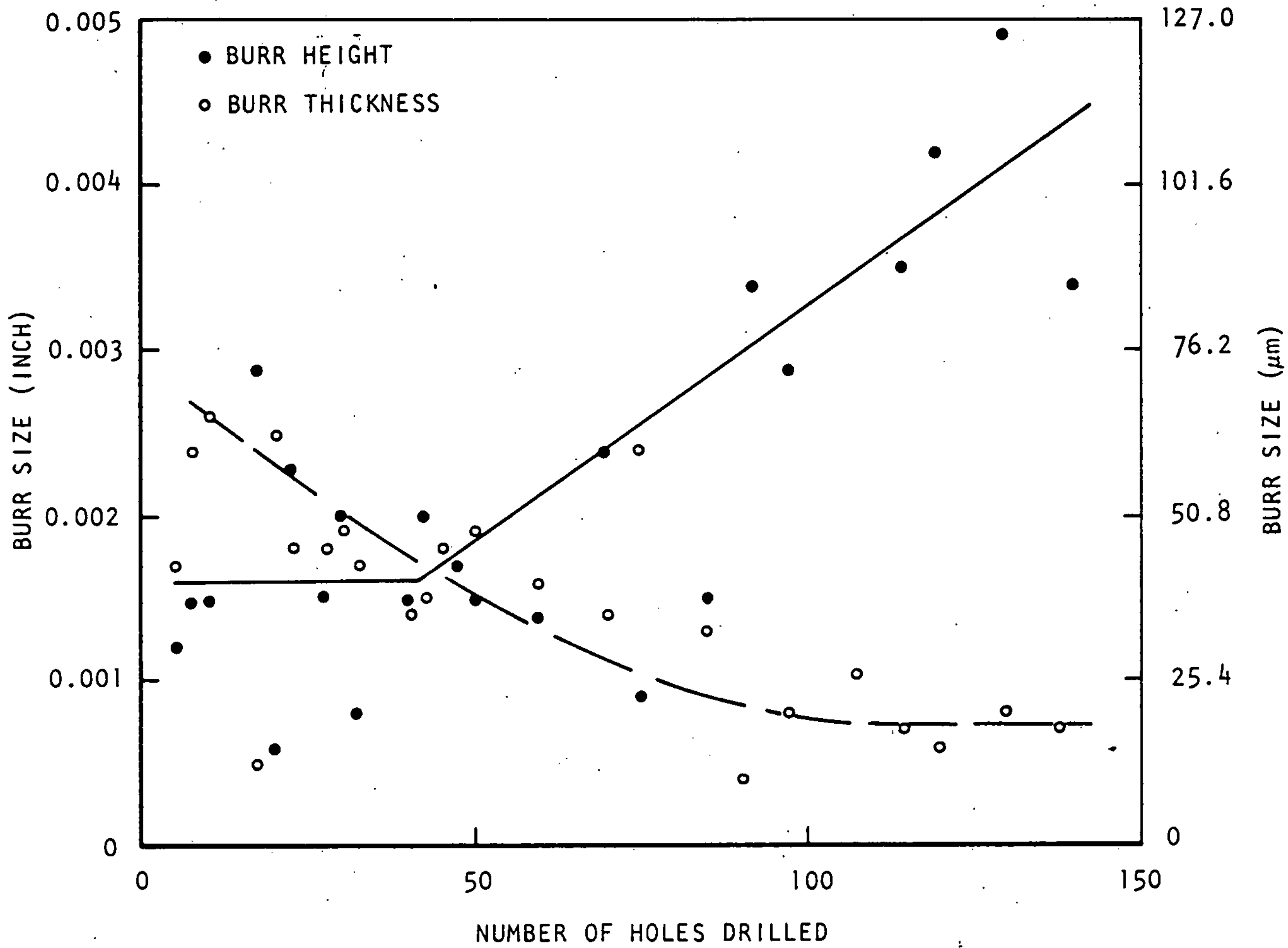

Figure 25. Effect of Number of Holes Drilled on Entrance-Burr Size Using Radial-Lip Drill in 6061-T6 Aluminum (R_B55)

Drill-Point Geometry Influences

- The radial-lip drill point did not result in smaller burrs being produced in the short-run tests (effect-of-geometry tests), but it did result in smaller burrs in the drill-wear tests when 303Se stainless steel was drilled. This implies that when more than 50 holes are drilled in 303Se stainless steel with a single drill, the radial-lip point should be used; no apparent advantage is obtained by the radial-lip point in short-run applications for the materials tested in this study.

- The use of drills with high helix angles (37-1/2 degrees) reduces burr height up to 50 percent, burr thickness up to 20 percent, and burr radius by 6 percent.

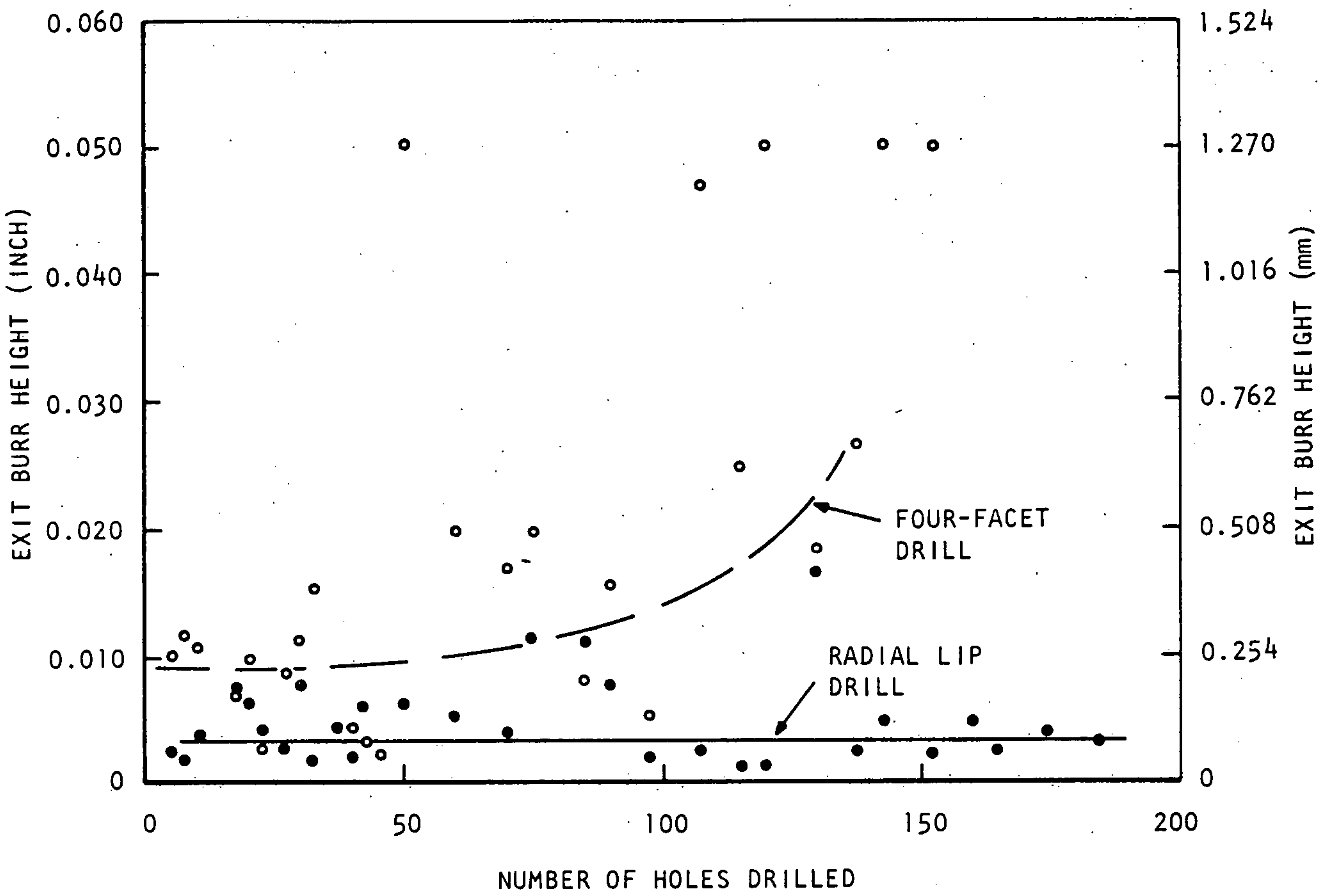

Figure 26. Effect of Number of Holes Drilled on Exit-Burr Height in 303Se Stainless Steel (R_C33)

- Burr height increases with increased drill diameter.

Other Influences

- Subland drills can be used to minimize the size of entrance burrs. Their use, however, can increase tool costs by a factor of six, and it necessitates additional care in drilling to prevent objectionable spot-facing.

- With two exceptions, no noticeable change occurred in burr properties during the drilling of 150 holes. At different speeds and feedrates, however, noticeable changes can be expected.

- The size of burrs produced in drilling intersecting holes can be minimized by the use of a sacrificial backup-rod. Removing the rod can be a problem, however, because the burr which does form tends to capture the rod and may scratch the wall of the hole.

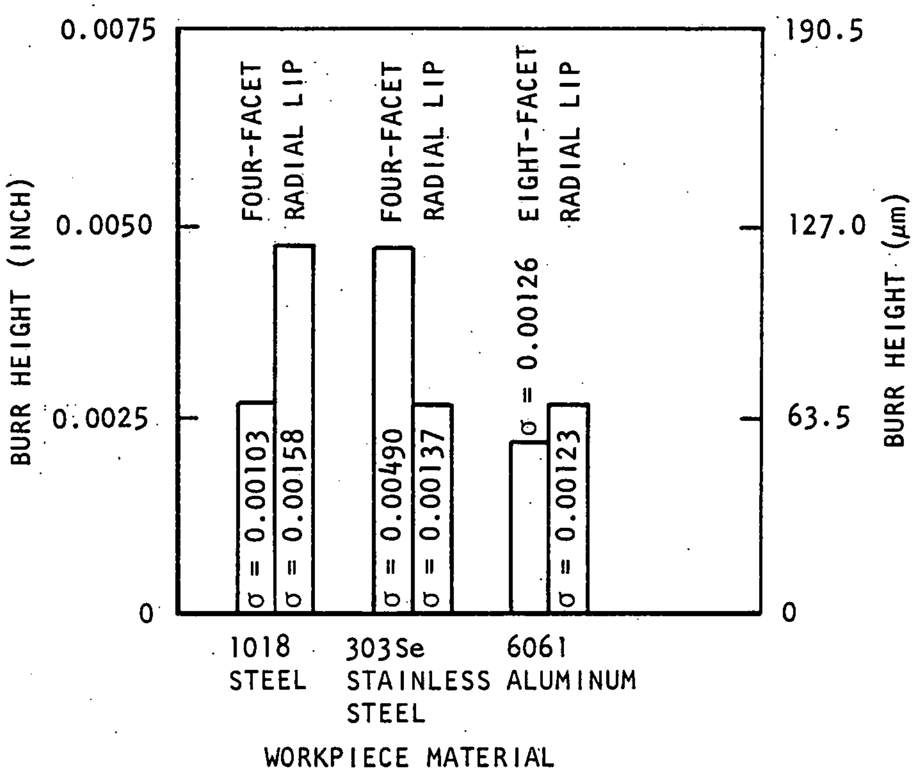

Figure 27. Effect of Drill-Point Geometry on Entrance-Burr Height (From Drill-Wear Study)

Implications from Published Reports

- The use of correct coolants can minimize burr size, but, in general, the difference between coolants is rather slight.
- Burrs from titanium tend to be short (0.003 to 0.010 inch or 76.2 to 254 μm) and very thick (0.010 inch or 254 μm).
- Tool sharpness is the single most significant factor in minimizing burr size.

The results of this study of drilling burrs, of the previous study,[1] and of published observations are summarized in Tables 8 through 11. Specific production recommendations are presented in Tables 12 and 13.

