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BURRS PRODUCED BY DRILLING

PDO 6984405, Topical Report

L. K. Gillespie, Project Leader

Project Team:
R. K. Albright
B. J. Neal

Published August 1976

Prepared for the United States Energy Research and Development Administration Under Contract Number E(29-1)-613 USERDA

Bendix Kansas City Division

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

The reliability of small precision mechanisms greatly depends upon the production of burr-free, sharp-edged parts. An investigation was conducted to determine the influence of variables in controlling the size and repeatability of drilling burrs to minimize burr-removal costs and improve part quality. Entrance burrs are typically triangular in cross section with length equal to thickness; exit burrs are rectangular with length from two to ten times the thickness. For stainless steel, exit-burr thickness and length are proportional; no similar relationship was found for other materials. Burr size is best minimized by use of a backup material having a hole the same diameter as that of the drill. For some materials, decreasing the feedrate also decreases the exit-burr length.

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SUMMARY

Component parts of small precision mechanisms typically require nearly sharp edges to assure reliable operation. A burr-free condition also is needed to minimize a possible jamming of the mechanism because of burrs breaking loose. 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 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 and 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.

Increasing the feedrate resulted in longer exit burrs from 303Se stainless steel and 1018 steel. Drill geometry, workpiece material, and workpiece thickness also affected the exit-burr length. Radial-lip drills produced shorter exit burrs at fast feedrates in 303Se stainless steel than did the other drills, and they produced thinner exit burrs at all feedrates. Little difference was observed in the results from different drill points used in other materials. Beryllium-copper-style drill points should not be used in steel or aluminum because of the large burrs they produce. The 17-4PH stainless-steel specimens had smaller burrs than did the other materials, apparently the direct result of the lower ultimate elongation of 17-4PH stainless steel.

Burr size varied with the number of holes drilled in a typical wear-life pattern. Exit-burr thickness was a linear function of exit-burr length for the stainless steel specimens. No relationship between these properties was observed for either 1018 steel or 6061-T6 aluminum.

Under proper machining conditions, reaming after drilling resulted in smaller burrs than those produced by drilling alone.

The use of a backup material having a hole equal in diameter to that of the drill resulted in significantly shorter and thinner exit burrs than did any other drilling method studied. The use of a hard (R_C 42), solid backup material was the second most effective technique for minimizing burr size. Previously published reports indicate that burr sizes are also functions of coolant, helix angle, and drill diameter.

The information obtained in this study will be combined with the information from similar tests of other machining operations to determine optimum machining conditions for minimizing deburring and total fabrication costs.

DISCUSSION

SCOPE AND PURPOSE

This study was initiated to determine the influence of conventional drilling practices upon burr size. Specifically, the study sought to determine how drill-point geometry, feedrate, workpiece material, workpiece thickness, and the use of a backup material affect burr thickness and length.

PRIOR WORK

Earlier Bendix studies provided some background data for this investigation. In a preliminary study, typical burr lengths, thicknesses, and hardness values were evaluated for two drill geometries in three materials.[1] A subsequent study evaluated the effects of helix angle, drill-point angle, and feedrate in 303Se stainless steel.[2] The effects of reaming and ball-broaching parameters on burr properties also have been studied.[3,4]

In related investigations, grinding and milling burrs were analyzed,[2] and a general theory of burr formation was developed.[2,5,6] Some experimental work has been reported by other agencies on drilling burrs,[7-11] punching burrs,[12-18] and EDM burrs.[19]

ACTIVITY

All conventional machining operations produce burrs. The size of the burrs depends upon the tool geometry used, the cutting speed, the feedrate, and the properties of the workpiece material. The cost of removing the burrs is proportional to the burr size. For miniature precision parts, because of close tolerances, small part size, and large burr size, the burr-removal costs often approach the cost of machining the parts.

To minimize these fabrication costs, the influence of machining conditions on burr size and the effect of burr size on cost must be analyzed. A series of tests therefore were initiated to provide data on burr properties as a function of machining conditions. These tests will include most of the common machining operations.

The first of the studies was concerned with drilling and was composed of four distinct tests. In the initial test, four drill-point geometries were evaluated in four workpiece materials, using two feedrates and two workpiece thicknesses. The second study consisted of a drill-life evaluation of three drill geometries in four materials; burr properties were measured at various times during the life of the drill. In the third study, burr properties produced by drilling were compared to those produced by drilling, then reaming. The final test was an evaluation of the effectiveness of backup material in preventing burrs. A detailed explanation of how burrs form in drilling operations also was developed in order to better understand the implications of the test results.

The size of burrs produced by drilling are determined by three principal factors:

- Plasticity of the workpiece;
- Drill-corner sharpness; and
- Amount of built-up-edge (BUE) on the drill lips.

Material which cannot plastically deform, such as cast iron, ceramics, and graphite, cannot form burrs. Throughout this report, material elongation at the ultimate load will be used to indicate the plasticity of a material.

Drill-corner sharpness determines how much of the burr material remains attached to the workpiece. While a long burr may form as a result of chisel-edge pressure and workpiece elongation, sharp drill corners will either cut the burr free or produce a very thin burr which is easily removable.

When built-up-edge (BUE) occurs on the drill, the burrs become larger and the repeatability of the burr properties becomes worse.

The results of the initial test indicate that the thickness of the burr on the exit-side of the hole is affected by the drill geometry. The length of the burr is a function of the workpiece properties and the feedrate. (The length is also proportional to the drill diameter; however, that relationship was not studied in this test.)