In evaluating the effectiveness of the radial-lip drills, two factors should be noted. First, the principal advantage of the radial-lip drill is its longer tool life. The wear tests described in this report provided some support for the observation that tool wear (as evidenced by burr size) occurs at a slower

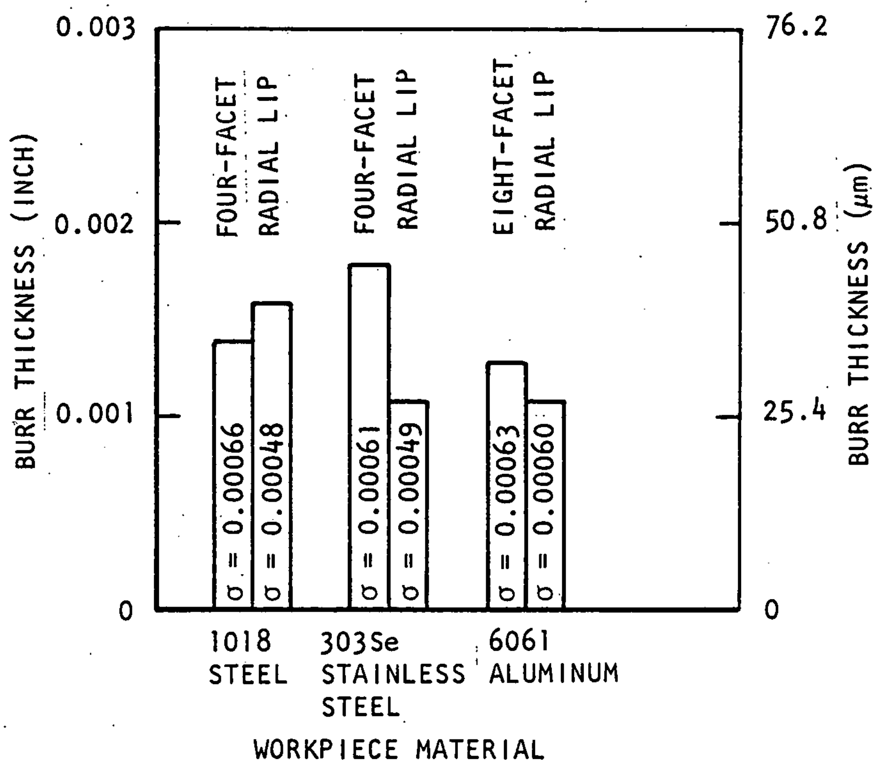

Figure 28. Effect of Drill-Point Geometry on Entrance-Burr Thickness (From Drill-Wear Study)

rate for this drill than for the more conventional drills. The real advantage of the radial-lip drill, however, appears to be for applications which require that more than 200 holes be made per drill.

The second factor that should be noted is that the feedrates used in this study were below those recommended by the manufacturer of radial-lip drills. Faster feedrates possibly would have shown a greater difference in performance between the drills. Table 14 presents the machining conditions recommended by the manufacturer of radial-lip drills and grinders.

The radial-lip drills used in this study were ground for the material in which they were to be used. Although it is not apparent, each material requires a slightly different radial geometry. At the time the studies were being performed, the smallest available size of drill on which a radial lip could be ground was 0.125 inch (3.175 mm).

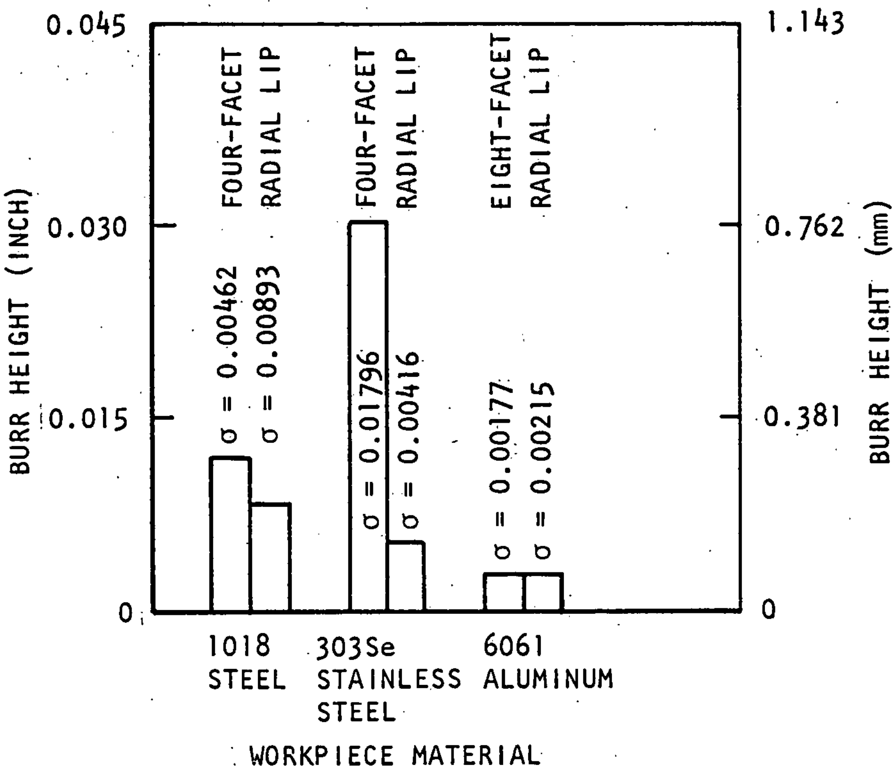

Figure 29. Effect of Drill-Point Geometry on Exit-Burr Height (From Drill-Wear Study)

ACCOMPLISHMENTS

The effects of feedrate, drill-point geometry, cutting velocity, helix angle, workpiece material, and drill wear have been evaluated for 0.125- and 0.250-inch (3.175 and 6.350 mm) drills. Subland drills have been proven capable of minimizing the size of entrance burrs. Drill wear, as indicated by burr size, was found to be negligible after producing 150 holes. The initial formation of the drill-exit burr has been documented by photographs of cross sections of the workpiece as the drill was breaking through the bottom surface. These results will assist engineers in selecting the manufacturing technique which will produce the smallest and most easily removed burrs for the desired application.

FUTURE WORK

Although no additional work on drilling burrs is planned, a study of the burrs produced by turning remains to be reported. Some additional work remains to be done in defining the capabilities of the various deburring processes.

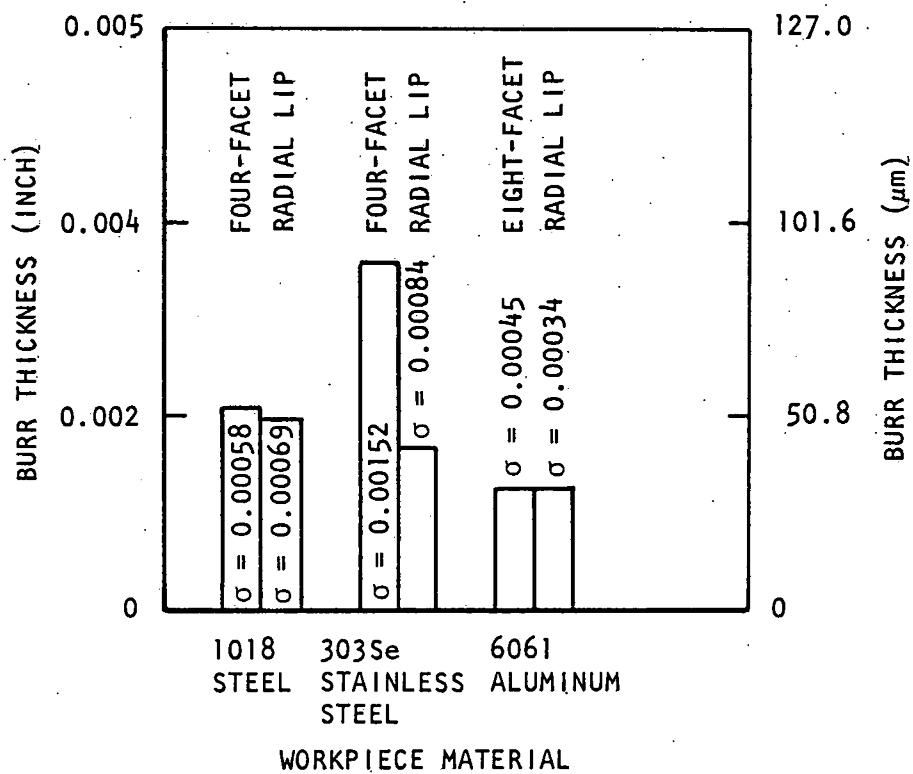

Figure 30. Effect of Drill-Point Geometry on Exit-Burr Thickness (From Drill-Wear Study)

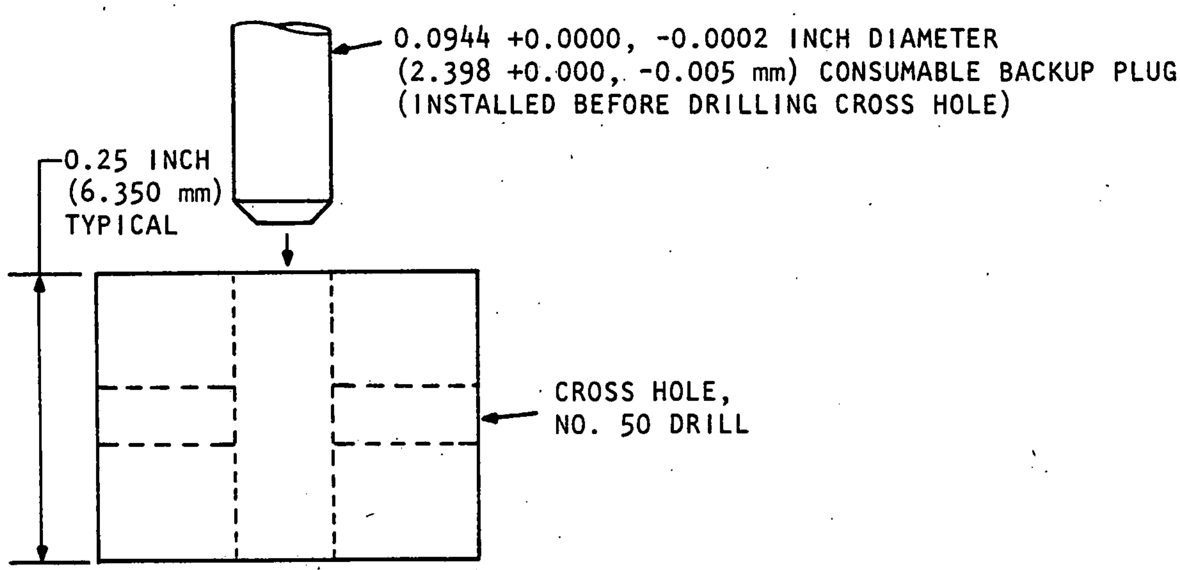

Figure 31. Test Sample With Consumable Backup Plug Used in Study of Cross-Hole-Burr Minimization

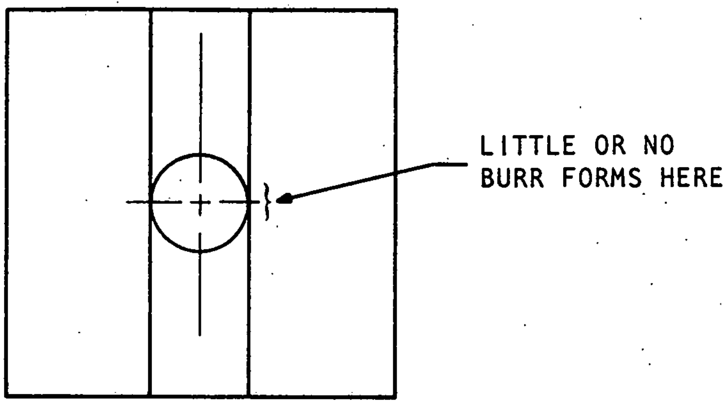

Figure 32. Minimization of Burr at Intersection of Two Holes of Equal Size

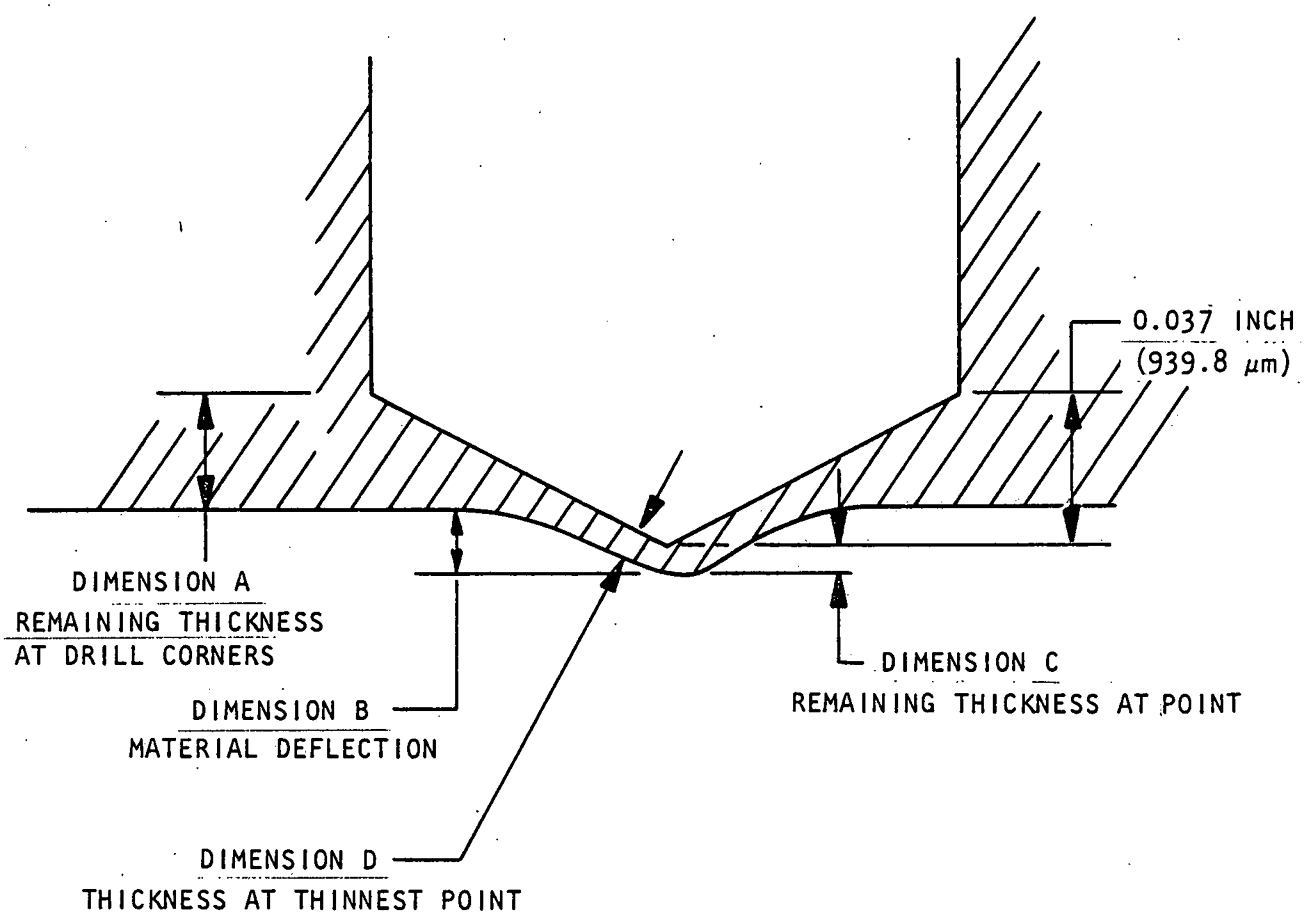

Figure 33. Material Deflection Below Drill Point

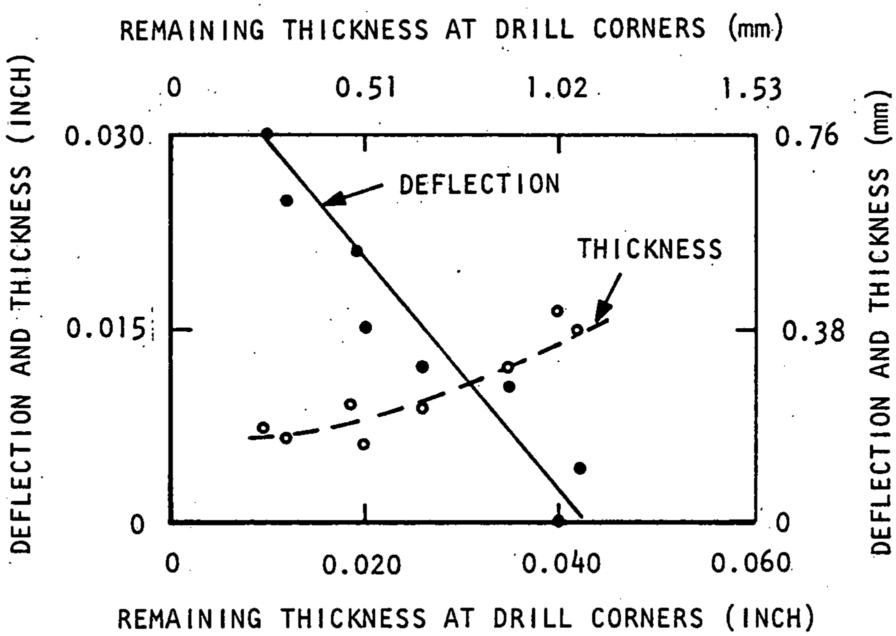

Figure 34. Deflection and Thickness of 303Se Stainless Steel Below Drill Point as Drill Exits

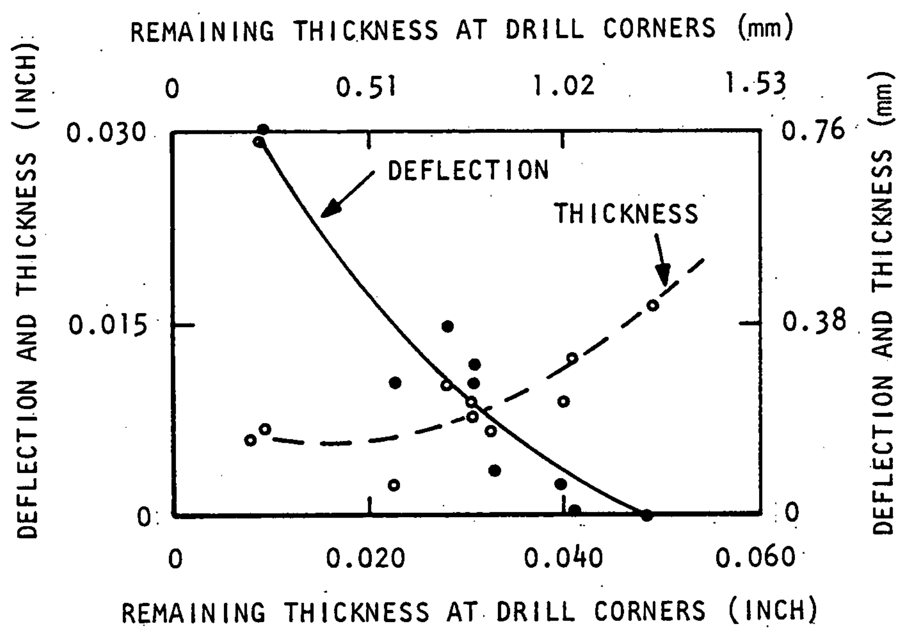

Figure 35. Deflection and Thickness of 1018 Steel Below Drill Point as Drill Exits

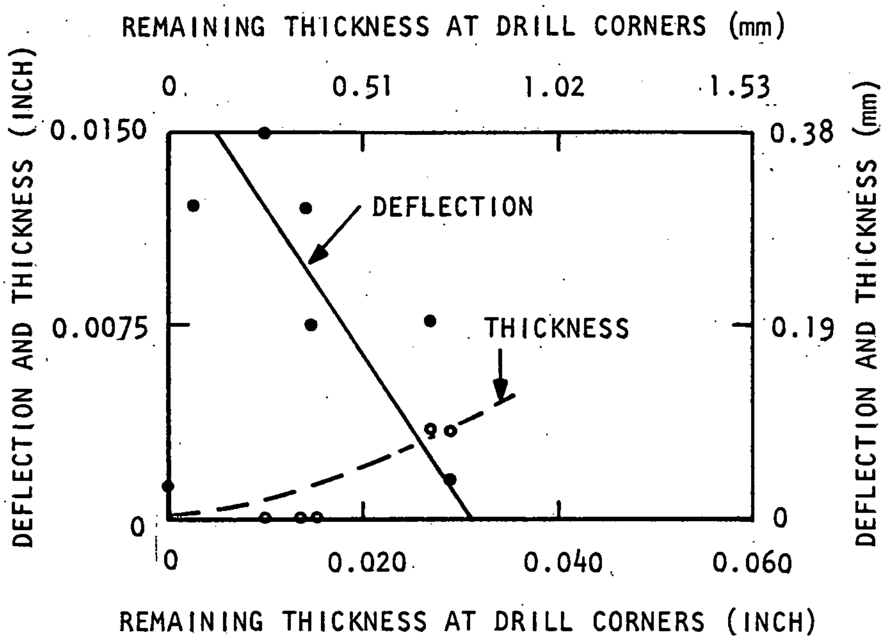

Figure 36. Deflection and Thickness of 17-4PH Stainless Steel (H900) Below Drill Point as Drill Exits

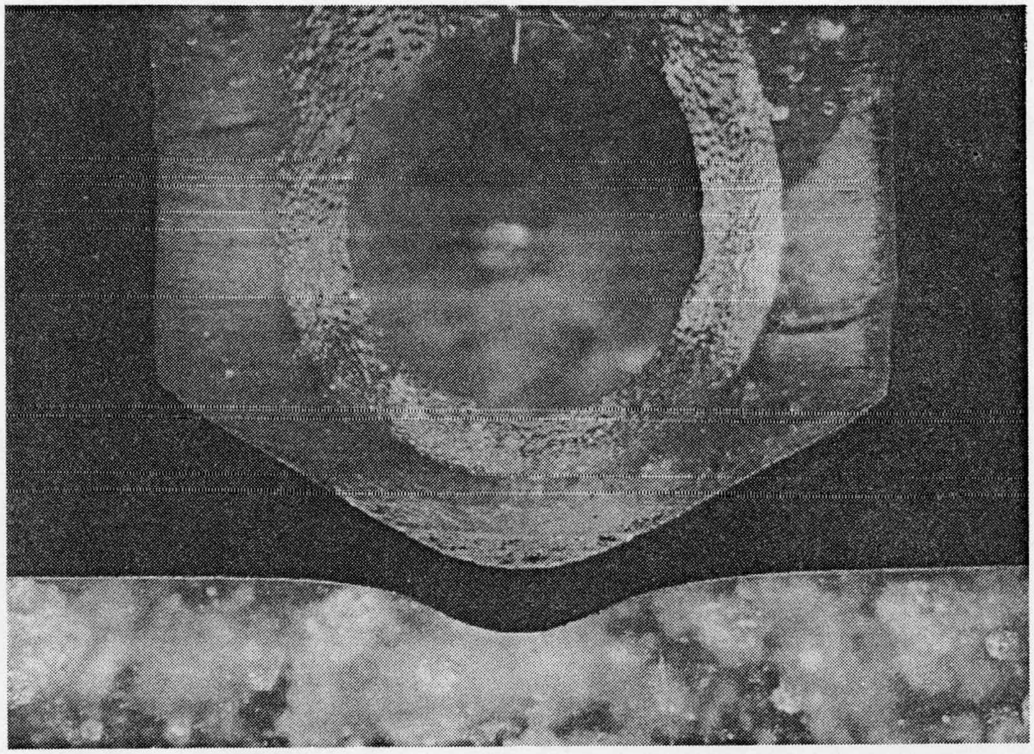

Figure 37. Material Deflection Below 0.125-Inch-Diameter (3.175 mm) Drill Point in 303Se Stainless Steel (Specimen 14)

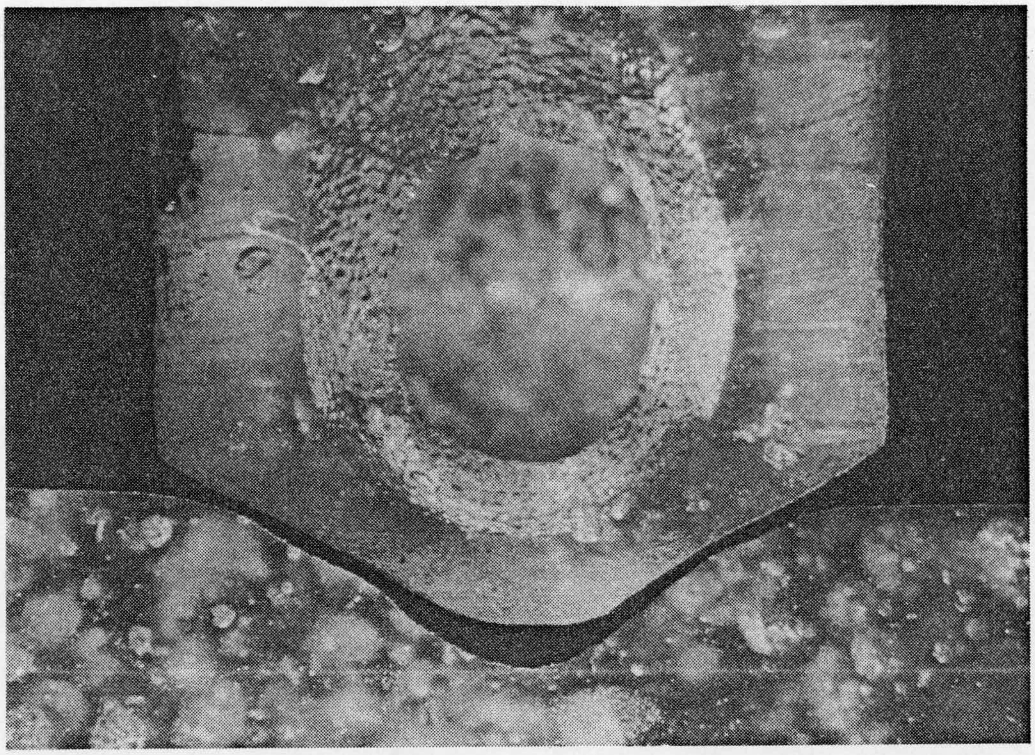

Figure 38. Material Deflection Below Drill Point as Drill Nears Breakthrough in 303Se Stainless Steel (Specimen 25)