In the drill-life tests, a typical wear-life curve was observed for the drills in which drill breakage occurred. The materials which elongate the easiest and which also frequently exhibit BUE showed the largest variation in burr properties.

Attempts to correlate burr thickness to burr length were reasonably successful for exit burrs when stainless steel was used. No linear relationship could be found between burr properties for either aluminum or 1018 steel. The implication that long burrs do not necessarily indicate thick burrs in the latter two materials is not necessarily true, since only linear fits were tried and the true relationship is probably considerably more complex.

Reaming a drilled hole with a conventional chamfered reamer does not necessarily result in smaller burrs. For the conditions studied, there was little significant difference between either burr length or thickness when stainless steel was used, although a notable improvement occurred when 1018 steel was reamed. Previous tests, however, indicate that certain combinations of machining conditions and workpiece properties will produce reaming burrs which are smaller than drilling burrs. The use of radial-lip reamers should result in smaller burrs being produced.

Exit-burr thickness and length can be minimized by using a supporting material beneath the hole. Burr length and thickness decrease considerably as the hardness of the backup material is increased.

The most effective approach for minimizing the size of exit burrs appears to be the use of a backup material having a hole in it. If the hole is in line with the hole to be drilled and is not more than 0.0005 to 0.0010 inch (12.7 to 25.4 μm) larger than the drill, the burr length and thickness will be limited to approximately 0.0003 inch (8 μm), or less. If the backup material is made from the same material as the workpiece, no significant change in drill-life will occur.

<u>Drilling-Burr Formation</u>

Drilling burrs form from a combination of lateral extrusion (the Poisson effect), bending, and tearing. The burr that is formed at the entrance of a hole can be either the result of a bending action followed by clean shearing, or the result of a Poisson action in which material flows normal to the direction of the applied forces.

The burr that is formed as the drill breaks through the bottom of the workpiece begins as a bending of the material away from the path of the drill. Eventually, radial tears develop in the bending material and extend to the edge of the hole. The root of the burr then is formed by the drill corners as they further push or bend the material out of the way.

Although the concepts of extrusion, bending, and tearing adequately portray the visible effects of burr formation, the forces, stresses, and movements involved are much more complex and difficult to describe. The drilling forces actually set up a three-dimensional stress field in which the stresses are a function of the distance from the cutting-edge, the properties of the workpiece, and the location of the nearest free surface.

Entrance Burrs

The entrance burr is formed by the corners of the drill as they enter the workpiece (Point A in Figure 1). As the drill lips

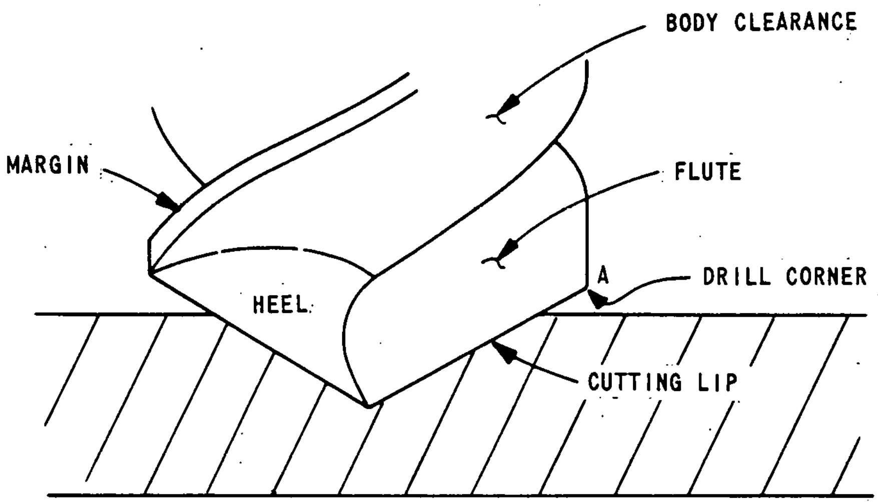

Figure 1. Definition of Drill Features

advance into the workpiece, a small mound of material may form at the point where the drill lips meet the top surface of the workpiece (Figure 2). This small mound of material is a result of lateral extrusion (the Poisson effect). When the lips are sharp, the bulge should be almost immeasurable. As the lips become dull, a more pronounced bulge is formed. The formation of the bulge is a continuous process, but not until the drill corners enter the workpiece does the bulge contribute to the burr remaining on the part.

When the corners of the drill enter the workpiece, they take a gradually increasing depth-of-cut for the first one-half revolution (Figure 3). As shown in a side view of the corner (Figure 4), the cutting force F lifts the material upward. In the forming and lifting of the chip, the material reacts two ways. Initially, the force pushes the top-surface material upward to cause a small bulge which extends radially a short distance away from the hole (Figure 5). The leading edge of the drill margin then shears the bulge. This produces a relatively short burr having no ragged edges. Since the depth-of-cut is constantly changing during the first one-half revolution, the force at the corner and the height of the bulge also vary around the circumference of the hole.

Worn or chipped drill corners (Figure 6) dramatically increase the effective rake angle of the lips at the corner. This, in turn, increases the cutting force at the corner and results in much greater local deformation and therefore a noticeably larger burr.