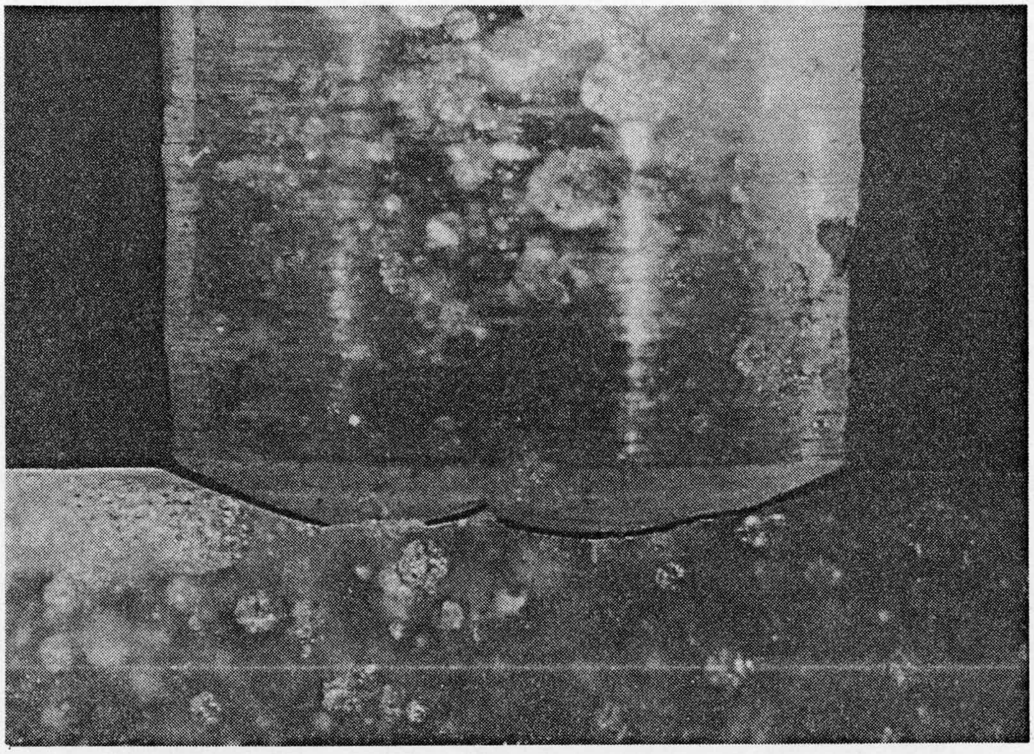

Figure 39. Tearing of Material Below Drill Point in 17-4PH (H900) Stainless Steel

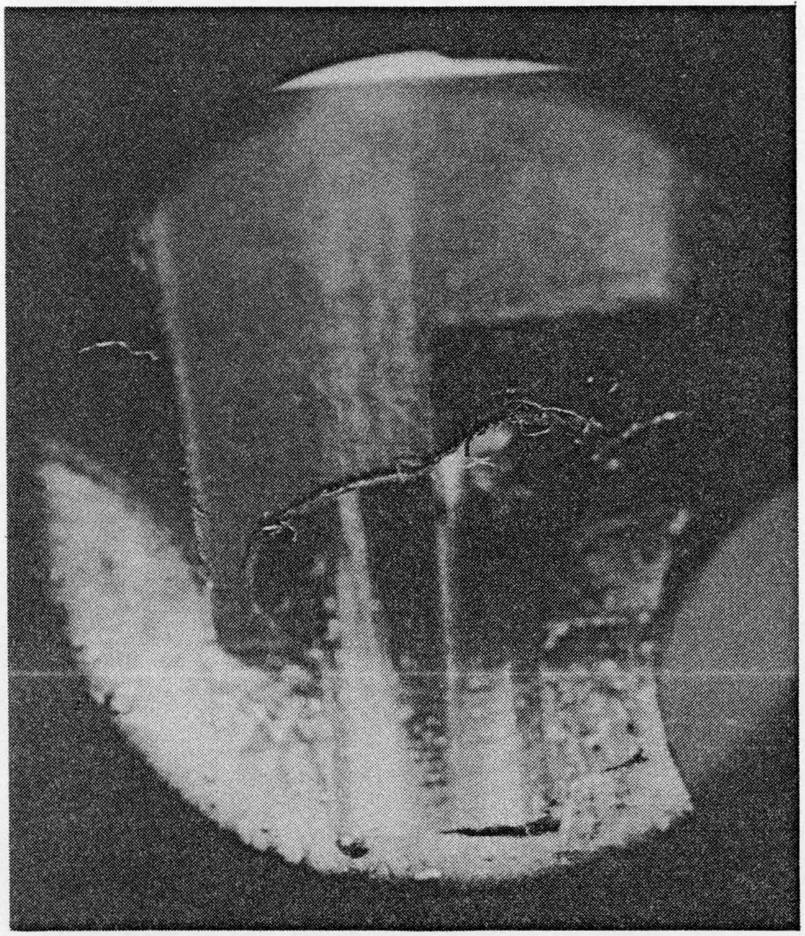

Figure 40. Short, Curled Drill-Exit Burr From 17-4PH (H900) Stainless Steel

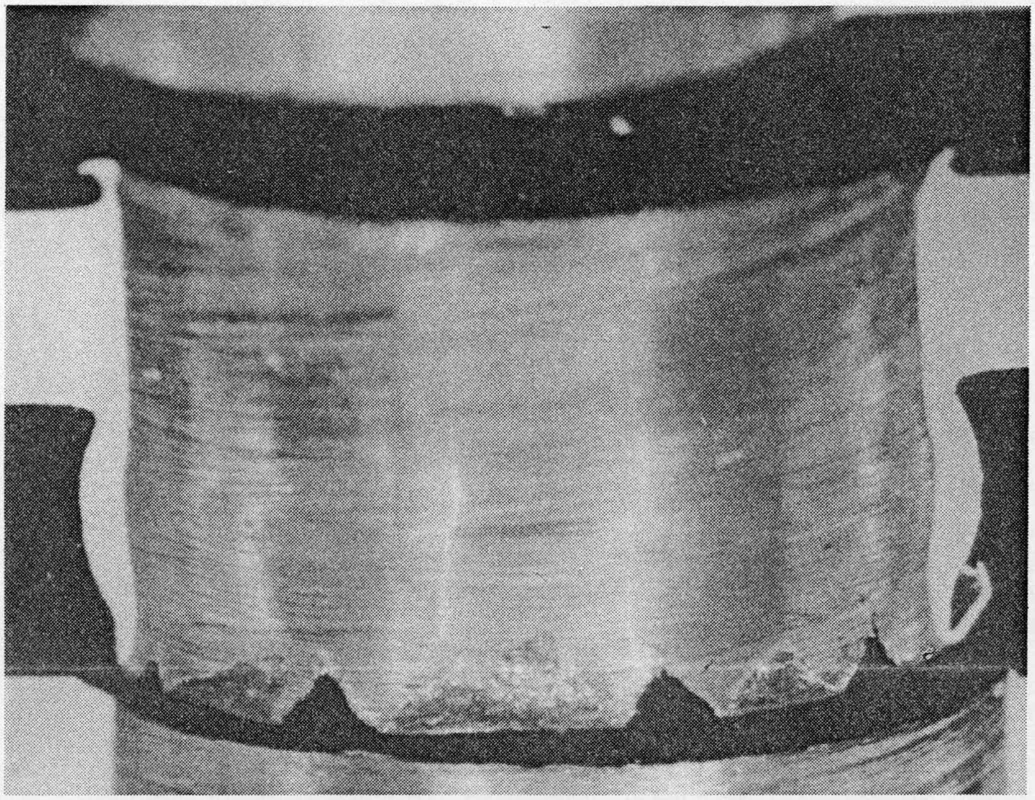

Figure 41. Cross Section of Long, Semiuniform Drill-Exit Burr From 6061-T6 Aluminum

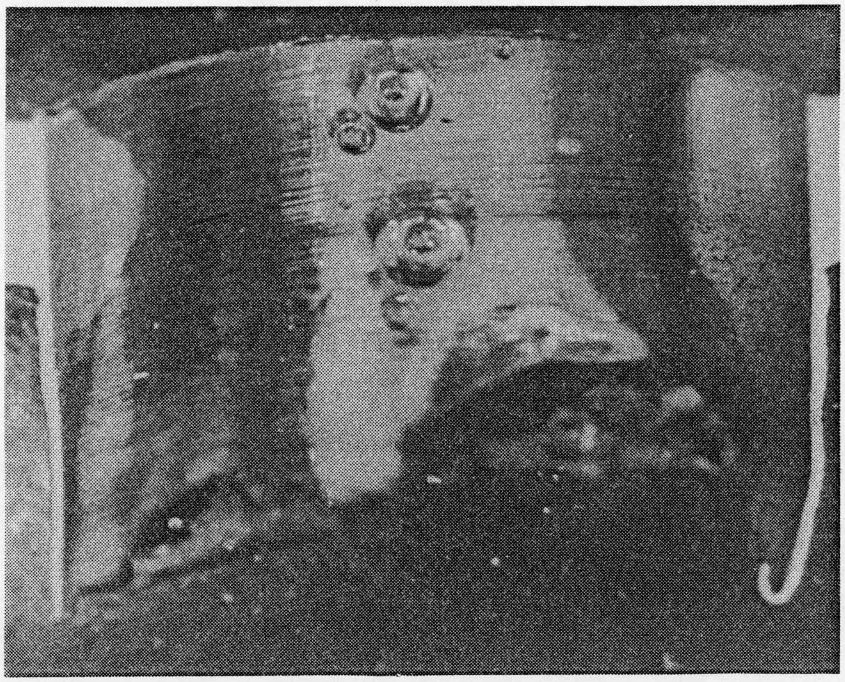

Figure 42. Cross Section of Long, Semiuniform Drill-Exit Burr From 1018 Steel

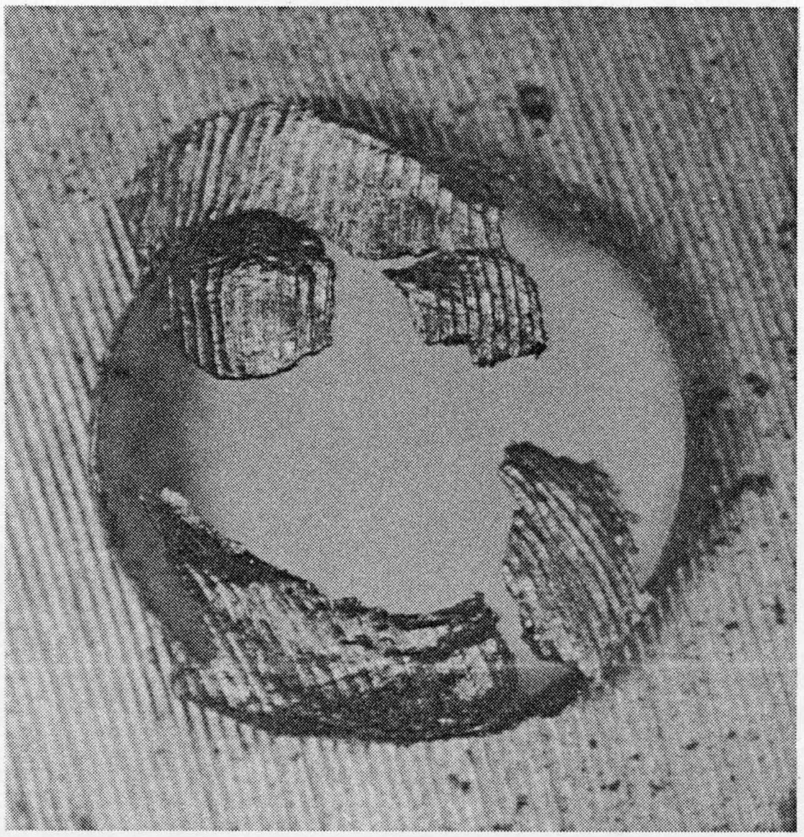

Figure 43. Ragged Drill-Exit Burr
From 1018 Steel

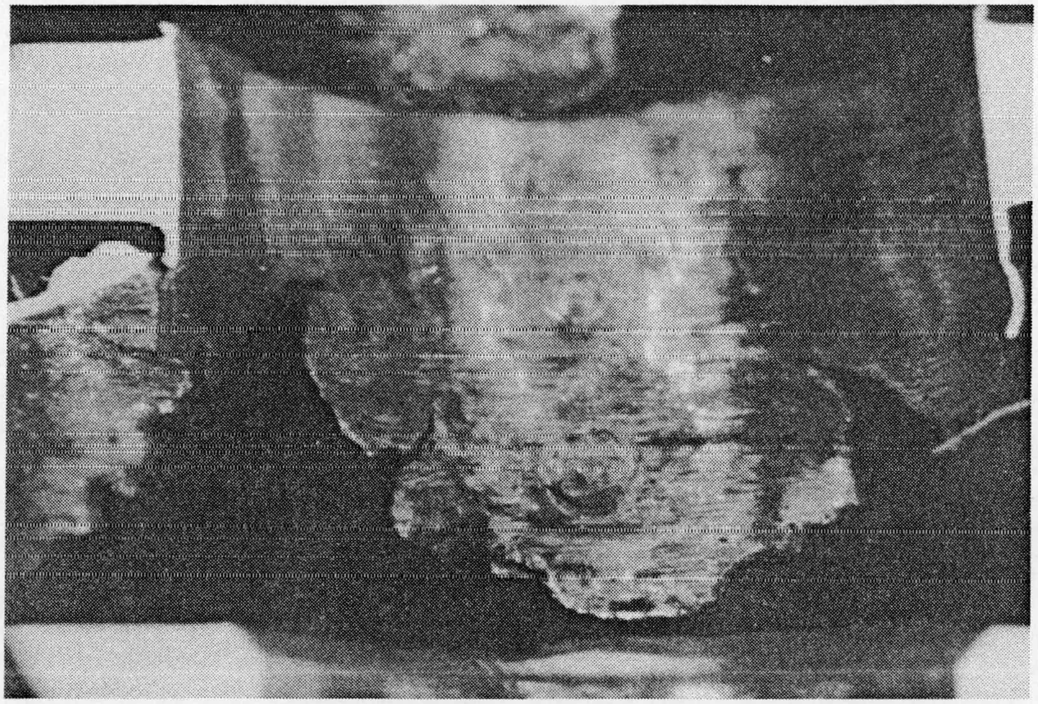

Figure 44. Cross Section of Ragged Drill-Exit Burr From 303Se Stainless Steel

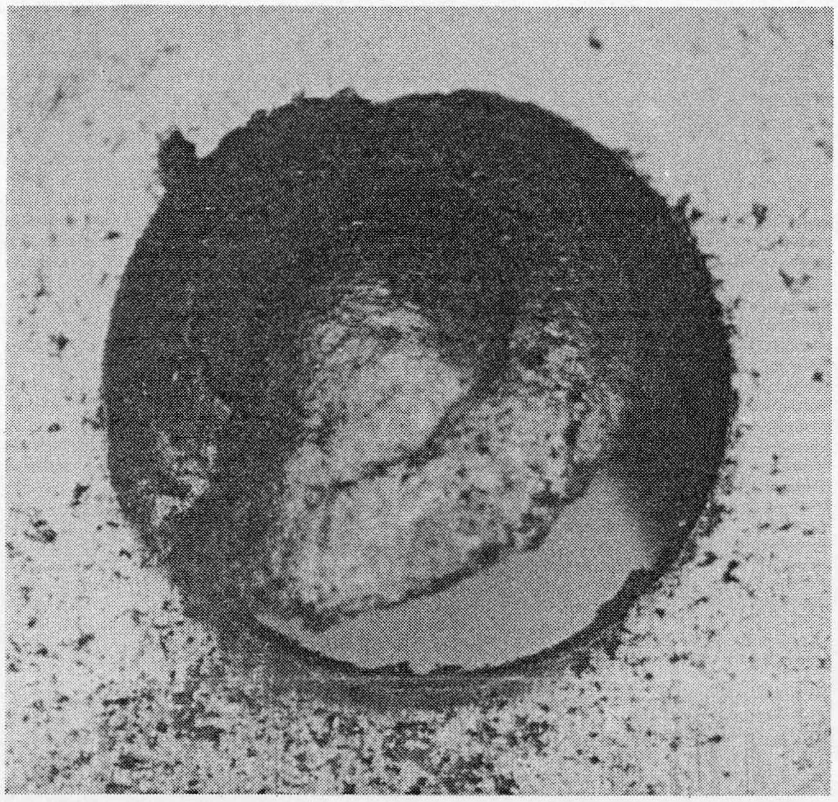

Figure 45. Cap of Metal Produced From 1018 Steel

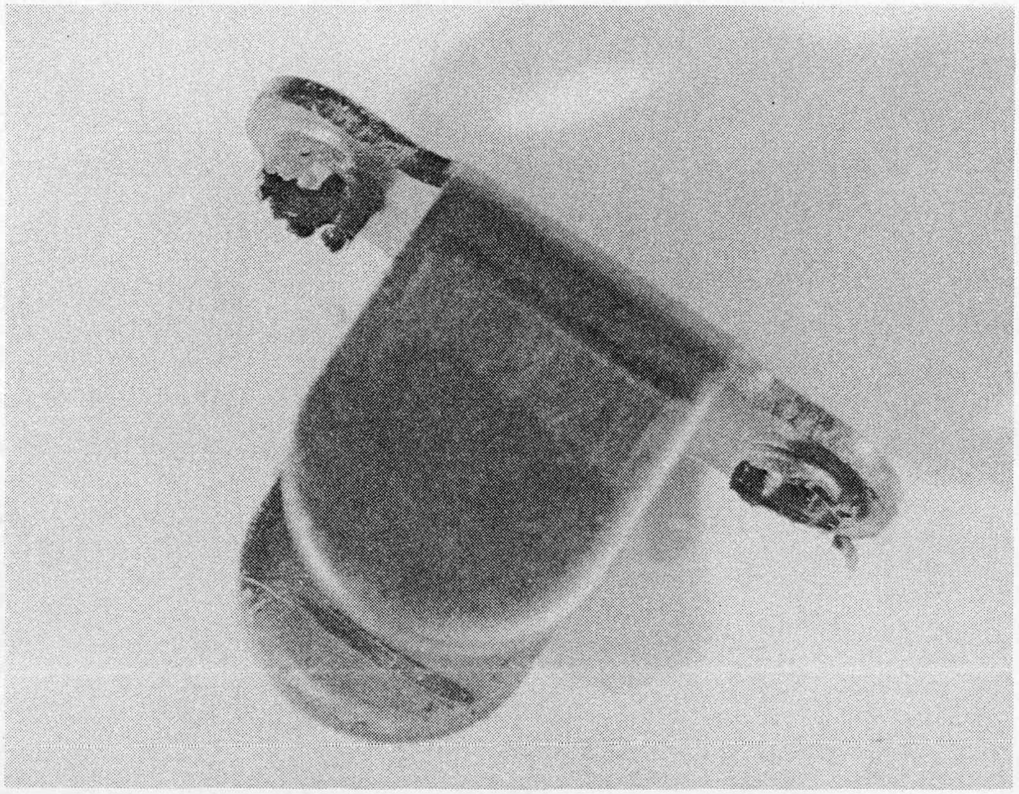

Figure 46. Consecutive Burrs From 302 Stainless Steel

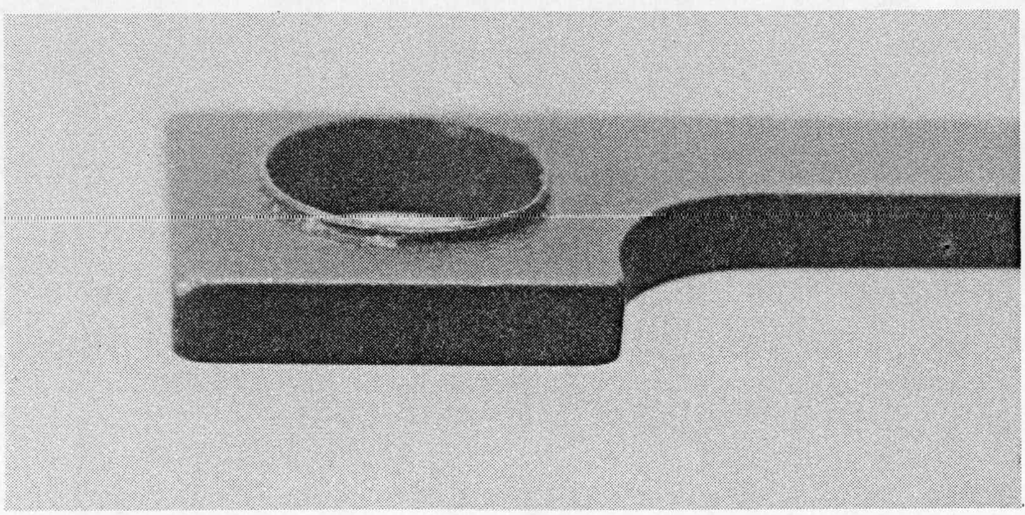

Figure 47. Extruded Burr Formed by Dull Drill in Beryllium-Copper

Table 8. Effect of Drilling Variables on Entrance-Burr Thickness

Variable	Effect of Increasing Variable for Indicated Material*					
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass
Feedrate	+	0	+		+	
Lip Wear						
Corner Wear						
Corner Angle						
Helix Angle	-		-		-	
Diameter	0		0		0	
Surface Velocity	+		+		+	
Helix Direction						
Workpiece Thickness	-	-	-		-	
Number of Holes**	0	+	0		0	
Lip-Relief Angle						

*+ indicates the burr gets larger as the indicated variable is increased; - indicates the burr gets smaller as the variable is increased; 0 indicates the burr is unaffected by the variable; and no entry indicates test data are not available.

**Up to 150 holes.

Table 9. Effect of Drilling Variables on Entrance-Burr Height

Variable	Effect of Increasing Variable for Indicated Material*					
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass
Feedrate	+		+		+	
Lip Wear						
Corner Wear						
Corner Angle						
Helix Angle	-		-			
Diameter	-		-		-	
Surface Velocity	-		-		-	
Helix Direction						
Workpiece Thickness	-	-	-		-	
Number of Holes**	0	+	0		0	
Lip-Relief Angle						

*+ indicates the burr gets larger as the indicated variable is increased; - indicates the burr gets smaller as the variable is increased; 0 indicates the burr is unaffected by the variable; and no entry indicates test data are not available.

**Up to 150 holes.

Table 10. Effect of Drilling Variables on Exit-Burr Thickness

Variable	Effect of Increasing Variable for Indicated Material*					
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass
Feedrate	+	0	0		0	
Lip Wear						
Corner Wear						
Corner Angle	-					
Helix Angle	-		-		-	
Diameter	+		0		+	+
Surface Velocity	+		+		+	
Helix Direction					0***	
Workpiece Thickness	0	0	-		0	
Number of Holes**	0	+	0		0	
Lip-Relief Angle					0***	

*+ indicates the burr gets larger as the indicated variable is increased; - indicates the burr gets smaller as the variable is increased; 0 indicates the burr is unaffected by the variable; and no entry indicates test data are not available.

**Up to 150 holes.

***From Zaima's study.[12]

Table 11. Effect of Drilling Variables on Exit-Burr Height

Variable	Effect of Increasing Variable for Indicated Material*					
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass
Feedrate	+	0	+		0	
Lip Wear						
Corner Wear						
Corner Angle	+					
Helix Angle	-		-		-	
Diameter	+		+		+	+
Surface Velocity†					0***	
Helix Direction						
Workpiece Thickness	0	+	0		0	
Number of Holes**	0	+		-††		
Lip-Relief Angle						

*+ indicates the burr gets larger as the indicated variable is increased; - indicates the burr gets smaller as the variable is increased; 0 indicates the burr is unaffected by the variable; and no entry indicates test data are not available.

**Up to 150 holes.

***From Saito's study.[15]

†Assumes that surface velocity is maintained below the value recommended for the particular tool-workpiece combination.

††From Fleming's study.[14]

Table 12. Recommended Variable Combinations to Minimize Exit-Burr Thickness

	Recommended Variable Combination*			
Workpiece Material	Drill Point	Feedrate (IPR)**	Helix Angle	Surface Velocity (SFPM)***
303Se Stainless Steel	Radial Lip	0.0005	High†	50
17-4PH Stainless Steel	Not Critical	0.0005 to 0.0015	High	
1018 Steel	Not Critical	0.0005 to 0.0015	High	50
6061-T6 Aluminum	Not Critical	0.0005 to 0.0015	High	50

*Based on drilling 150 holes, or less, and using feedrates and speeds compatible with the workpiece material.

**0.001 ipr = 25.4 μm/rev.

***100 sfpm = 510 mm/s.

†A high helix angle implies 37-1/2 degrees; standard helix angles are 27-1/2 degrees.