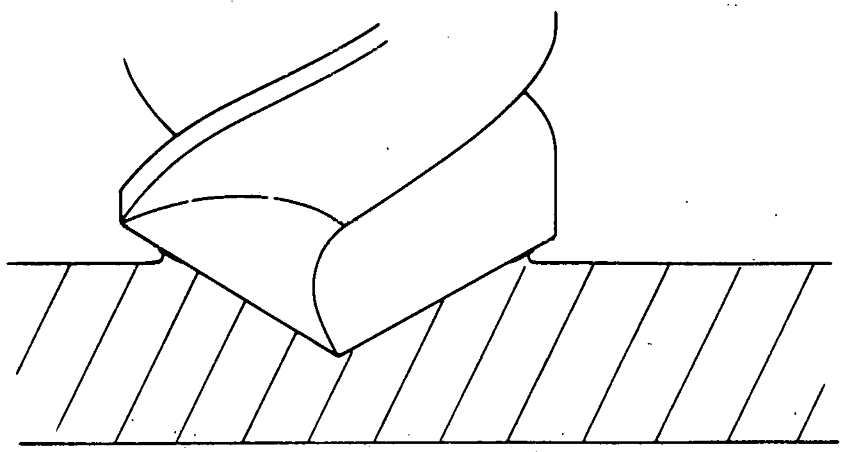

Figure 2. Small Bulge Formed on Top Workpiece Surface by Drill Lips

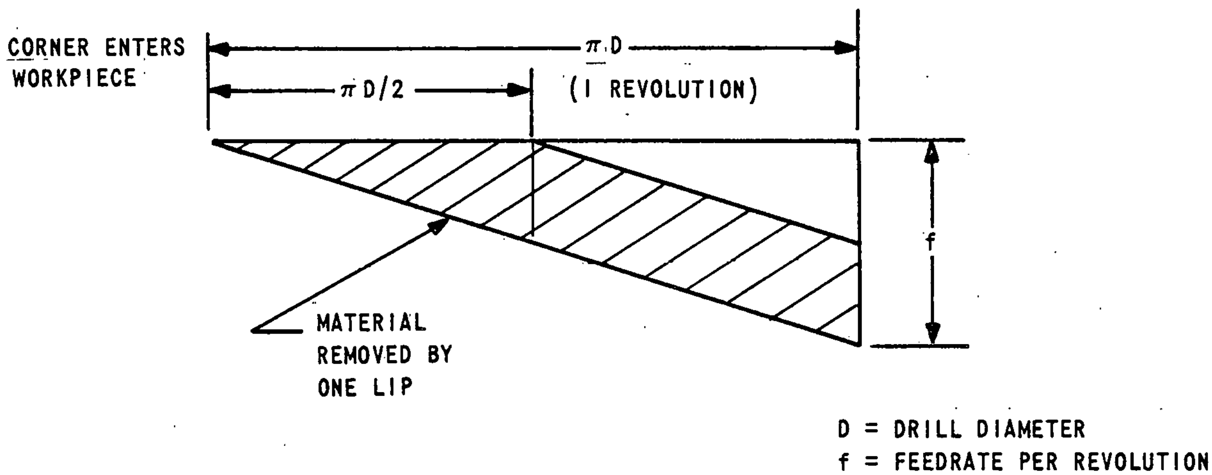

Figure 3. Depth-Of-Cut Taken by Drill Lips

The worn corners of the drill act essentially as a blunt indenter which tends to push the metal rather than cut it. The net result can be better visualized by assuming that the worn corners are hemispherical rather than flat. As shown in Figure 7, a sphere which indents the workpiece near free edges causes a flow of material toward all free edges. This flow of material produces the burr. If the cutting lips of the drill also are dull, some of the material will be extruded laterally along the lips, as previously described. This condition further accentuates the formation of the bulge at the edge of the hole.