Table 13. Recommended Variable Combinations to Minimize Exit-Burr Length

	Recommended Variable Combination*		
Workpiece Material	Drill Point	Feedrate (IPR)**	Helix Angle
303Se Stainless Steel	Radial Lip	0.0005 to 0.0030	High***
17-4PH Stainless Steel	Not Critical	0.0005 to 0.0015	
1018 Steel	Not Critical	0.0005	High
6061-T6 Aluminum	Not Critical	0.0005 to 0.0015	High

*Based on drilling 150 holes, or less, and using feedrates and speeds compatible with the workpiece material.
**0.001 ipr = 25.4 μm/rev.
***A high helix angle implies 37-1/2 degrees; standard helix angles are 27-1/2 degrees.

Table 14. Surface Velocities and Feedrates Recommended for Radial-Lip Drills by the Manufacturer

Workpiece Material	Surface Velocity (SFPM)*	Feedrate (IPR)**
303Se Stainless Steel	60 or less	0.003 to 0.004
17-4PH Stainless Steel	30 or less	0.001 to 0.003
1018 Steel	70 or less	0.003 to 0.004
6061-T6 Aluminum	200 or less	0.004 to 0.008

*100 sfpm = 510 mm/s.
**0.001 ipr = 25.4 μm/rev.

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[1]L. K. Gillespie, *Burrs Produced by Drilling* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-1248, December, 1975.

[2]L. K. Gillespie, *Vibratory Deburring* (Final Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-735 (Rev.), January, 1974 (Available from NTIS).

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Appendix

TABULAR DATA ON BURRS OBTAINED FROM STUDY OF DRILLING VARIABLES

Table A-1. Effects of Drill Geometry on Burr Size

CODE NO.** ABCDEF	SAMPLE NO.	ENTRANCE BURR THICKNESS	ENTRANCE BURR HEIGHT	ENTRANCE BURR RADIUS	EXIT BURR THICKNESS	EXIT BURR HEIGHT	EXIT BURR RADIUS
111111	S9	16, 0	45, 0	0, 0	17,85	7, 13	14, 84
111112		27,53	17,20	20,100	17,17	8, 20	12, 11
111113		25,22	27,19	9, 3	23,25	36, 25	42, 12
111114		49,56	15,15	100,100	34,44	44, 36	26, 29
111115		33, 0	21, 0	52, 0	36,31	28, 34	40, 15
111121	C15	0, 0	0, 0	0, 0	23,20	68, 48	23, 7
111122		0, 0	0, 0	0, 0	0,37	0, 27	0, 10
111123		0, 0	0, 0	0, 0	24,26	78, 78	10, 9
111124		0, 0	0, 0	0, 0	24,23	67, 72	8, 4
111125		18, 0	30, 0	0, 0	26,22	75,107	9, 18
111211	S15	0,47	0,48	0, 2	22,19	82, 21	15, 21
111212		30,36	15,26	34, 29	20,18	79, 12	12, 19
111213		70,22	14,41	31, 7	31,19	84, 14	19, 18
111214		21,20	24,12	9, 7	20,30	27, 17	15, 24
111215		0,53	0,86	0,101	93,25	45, 13	28, 15
111221	C14	33,33	14,20	13, 14	0,10	0, 15	0, 10
111222		23,15	12,18	23, 10	0,33	0, 40	0, 33
111223		0, 0	0, 0	0, 0	31, 0	59, 0	32, 0
111224		17, 6	12,16	11, 3	0,34	0, 37	0, 27
111225		24,16	10, 5	42, 24	20,14	32, 39	0, 0
112111	S14	0, 0	0, 0	0, 0	27,30	62, 69	47, 20
112112		32,18	11,22	30, 11	35,26	43, 34	17, 22
112113		0,26	0, 9	0, 25	25,26	66, 31	13, 13
112114		17,27	14,22	3, 15	20,19	46, 63	13, 6
112115		0, 0	0, 0	0, 0	26,26	82, 35	11, 11
112121	C1	7,20	7,20	2, 3	20,26	24, 9	4, 25
112122		0,33	0, 5	0, 16	17,15	10,151	17, 4
112123		0, 0	0, 0	0, 0	26,17	79, 89	17, 10
112124		0,14	0,24	0, 2	8, 8	13, 17	3, 5
112125		19,20	8,20	19, 4	0, 5	0, 72	0, 15
112211	S3	9,19	37,24	2, 4	24,32	47, 16	9, 27
112212		11,26	19,46	0, 2	27,31	54, 18	6, 16
112213		23,35	23,35	3, 13	31,29	40, 52	12, 11
112214		16,21	3,20	15, 3	56,56	182, 75	40, 44
112215		0,34	0, 6	0,200	23,18	157, 79	5, 3
112221	C11	0,28	0,22	0, 0	5, 0	5, 0	0, 0
112222		0,26	0,39	0, 39	16,12	11, 23	5, 7
112223		13, 0	6, 0	16, 0	59,32	54, 55	101, 26
112224		17,13	4, 6	7, 11	46,27	30, 74	100, 25
112225		66, 0	22, 0	55, 0	16,16	10, 15	19, 14
121111	S10	32,18	11,11	29, 2	19,25	27, 43	9, 9
121112		34,39	35,21	21, 34	38,58	16, 23	23,100
121113		50,24	10, 8	100, 41	37,34	30, 37	28, 17
121114		27,41	32,14	14, 85	29,59	30, 40	35, 71
121115		24,29	35,39	16, 34	38,58	16, 23	23,100
121121	C5	0,12	0, 3	0, 4	10,11	10, 10	40, 40
121122		22, 4	7,35	26, 2	19,11	34, 12	8, 5
121123		0, 0	0, 0	0, 0	22,0	69, 0	8, 10
121124		22,32	9,11	11, 39	18,28	42, 25	2, 22
121125		61,11	20,18	31, 2	32,22	42, 12	5, 10
121211	S6	43, 0	21, 0	37, 0	20,55	73, 57	8, 71

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
**CODE NUMRERS ARE IDENTIFIED IN TABLE 1 IN THE MAIN BODY OF THIS REPORT.

Table A-1 Continued. Effects of Drill Geometry on Burr Size

CODE NO.** ABCDEF	SAMPLE NO.	ENTRANCE BURR THICKNESS	ENTRANCE BURR HEIGHT	ENTRANCE BURR RADIUS	EXIT BURR THICKNESS	EXIT BURR HEIGHT	EXIT BURR RADIUS
121212		13, 0	27, 0	14, 0	19,51	26, 14	9,100
121213		43,36	25,18	41,101	9,20	9, 16	2, 14
121214		23,56	26,15	8,100	23,15	54, 36	6, 10
121215		18,18	18,20	4, 3	44,31	38, 46	36, 30
121221	C6	10, 6	12,13	2, 5	0,31	0, 22	0, 21
121222		0, 4	0, 3	0, 0	30,26	7, 9	25, 2
121223		10,11	11, 8	2, 0	23,31	8, 13	9, 8
121224		10,11	5, 7	2, 2	31,33	9, 28	15, 10
121225		0,19	0, 8	0, 21	17,20	8, 9	7, 12
122111	S4	24,27	11, 9	40, 23	23,19	33, 37	9, 10
122112		23, 0	35, 0	7, 0	52,37	44, 48	43, 24
122113		31,45	20,21	23, 62	32,28	45, 46	15, 9
122114		28,20	13,16	19, 3	61,34	47, 42	63, 45
122115		57,27	10,33	100, 6	38,39	35, 48	11, 20
122121	C8	79,41	43, 9	100, 48	18,31	54, 23	7, 8
122122		19,29	18,22	4, 19	54,40	120,141	41, 17
122123		34, 0	29, 0	32, 0	22,17	93, 92	15, 5
122124		14, 8	17, 7	3, 2	18,26	18, 26	8, 22
122125		14, 0	25, 0	2, 0	11,22	15,106	5, 6
122211	S8	33,43	44,40	17, 15	43,76	19, 32	63, 89
122212		36,41	47,29	24, 35	30,34	35, 50	24, 24
122213		34,32	29,31	33, 6	56,47	60, 50	58, 43
122214		56,97	40,54	44,200	25,29	43, 77	10, 6
122215		34,31	26,42	17, 15	51,38	48, 31	80, 18
122221	C3	35,37	16,39	12, 11	26, 8	8, 31	17, 0
122222		5, 0	15, 0	7, 0	91,84	31, 36	96,200
122223		0,25	0,10	0, 15	61,12	39, 54	31, 10
122224		0,35	0,20	0, 18	48,41	22, 30	99, 31
122225		0,19	0, 8	0, 17	25,23	8, 12	17, 25
211111	S1	0, 0	0, 0	0, 0	20,18	49, 36	10, 11
211112		13, 7	5,12	5, 4	9,13	35, 42	7, 6
211113		0,11	0,25	0, 4	22,20	59, 51	6, 7
211114		0, 0	0, 0	0, 0	21,22	63, 20	6, 13
211115		60, 0	13, 0	38, 0	22,15	39, 71	9, 0
211121	C9	34,23	40,36	0, 0	24, 9	15, 27	26, 0
211122		0,34	0,74	0, 5	38,30	62, 34	15, 12
211123		40,31	4,45	2, 2	13,16	11, 11	10, 14
211124		42,24	35, 7	9, 18	18, 0	59, 0	10, 0
211125		20, 0	8, 0	15, 0	25,12	66, 24	11, 2
211211	S11	13,28	19,27	3, 8	11,15	12, 28	4, 11
211212		15,42	17,22	8, 63	23,10	80, 18	7, 2
211213		11,12	14,12	2, 3	16, 0	35, 0	8, 0
211214		12, 9	5,16	3, 3	13,15	18, 21	5, 18
211215		7,21	5,15	6, 16	13, 8	19, 7	5, 10
211221	C7	19, 0	10, 0	2, 0	86,24	43, 18	101, 25
211222		35, 9	11,18	17, 0	26,40	20, 21	16, 26
211223		29,54	4,11	2, 41	13,10	14, 10	8, 2
211224		18,26	6, 8	0, 25	19,19	7, 9	18, 17
211225		0, 0	0, 0	0, 0	17,29	15, 18	15, 15
212111	S7	30,31	27,58	22, 7	31,31	19,106	33, 9
212112		35,31	7,33	36, 22	33,21	77,106	26, 11
212113		28,38	45,19	8, 30	24,28	17, 54	11, 14

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

Table A-1 Continued. Effects of Drill Geometry on Burr Size

CODE NO.** ABCDEF	SAMPLE NO.	ENTRANCE BURR THICKNESS	ENTRANCE BURR HEIGHT	ENTRANCE BURR RADIUS	EXIT BURR THICKNESS	EXIT BURR HEIGHT	EXIT BURR RADIUS
212114		30,26	28,35	7, 2	30,19	19, 26	29, 6
212115		57,26	10,49	100, 13	22,25	178, 53	0, 13
212121	C2	16, 8	36,30	2, 0	15,28	28, 52	10, 12
212122		0, 0	0, 0	0, 0	14,17	33, 42	8, 7
212123		0, 0	0, 0	0, 0	11,11	163,111	11, 10
212124		0, 0	0, 0	0, 0	20,21	51, 52	12, 9
212125		0, 0	0, 0	0, 0	21,18	27, 37	11, 6
212221	C10	0,33	0,18	0, 21	38,55	21, 20	20, 30
212222		64,40	17, 4	55, 20	13,14	10, 12	2, 2
212223		15,21	56, 6	2, 20	6, 6	5, 10	3, 3
212224		16, 0	22, 0	3, 0	21,21	16, 12	11, 14
212225		33,24	9, 8	32, 14	19,14	16, 16	17, 11
221111	S13	21,29	18, 9	8, 37	36,29	35, 62	9, 9
221112		46,50	14, 8	44, 44	38,32	28, 36	34, 43
221113		39, 0	20, 0	27, 0	43,34	70, 72	15, 18
221114		45, 0	19, 0	26, 0	65,25	14, 19	32, 24
221115		46,67	8,34	95,100	38,32	66, 72	16, 14
221121	C4	10,28	10,13	0, 17	41,46	64,103	4, 2
221122		31,35	43,35	13, 10	28,22	92,129	2, 8
221123		40,15	22, 9	13, 3	33,22	121,139	14, 10
221124		0,34	0,33	0, 14	32,31	156,153	10, 16
221125		12,10	7,10	5, 5	39,32	128,120	13, 16
221211	S16	20,37	16,31	18, 30	27,32	47, 36	13, 28
221212		43,73	24,25	10,110	31,34	39, 42	9, 15
221213		39,38	18,19	45, 33	21,44	21, 29	6, 45
221214		27,35	23,33	21, 28	28,33	36, 90	7, 45
221215		27,16	24,19	10, 3	39,39	48, 33	23, 30
221221	C16	36,29	28,23	24, 7	23,30	11, 14	31, 28
221222		25,51	39,19	9, 39	12,19	12, 24	3, 4
221223		28,66	36,24	32,101	15,18	10, 20	2, 5
221224		53,29	27,26	38, 7	14, 0	11, 0	18, 0
221225		30,42	32,28	13, 31	23,18	11, 10	2, 8
222111	S2	93,99	20,80	200, 40	28,30	70, 86	16, 18
222112		47,40	31,20	42, 38	58,58	115,155	24, 25
222113		7, 0	17, 0	3, 0	67,64	622,153	31, 30
222114		72,87	74,77	63, 90	01,77	633,279	89,501
222115		45,33	51,26	29, 13	28,32	69,301	12, 9
222121	C13	62,47	46,33	58, 33	53,50	167,278	28, 27
222122		47,25	33,13	29, 31	30,35	173,176	33, 26
222123		0,21	0,20	0, 13	29,34	172,171	14, 17
222124		0,53	0,16	0, 62	22,28	60, 82	15, 18
222125		36,30	18,17	27, 22	28,29	91, 88	4, 7
222211	S5	29,25	37,33	16, 13	60,63	50, 59	31, 77
222212		17, 0	23, 0	18, 0	33,25	38, 28	32, 25
222213		84,20	26,28	127, 9	61,52	31, 35	88, 82
222214		69,47	21,34	102, 53	27,27	28, 32	26, 31
222215		14,72	29,33	5,100	47,69	37, 41	85,107
222221	C12	17,16	13,23	8, 3	60,61	43, 24	26, 39
222222		22,14	21,21	2, 2	39,10	33, 12	20, 2
222223		29,25	27,28	20, 23	15,61	25, 31	4, 40
222224		40,28	18,20	39, 18	15,38	26, 40	2, 16
222225		24,50	18,18	6, 50	15,26	25, 20	6, 8