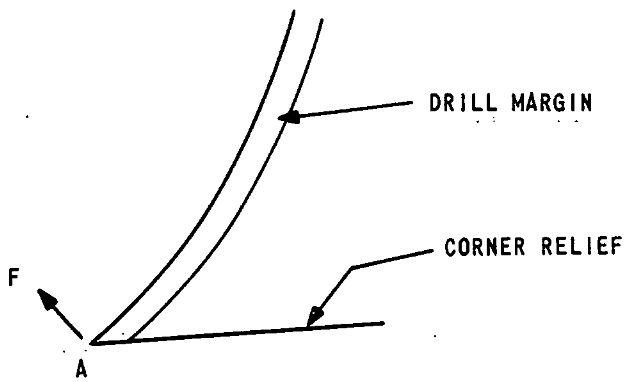

Figure 4. Drill Margin and Typical Cutting Force

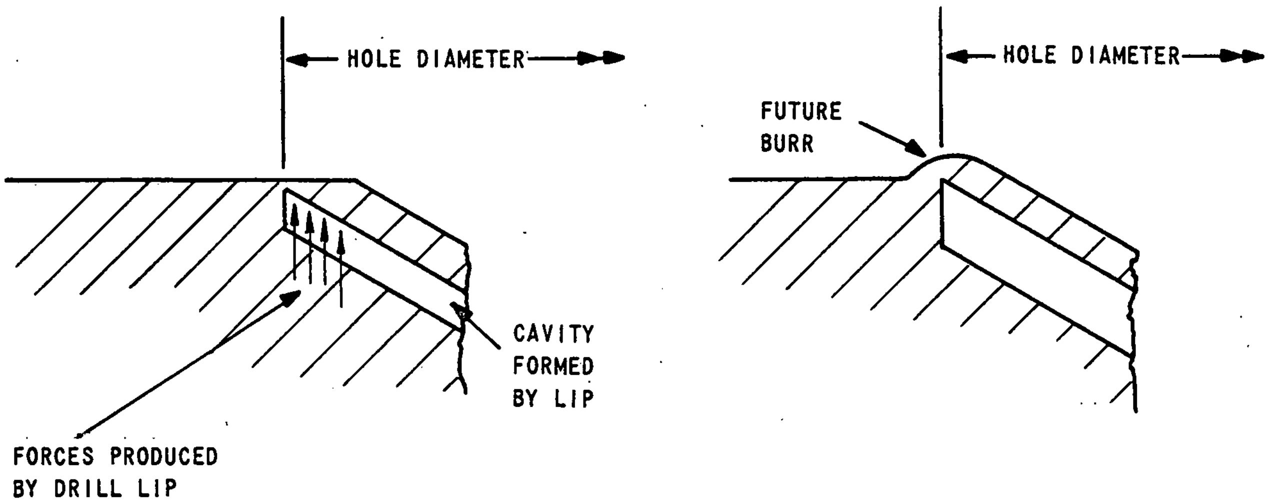

Figure 5. Formation of Entrance Burr, Initially (Left) and After Some Material Movement (Right)

Exit Burrs

A brief mention of two drilling forces is in order before describing the formation of the exit burr. First, the chisel-edge of most drills contributes nothing to the cutting action of the drill. All of the thrust exerted by the center of the drill, representing approximately half of the total drill thrust, is essentially wasted. As an example, other investigators have reported that this force represents 53 percent of the total thrust for a drill having a chisel-edge length-to-diameter ratio of 0.180:1, and 63 percent of the total thrust for a drill having a chisel-edge length-to-diameter ratio of 0.240:1.[20]

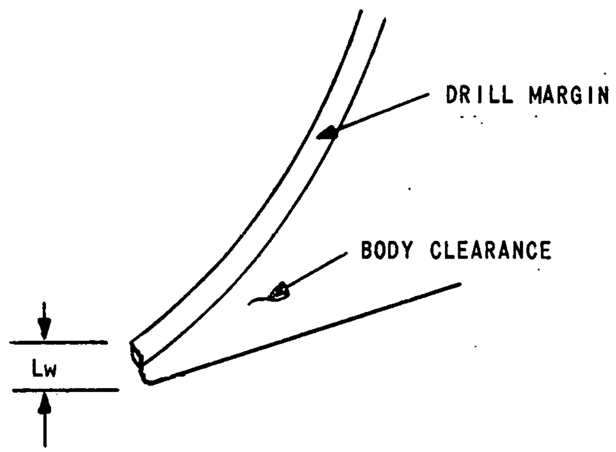

Figure 6. Simplified Illustration of Drill-Corner Wear

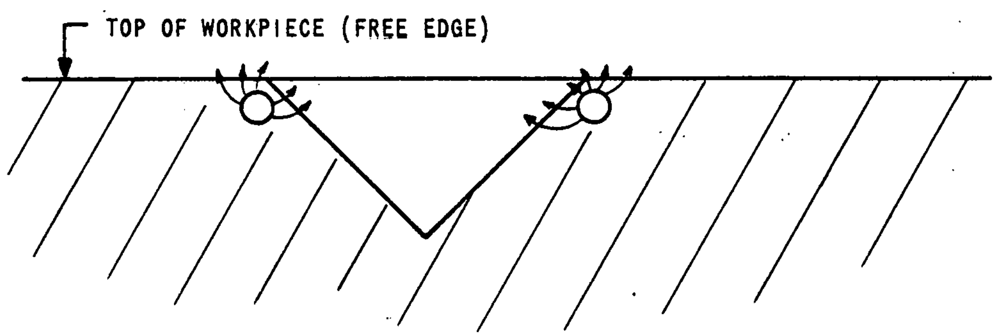

Figure 7. Material Flow Paths Produced by Spheres Indenting the Midplane of a Workpiece

Second, only a small portion of the bottom of the drill pushes against the material below it. Indentation tests have indicated that this zone of contact extends for a radius of only L/2, where L is the chisel-edge length (Figure 8).[21] Of course, the cutting lips also contact the bottom, but this contact involves only a narrow band along each lip.

Exit burrs can be described as being basically long and ragged or short and uniform. Although other subcategories can be listed, these two divisions are adequate at this point. Both categories of exit burrs begin in the same manner. As the drill-point nears the bottom of the workpiece, it begins to push metal ahead of it (Figure 9). A bulge begins to develop on the bottom surface of the workpiece and continues to enlarge until the

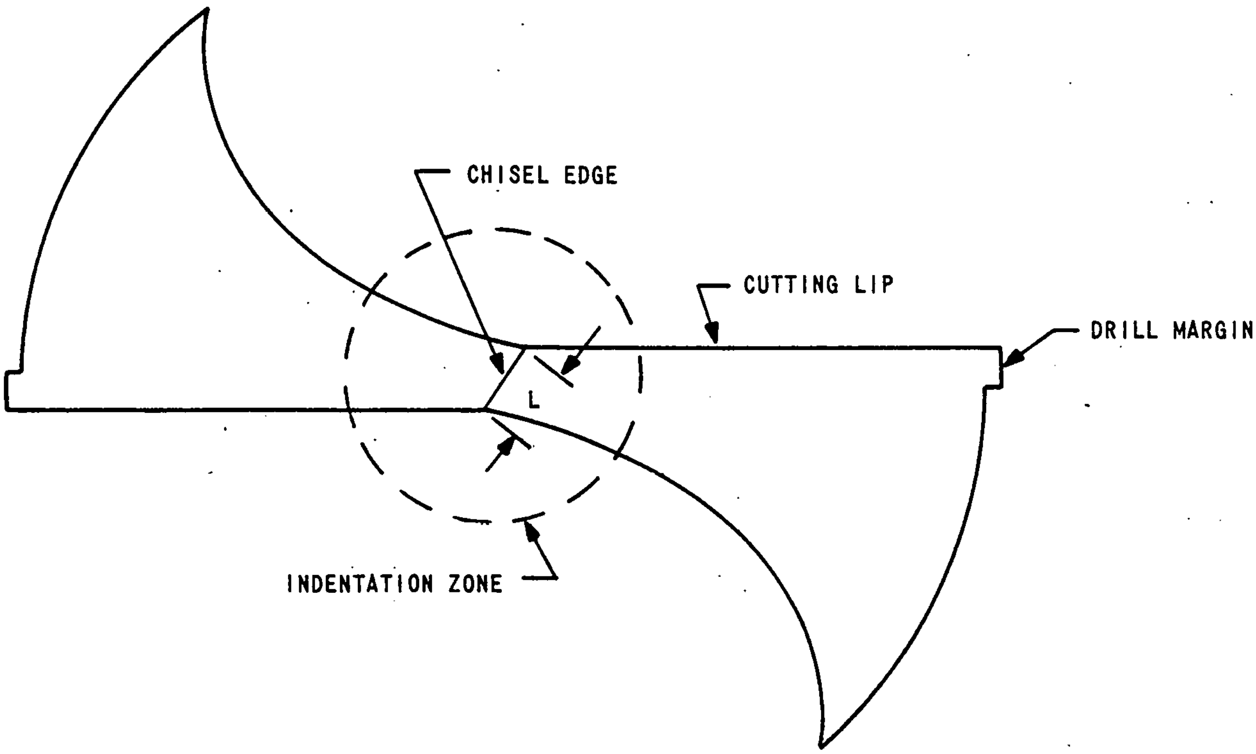

Figure 8. Zone of Contact Between Drill-Point Surfaces and Workpiece

material beneath the point has stretched to its maximum possible elongation. At that stage, the drill point breaks through the bottom surface of the workpiece. Radial tears begin to develop and, as the drill continues to advance, some of the long pie-shaped pieces of metal bend into the flutes and are cut off while others bend away from the flutes and remain attached to the workpiece as burrs (Figure 10).

The deciding factor in determining whether a burr will be long and ragged or short and uniform appears to be the ability of the workpiece to stretch. The percent elongation of a material in a normal tensile test therefore should serve as an index to predicting which materials might form long burrs. Strain-hardening also plays a significant role with some metals.

Not all ductile materials will form a ragged burr. With materials such as 1018 steel and some titanium alloys, the drill point never breaks through the material ahead of it. As a result, drilling produces a conical cap of metal which is pushed to one side or dislodged entirely from the workpiece as the drill emerges from the bottom of the hole (Figure 11). Haggerty's spiral-point sheet-metal