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

Table A-1 Continued. Effects of Drill Geometry on Burr Size

CODE NO.** ABCDEF	SAMPLE NO.	ENTRANCE BURR THICKNESS	ENTRANCE BURR HEIGHT	ENTRANCE BURR RADIUS	EXIT BURR THICKNESS	EXIT BURR HEIGHT	EXIT BURR RADIUS
111131	A9	0, 0	0, 0	0, 0	41,34	47, 28	25, 29
111132		11, 0	3, 0	0, 0	38,43	31, 27	21, 33
111133		0, 0	0, 0	0, 0	29,28	39, 35	18, 18
111134		0, 0	0, 0	0, 0	22,37	30, 28	10, 37
111135		0, 0	0, 0	0, 0	31,32	29, 29	27, 28
111231	A12	17,34	23,33	2, 13	26,31	71, 27	13, 12
111232		0,40	0,19	0, 36	12,41	100, 24	38, 31
111233		0,45	0,25	0,100	35,40	908, 16	13, 21
111234		43,35	27,35	100, 33	35,32	167, 16	33, 25
111235		22,36	33,44	5, 28	40,38	115,262	30, 17
112131	A1	5,12	16,17	2, 5	25,20	37, 42	14, 14
112132		0, 5	0,14	0, 2	12,19	20, 17	4, 2
112133		8,17	8,21	0, 2	30,29	38, 49	9, 11
112134		19,12	31, 7	9, 13	24,27	34, 42	12, 13
112135		7,15	15,33	0, 3	24,27	34, 30	16, 17
112231	A2	0, 0	0, 0	0, 0	26,34	192, 24	5, 24
112232		3, 9	3,19	0, 2	8,22	509,734	0, 5
112233		22,20	60,46	3, 0	41,23	172, 10	21, 22
112234		16,14	38,35	0, 2	37,33	207, 68	20, 8
112235		17,15	42,29	3, 0	26,29	72, 65	11, 11
121131	A7	0, 0	0, 0	0, 0	28,37	68, 52	2, 27
121132		18,20	26,30	0, 2	32,27	59, 67	14, 10
121133		14,13	20,13	0, 2	32,35	47, 56	25, 24
121134		20, 5	8, 5	13, 2	32,32	65, 65	30, 38
121135		11,20	4, 7	11, 16	43,17	44, 39	32, 2
121231	A5	34,30	35,36	24, 14	43,70	34, 52	28, 25
121232		31,17	13, 9	11, 14	32,33	36, 42	28, 14
121233		62,43	18,26	100, 9	35,38	37, 50	45, 22
121234	A5	40,34	15,31	13, 14	55,36	81, 60	86, 41
121235		12, 0	21, 0	2, 0	40,23	23, 23	31, 8
122131	A11	0, 0	0, 0	0, 0	24,35	29, 38	5, 27
122132		30,31	19,15	11, 15	35,46	50, 35	17, 34
122133		24,32	13,12	16, 35	33,20	30, 29	16, 12
122134		39,22	41,30	38, 6	34,31	28, 31	34, 32
122135		29,25	20,23	22, 8	0, 0	0, 0	0, 0
122231	A6	26,60	28,33	11, 85	31,36	38, 87	17, 37
122232		28,46	38,33	12, 32	41,58	45, 58	51, 79
122233		73,50	30,29	200, 15	22,37	72, 48	7, 32
122234		90,40	37,21	200, 32	48,24	45, 28	100, 15
122235		40,36	36,39	41, 36	41,70	22, 37	12,113
211131	A16	39,23	14,32	20, 4	14,21	24, 28	12, 10
211132		46,19	29,33	44, 0	28,24	63, 42	10, 14
211133		27,19	41,28	4, 0	27,28	43, 48	7, 21
211134		28,41	9,41	10, 12	30,25	41, 52	12, 12
211135		28,16	26,21	3, 3	28,25	54, 54	11, 13
211231	A13	30,15	21,10	6, 0	35,34	38, 27	17, 25
211232		12, 0	31, 0	2, 0	34,33	45, 21	16, 24
211233		21,13	8,37	13, 2	32,25	50,152	16, 11
211234		16,10	7, 4	8, 3	32,32	75, 37	64, 17
211235		17,15	36, 8	2, 0	33,35	29, 91	10, 12
212131	A8	51,77	60,57	11,101	31,26	17, 35	26, 3
212132		23,18	56,14	13, 2	34,46	31, 45	19, 93

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*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
**CODE NUMBERS ARE IDENTIFIED IN TABLE 1 IN THE MAIN BODY OF THIS REPORT.

Table A-1 Continued. Effects of Drill Geometry on Burr Size

CODE NO.** ABCDEF	SAMPLE NO.	ENTRANCE BURR THICKNESS	ENTRANCE BURR HEIGHT	ENTRANCE BURR RADIUS	EXIT BURR THICKNESS	EXIT BURR HEIGHT	EXIT BURR RADIUS
212133		0,38	0,74	0, 23	48,26	26, 38	67, 12
212134		0,40	0,27	0, 36	27,32	53, 33	11, 22
212135		43,19	8,11	110, 2	0,24	0, 20	0, 3
212211	S12	12, 8	14,25	2, 6	32,14	34, 32	19, 9
212212		10,20	10,29	10, 6	21,23	24, 28	20, 16
212213		22,24	27,44	10, 10	15,20	44, 52	8, 7
212214		55,41	19, 9	100,150	26,25	47, 52	11, 13
212215		11,14	26,29	4, 3	23,22	47, 35	13, 21
212231	A10	0,23	0, 8	0, 15	33,25	18, 20	12, 9
212232		20,14	7, 7	9, 5	22,30	41, 95	2, 25
212233		20,25	10,10	0, 11	29,15	192, 22	19, 0
212234		0, 0	0, 0	0, 0	17,29	112, 21	0, 19
212235		17,56	31,24	0, 34	64,24	621,274	55, 8
221131	A15	27, 0	12, 0	24, 0	20,27	67, 51	8, 7
221132		16,11	2, 2	24, 20	28,26	81, 71	8, 7
221133		33, 0	16, 0	27, 0	27,31	63, 66	8, 10
221134		8, 7	8, 7	6, 3	19,29	56, 67	2, 10
221135		0, 0	0, 0	0, 0	33,23	68, 57	8, 6
221231	A14	28,36	29,18	10, 23	27,29	64, 36	9, 9
221232		45,35	53,40	62, 9	44,35	44, 41	30, 26
221233		43,34	52,22	23, 33	32,29	43, 30	12, 9
221234		52,35	28,37	32, 31	39,32	37, 49	14, 31
221235		36,45	35,23	48, 26	28,27	66, 21	15, 14
222131	A4	0,73	0,38	0, 63	11,26	22, 37	0, 12
222132		0,29	0,13	0, 21	27,26	12, 32	20, 24
222133		39,47	31,59	37, 52	16,36	38, 42	0, 24
222134		12, 0	13, 0	3, 0	14,12	22, 28	4, 6
222135		20,33	26,29	0, 17	46, 5	71, 4	20, 3
222231	A3	0, 0	0, 0	0, 0	20,22	61, 42	13, 12
222232		32, 0	21, 0	17, 0	29,21	24, 38	11, 8
222233		19,23	36, 7	2, 12	23,25	31, 40	11, 13
222234		0,27	0,22	0, 14	24,30	47, 56	10, 16
222235		30, 0	7, 0	21, 0	36,35	60, 61	20, 24

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
**CODE NUMBERS ARE IDENTIFIED IN TABLE 1 IN THE MAIN BODY OF THIS REPORT.

Table A-2. Effects of Subland Drills on Burr Size

CODE NO.	SAMPLE NO.	ENTRANCE BURR THICK.	ENTRANCE BURR HEIGHT	ENTRANCE BURR RADIUS	EXIT BURR THICK.	EXIT BURR HEIGHT	EXIT BURR RADIUS	COUNTERBORE BURR THICK.	COUNTERBORE BURR HEIGHT	COUNTERBORE BURR RADIUS
1111	S20	0, 0	0, 0	0, 0	99, 37	20, 43	200, 41	0,18	0,20	0, 10
1112	S20	0, 0	0, 0	0, 0	28, 13	18, 32	18, 6	23,22	8,11	21, 27
1113	S20	0, 0	0, 0	0, 0	24, 18	14, 15	16, 13	38,36	19,12	40, 34
1114	S20	23, 3	12, 3	24, 0	31, 35	60, 49	18, 23	0,12	0, 6	0, 10
1115	S20	0, 0	0, 0	0, 0	40, 20	23, 30	38, 13	41,48	19,11	87,100
1121	C17	0, 0	0, 0	0, 0	20, 17	122, 13	19, 10	26,27	12,14	10, 27
1122	C17	0, 0	0, 0	0, 0	25, 32	176,146	32, 48	0, 0	0, 0	0, 0
1123	C17	0, 0	0, 0	0, 0	31, 25	87,130	33, 13	40,39	13,11	75, 84
1124	C17	0, 0	0, 0	0, 0	34, 18	200,166	23, 13	41,45	16,13	90, 91
1125	C17	0, 0	0, 0	0, 0	33, 27	152,170	14, 19	0, 0	0, 0	0, 0
1131	A18	15, 0	10, 0	2, 0	38, 45	116,999	20, 19	49,30	14,12	62, 35
1132	A18	5, 0	3, 0	0, 0	41, 39	213,140	16, 20	30,36	16,15	26, 53
1133	A18	0, 4	0, 3	0, 0	37, 49	87,139	14, 26	0 , 0	0, 0	0, 0
1134	A18	15,25	2,10	15, 18	46, 43	70, 96	26, 19	36,36	18,13	37, 44
1135	A18	23, 0	6, 0	27, 0	39, 48	127,129	18, 37	48,55	8,12	99, 99
1211	S19	17,13	10, 8	48, 15	58, 51	18, 35	99, 71	30, 4	8,14	39, 12
1212	S19	21, 0	9, 0	28, 0	78, 58	56, 59	99, 44	0, 0	0, 0	0, 0
1213	S19	20,17	11,13	17, 23	29, 34	22, 32	16, 19	0,25	0,13	0, 25
1214	S19	0, 0	0, 0	0, 0	27, 52	39, 37	1, 48	17,15	7, 9	2, 0
1215	S19	0,10	0, 8	0, 0	36, 28	48, 30	27, 16	54,36	27,22	99, 33
1221	C19	43, 5	17, 5	99, 2	41, 29	94, 84	22, 16	0,15	0,12	0, 12
1222	C19	10, 3	10, 3	3, 15	17, 37	63, 40	2, 73	20,50	3,17	2, 34
1223	C19	0, 2	0, 4	0, 2	41, 31	60, 47	92, 74	0,21	0, 9	0, 21
1224	C19	0, 0	0, 0	0, 0	19, 52	20, 24	8, 99	0, 0	0, 0	0, 0
1225	C19	25, 0	6, 0	18, 0	28, 38	60,240	9, 24	46,44	13,15	99, 99
1231	A17	0,24	0,15	0, 11	40, 40	138,122	21, 23	47,41	14,24	99, 29
1232	A17	16,22	10,11	13, 8	35, 34	32, 86	11, 11	34,38	16,11	27, 80
1233	A17	26,12	10, 6	13, 9	26, 25	37, 41	13, 20	36,26	12,15	95, 27
1234	A17	43,44	13,13	99, 66	43, 39	132,128	30, 27	22,24	17,12	10, 18
1235	A17	0, 0	0, 0	0, 0	38, 44	82,639	20, 26	84,38	10,19	99, 34
2111	S17	7, 0	6, 0	0, 0	45, 26	44, 30	23, 14	35,17	27,14	31, 38
2112	S17	0, 0	0, 0	0, 0	51, 44	39, 40	55, 24	48,48	15, 7	98, 99
2113	S17	0,47	0,14	0, 99	49, 37	50, 27	35, 35	23,56	15,32	24, 51
2114	S17	0,83	0,21	0,200	61, 55	59, 56	46, 36	0,69	0,44	0, 54
2115	S17	29, 0	9, 0	22, 0	68, 64	75, 25	52, 52	53,47	27,22	53, 55
2121	C20	0, 9	0, 5	0, 10	24, 48	70,165	44, 27	48,51	11,16	200, 77
2122	C20	6, 0	7, 0	3, 0	43, 35	127,131	21, 18	31,50	15,25	44, 39
2123	C20	0,12	0,23	0, 3	43, 33	78, 86	25, 13	34,51	9,12	35, 40
2124	C20	0, 0	0, 0	0, 0	35, 26	22,136	34, 11	31, 0	12, 0	3, 0
2125	C20	0, 0	0, 0	0, 0	28, 29	127,173	17, 5	0,49	0, 8	0,100
2131	A19	0,38	0,12	0,100	52, 64	119,138	23, 38	0, 0	0, 0	0, 0
2132	A19	0,51	0,13	0,100	58, 56	85, 78	27, 31	0,67	0,17	0,100
2133	A19	0, 0	0, 0	0, 0	63, 68	77, 90	33, 48	21,32	11,13	11, 35
2134	A19	6,55	7,14	4,110	54, 44	80, 69	66, 35	52, 4	38, 3	30, 10
2135	A19	24,32	9,15	23, 35	45, 54	65, 85	20, 16	0, 0	0, 0	0, 0
2211	S18	23, 0	13, 0	29, 0	69, 37	42,257	39, 14	35,29	10,17	100, 13
2212	S18	26,25	8, 6	23, 24	75, 57	489,356	76, 34	25, 3	18, 5	20,100
2213	S18	0, 0	0, 0	0, 0	21, 77	95,181	55, 65	40,14	24,24	26, 0
2214	S18	0, 0	0, 0	0, 0	75, 58	427,154	93, 36	24,49	21,20	39, 38
2215	S18	5, 0	6, 0	5, 0	49,144	69,184	12, 8	0,47	0,26	0, 51
2221	C18	21, 0	13, 0	22, 0	28, 30	70,115	29, 16	53,32	21, 9	43, 21