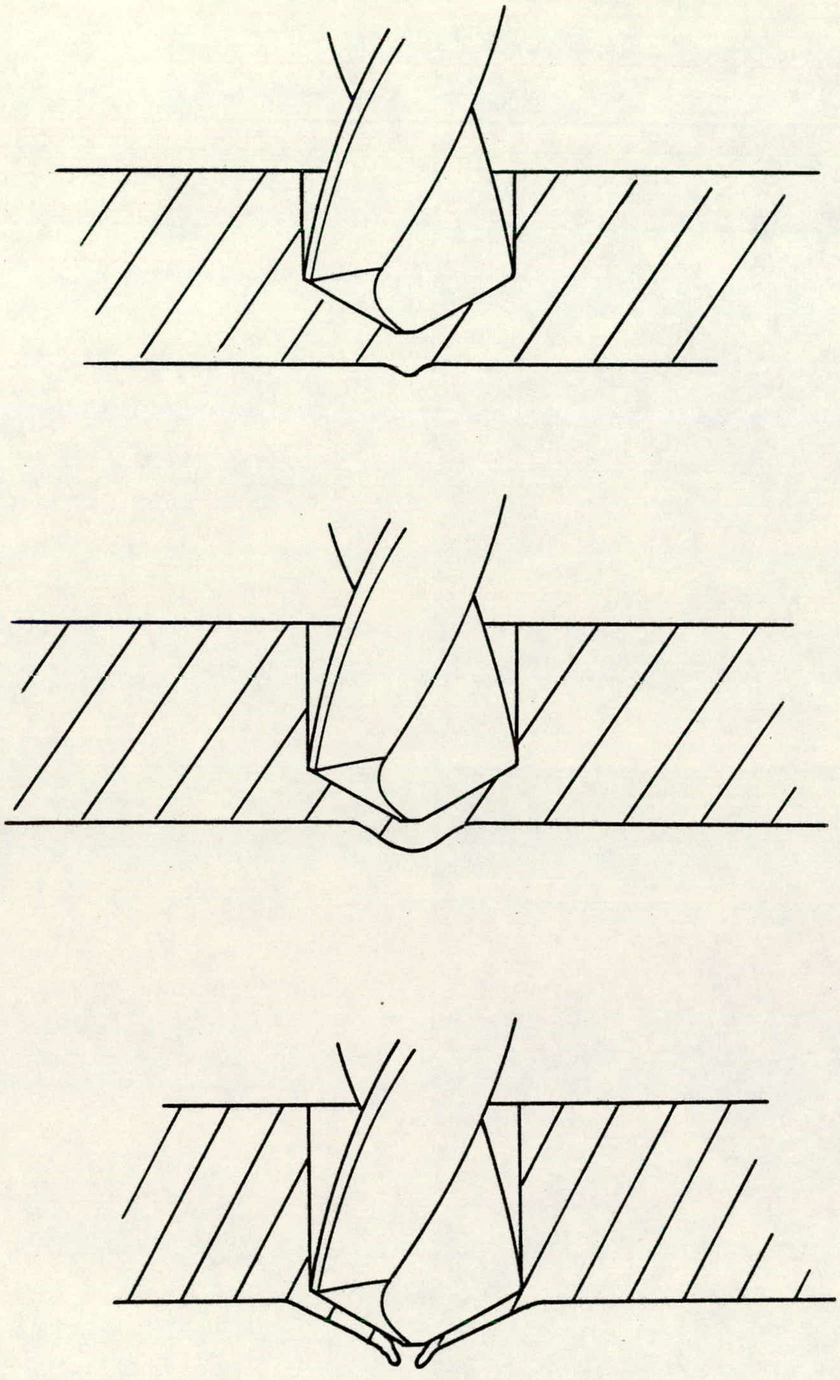

Figure 9. Three Stages of Exit-Burr Formation

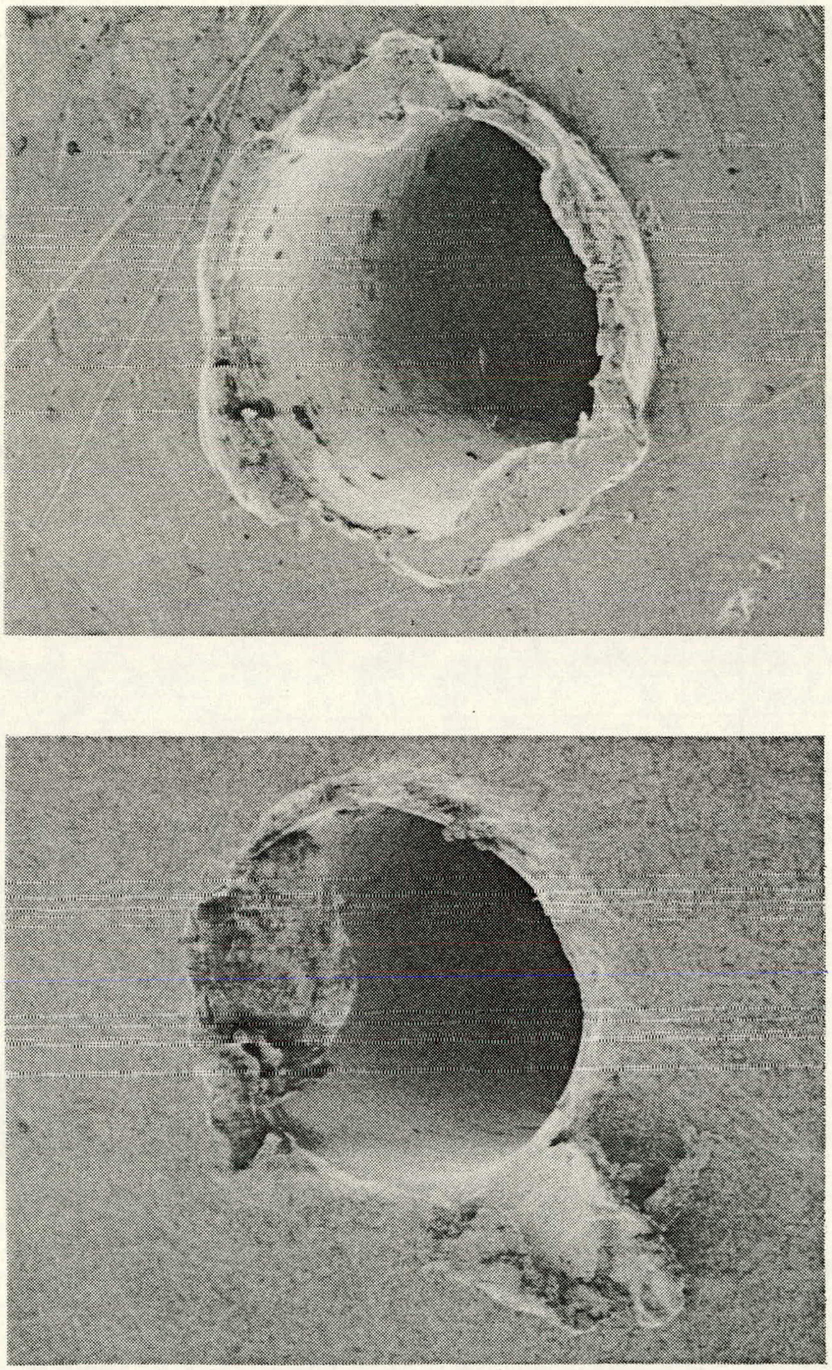

Figure 10. SEM Photographs of Drill-Exit Burrs: Aluminum (Top) and Brass (Bottom) (Magnification 100X)

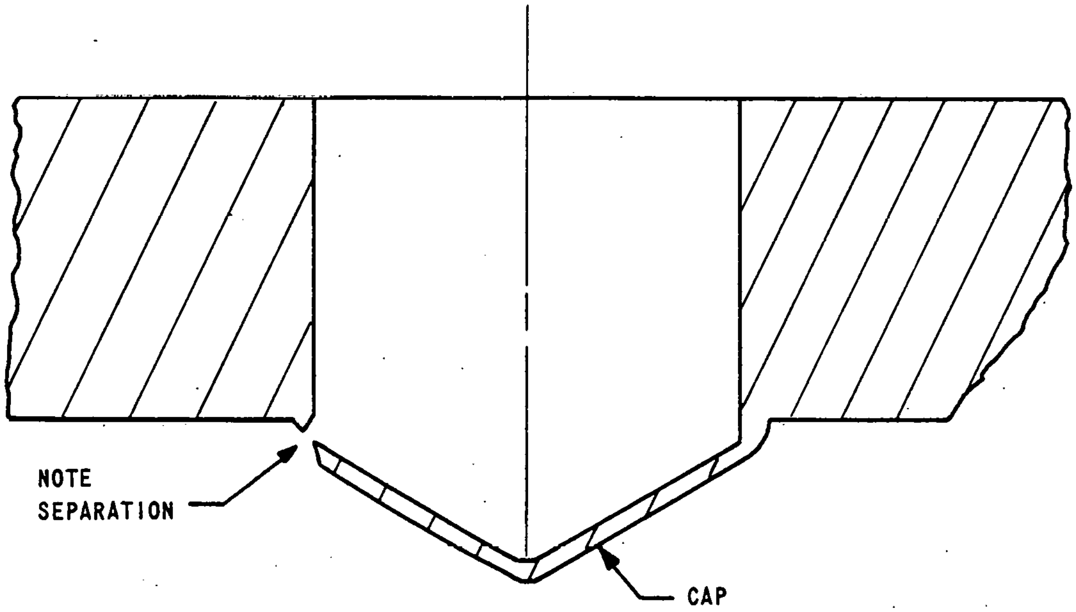

Figure 11. Metal Cap Formed at Drill Exit

drill,[22] for example, typically produces this cap of material. In this situation, drill geometry and workpiece strain-hardening appear to offset some of the problems associated with materials having high ultimate elongations.

In many cases, one hole on a workpiece will have a long, ragged burr while the next hole will have only a cap and a very short burr. This condition apparently is the result of the material being heterogeneous or of some fluctuation in the cutting process (such as a BUE). In either case, the long, ragged burr probably will become more prominent with additional drill wear.

Assuming that the workpiece material is easily stretched, the material below the drill point can only stretch or tear since the point cannot cut. If the force at the point causes the material beneath it to stretch, the material adjacent to the point also will stretch (Figure 12). This prevents the drill lips from cutting beneath the cap except at a distance from the point where the drill-point force is somewhat dissipated. Since the chisel edge comprises approximately 20 percent of the drill diameter, the assumption that its sphere of influence extends outward to at least 33 percent of the drill diameter seems reasonable. Thus if the lips do cut through the cap, they would tend to do so at a distance of D/3 from the hole wall.