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
CODE NUMBERS ARE IDENTIFIED IN TABLE 5 IN THE MAIN BODY OF THIS REPORT.

Table A-2 Continued. Effects of Subland Drills on Burr Size

CODE NO.	SAMPLE NO.	ENTRANCE BURR THICK.	ENTRANCE BURR HEIGHT	ENTRANCE BURR RADIUS	EXIT BURR THICK.	EXIT BURR HEIGHT	EXIT BURR RADIUS	COUNTERBORE BURR THICK.	COUNTERBORE BURR HEIGHT	COUNTERBORE BURR RADIUS
2222	C18	0, 0	0, 0	0, 0	41, 53	67, 92	24, 37	40, 0	12, 0	31, 0
2223	C18	27, 0	3, 0	27, 0	37, 33	21, 67	99, 17	0, 0	0, 0	0, 0
2224	C18	18, 0	4, 0	19, 0	41, 34	60, 42	36, 32	26,12	14, 3	25, 10
2225	C18	0, 0	0, 0	0, 0	42, 50	71, 69	39, 38	28,43	8,20	26, 67
2231	A20	25,26	9, 8	23, 16	70, 74	630,583	29, 39	35,39	12,12	33, 45
2232	A20	48, 4	11, 4	102, 2	68, 61	91, 93	38, 27	40,24	38,14	26, 25
2233	A20	42,50	10,17	122,102	62, 66	85,106	39, 57	38,55	10,36	100, 33
2234	A20	19,51	7, 9	24,100	66, 60	60, 79	38, 42	64,27	45,16	45, 21
2235	A20	31,43	15,20	35, 20	56, 60	89, 86	29, 31	37,50	23,21	42,100

*VALUES SHOWN ARE IN 0.0001 INCH UNITS. 0.0001 INCH EQUALS 2.54 MICROMETERS.
CODE NUMBERS ARE IDENTIFIED IN TABLE 5 IN THE MAIN BODY OF THIS REPORT.

Table A-3. Effect of Tool Wear on Burr Properties

SAMPLE NO.	TOTAL NO. HOLES	MATERIAL	DRILL	ENTRANCE BURR		EXIT BURR	
				HEIGHT	THICKNESS	HEIGHT	THICKNESS
4	51	1018	FOUR FACET	9	26	95	25
4	61	1018	FOUR FACET	28	8	102	18
4	69	1018	FOUR FACET	37	8	40	14
4	74	1018	FOUR FACET	29	7	88	19
4	84	1018	FOUR FACET	19	6	134	30
4	92	1018	FOUR FACET	29	9	94	16
5	97	1018	FOUR FACET	24	23	91	30
5	107	1018	FOUR FACET	8	16	127	25
5	115	1018	FOUR FACET	33	8	151	22
5	120	1018	FOUR FACET	40	12	114	32
5	130	1018	FOUR FACET	32	21	153	13
5	138	1018	FOUR FACET	26	18	142	19
6	143	1018	FOUR FACET	13	26	126	20
6	153	1018	FOUR FACET	39	14	158	12
6	161	1018	FOUR FACET	31	10	246	21
6	166	1018	FOUR FACET	43	9	85	18
6	176	1018	FOUR FACET	35	13	66	20
6	184	1018	FOUR FACET	35	13	71	24
7	51	1018	RADIAL LIP	35	21	149	21
7	61	1018	RADIAL LIP	29	9	51	14
7	69	1018	RADIAL LIP	23	16	25	22
7	74	1018	RADIAL LIP	58	18	43	21
7	84	1018	RADIAL LIP	57	9	26	13
7	92	1018	RADIAL LIP	31	9	94	29
8	97	1018	RADIAL LIP	42	16	153	15
8	107	1018	RADIAL LIP	44	27	28	34
8	115	1018	RADIAL LIP	41	16	49	15
8	120	1018	RADIAL LIP	41	14	109	20
8	130	1018	RADIAL LIP	74	15	55	32
8	138	1018	RADIAL LIP	43	20	42	17
9	143	1018	RADIAL LIP	55	19	20	13
9	153	1018	RADIAL LIP	63	15	69	11
9	161	1018	RADIAL LIP	34	11	59	23
9	166	1018	RADIAL LIP	79	21	396	24
9	176	1018	RADIAL LIP	36	18	27	11
9	184	1018	RADIAL LIP	62	20	19	17
14	51	6061	EIGHT FACET	9	16	11	17
14	61	6061	EIGHT FACET	26	18	44	20
14	69	6061	EIGHT FACET	29	4	8	102
14	74	6061	EIGHT FACET	27	10	34	8
14	84	6061	EIGHT FACET	35	7	36	5
14	92	6061	EIGHT FACET	15	7	57	17
16	143	6061	EIGHT FACET	17	12	76	12
16	153	6061	EIGHT FACET	40	25	26	15
16	161	6061	EIGHT FACET	53	16	24	14
16	166	6061	EIGHT FACET	8	11	28	13
16	176	6061	EIGHT FACET	8	13	7	10
16	184	6061	EIGHT FACET	19	19	17	21
15	97	6061	EIGHT FACET	26	9	19	13
15	107	6061	EIGHT FACET	9	25	14	7
15	115	6061	EIGHT FACET	12	12	43	14
15	120	6061	EIGHT FACET	30	18	24	12
15	130	6061	EIGHT FACET	12	11	20	8
15	138	6061	EIGHT FACET	30	3	26	17
17	51	6061	RADIAL LIP	15	19	12	13
17	61	6061	RADIAL LIP	14	16	37	10

Table A-3 Continued. Effect of Tool Wear on Burr Properties

17	69	6061	RADIAL LIP	24	14	23	14
17	74	6061	RADIAL LIP	9	24	24	18
17	84	6061	RADIAL LIP	15	13	20	13
17	92	6061	RADIAL LIP	34	4	14	16
18	97	6061	RADIAL LIP	29	8	84	16
18	107	6061	RADIAL LIP	29	10	26	15
18	115	6061	RADIAL LIP	35	7	61	7
18	120	6061	RADIAL LIP	42	6	30	14
18	130	6061	RADIAL LIP	49	8	10	7
18	138	6061	RADIAL LIP	34	7	32	14
24	51	303SE	FOUR FACET	142	16	516	22
24	61	303SE	FOUR FACET	45	8	202	28
24	69	303SE	FOUR FACET	32	14	170	32
24	74	303SE	FOUR FACET	168	15	205	23
24	84	303SE	FOUR FACET	52	12	83	30
24	92	303SE	FOUR FACET	9	15	158	37
25	97	303SE	FOUR FACET	24	28	54	24
25	107	303SE	FOUR FACET	25	15	472	24
25	115	303SE	FOUR FACET	8	15	251	31
25	120	303SE	FOUR FACET	16	19	573	51
25	130	303SE	FOUR FACET	19	31	188	33
25	138	303SE	FOUR FACET	11	22	269	37
26	143	303SE	FOUR FACET	32	20	516	50
26	153	303SE	FOUR FACET	54	16	507	78
27	51	303SE	RADIAL LIP	35	9	64	17
27	61	303SE	RADIAL LIP	19	13	56	21
27	69	303SE	RADIAL LIP	19	5	42	15
27	74	303SE	RADIAL LIP	28	8	117	8
27	84	303SE	RADIAL LIP	22	8	114	11
27	92	303SE	RADIAL LIP	37	4	80	47
28	97	303SE	RADIAL LIP	46	13	22	13
28	107	303SE	RADIAL LIP	69	8	27	15
28	115	303SE	RADIAL LIP	38	13	13	13
28	120	303SE	RADIAL LIP	32	11	13	15
28	130	303SE	RADIAL LIP	22	8	168	19
28	138	303SE	RADIAL LIP	21	18	27	12
29	143	303SE	RADIAL LIP	27	11	49	12
29	153	303SE	RADIAL LIP	24	11	25	11
29	161	303SE	RADIAL LIP	31	11	48	19
29	166	303SE	RADIAL LIP	12	26	27	20
29	176	303SE	RADIAL LIP	11	10	42	15
29	184	303SE	RADIAL LIP	19	11	37	19

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

Table A-4. Material Deflection Below Drill Point

Workpiece Material	Specimen Number	Feature* A (Inch)**	B (Inch)	C (Inch)	D (Inch)
303Se Stainless Steel	11	0.0405	0.0000	0.0165	
	12	0.0420	0.0046	0.0154	
	13	0.0262	0.0121	0.0090	
	14	0.0350	0.0105	0.0112	
	23	0.0204	0.0152	0.0059	
	24	0.0187	0.0210	0.0090	0.0038
	25	0.0102	0.0300	0.0075	0.0022
	26	0.0119	0.0255	0.0068	0.0026
1018 Steel	3	0.0492	0.0000	0.0161	
	4	0.0280	0.0143	0.0105	0.0059
	9	0.0412	0.0000	0.0122	
	10	0.0404	0.0034	0.0094	
	15	0.0333	0.0036	0.0068	
	16	0.0316	0.0108	0.0085	0.0054
	21	0.0316	0.0119	0.0088	0.0064
	22	0.0228	0.0105	0.0022	0.0014
	27	0.0096	0.0305	0.0068	0.0009
	28	0.0087	0.0298	0.0064	0.0019

Table A-4 Continued. Material Deflection Below Drill Point

		Feature*			
Workpiece Material	Specimen Number	A (Inch)**	B (Inch)	C (Inch)	D (Inch)
17-4PH Stainless Steel	35	0.0272	0.0072	0.0035	0.0015
	36	0.0288	0.0014	0.0039	0.0014
	37	0.0153	0.0072	0.0000	0.0009
	38	0.0145	0.0119	0.0000	0.0017
	39	0.0025	0.0122	0.0012	0.0012
	40	0.0102	0.0153	0.0000	0.0012
6061-T6 Aluminum	18	0.0322	0.0000	0.0051	
	19	0.0222	0.0000	0.0131	
	20	0.0222	0.0000	0.0048	
	29	0.0102	0.0031	0.0136	
	30	0.0102	0.0043	0.0017	

*See Figure 33 of this report for definition of Features A, B, C, and D.
**0.0001 inch = 2.54 μm.

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