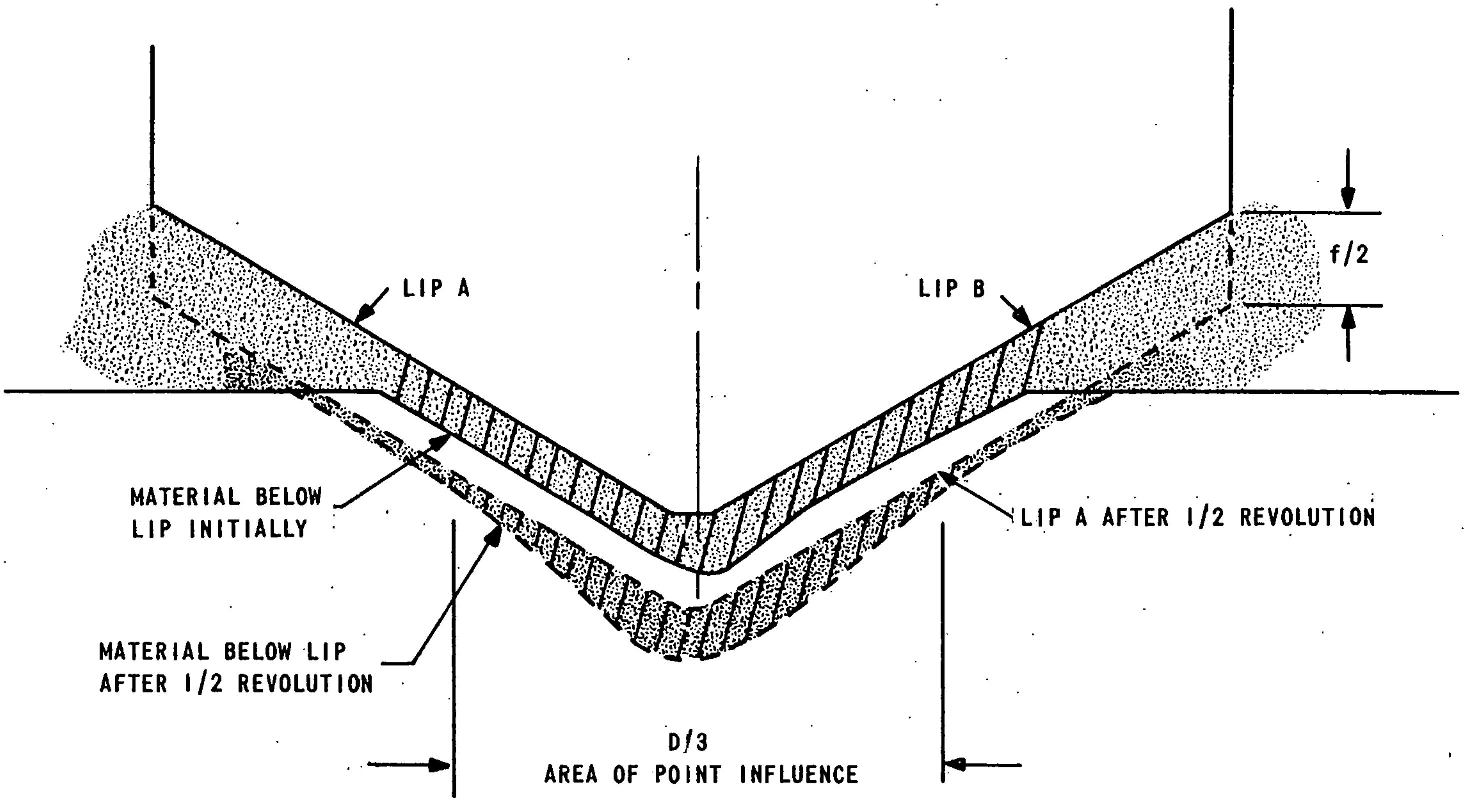

Figure 12. Elongation of Material Beneath Drill Point

The location of the drill break-through will vary with different workpiece materials and cutting forces. Once one of the lips breaks through the workpiece, the cap of material will be either torn off by one of the flutes or bent out of the path of the drill. The sharpness of the drill lips plays a major role in determining whether the drill will cut through the cap. With materials which form a BUE easily, even sharp drills can produce a full-diameter cap. Aluminum, for example, has an affinity for high-speed steel which causes a BUE to form easily. The BUEs were observed on half the drills that were used in the studies described later in this report.

One point often missed in discussing drilling burrs is that the length of the exit burr cannot be appreciably greater than one-half the diameter of the hole. If the material stretches considerably, the burrs might be 20 percent longer than this value; any particle longer than this is not representative of the mechanism producing the burr. If a ring of material forms around the hole exit with all but one end broken free of the hole, the burr length may appear to be equal to the circumference of the hole. However, the use of this value will mask the true mechanism of burr formation and will result in inconsistent data.

Table 1 lists representative elongation and strain-hardening data. As shown, 303Se stainless steel and titanium have the higher elongation values; low-carbon steel and brass have slightly lower elongations. From the preceding discussion, these materials would be expected to form long burrs or caps. This, in fact, is the case, as will be described later in this report.

Materials having elongations less than 30 to 40 percent have typical burrs less than one-half the hole diameter. However, the inference should not be made that burr length is proportional to elongation; more probably, long burrs cannot form with an elongation below a certain threshold. The higher the elongation value above this critical value, the higher the probability that a long burr will form.

While the elongation of the material serves as the primary indicator of exit-burr length, the cutting action at the corners of the drill determines what the burr length and thickness will be. Although a long burr will not form from a material which will not stretch, the fact that the material will stretch does not guarantee that a long burr will be produced. The sharpness and design of the drill corner dictate the burr size.

Assuming that the workpiece has little ability to stretch and that the drill corner is within one-half revolution of breaking through, a small triangular ring of material remains to be removed (Figure 13). The size of the ring varies around the diameter of

Table 1. Elongation and Strain-Hardening Data for Selected Materials[23-28]

Material	Ultimate Elongation (Percent)	True Strain at Failure E_f (in./in.)*	Strain-Hardening Data: Coefficient (psi) (N/m^2)	Exponent (n)	Hardness (BHN)
303 and 303Se SST					
Fully Annealed	60		185,000 (1.276×10^9)	0.45	160
Cold Drawn Bar	40	1.16	205,000 (1.413×10^9)	0.51	228
Cold Drawn to 60 Percent RA	10				425
Titanium (99 Percent Ti) Annealed	47				
1020 Steel Annealed	30-40	1.05	77,000 (0.53×10^9)	0.26	
17-4PH SST					
H900	14	0.65	328,000 (2.261×10^9)	0.22	420
H1100	17	0.65	260,000 (1.793×10^9)	0.01	332
416 SST Tempered and Cold Drawn	15				215
4340 Steel Drawn 400°F (204.4°C)					
Cast Iron	0				
Tobin Brass Rolled	40				

Table 1 Continued. Elongation and Strain-Hardening Data for Selected Materials[23-28]

Material	Ultimate Elongation (Percent)	True Strain at Failure E_f (in./in.)*	Strain-Hardening Data Coefficient (psi) (N/m^2)	Exponent (n)	Hardness (BHN)
6061-T6 Aluminum	17		60,000 (0.414 x 10^9)	0.05	
7075 Aluminum	8				
Beryllium Copper Half Hard	5				

*1.00 inch = 25.40 mm.

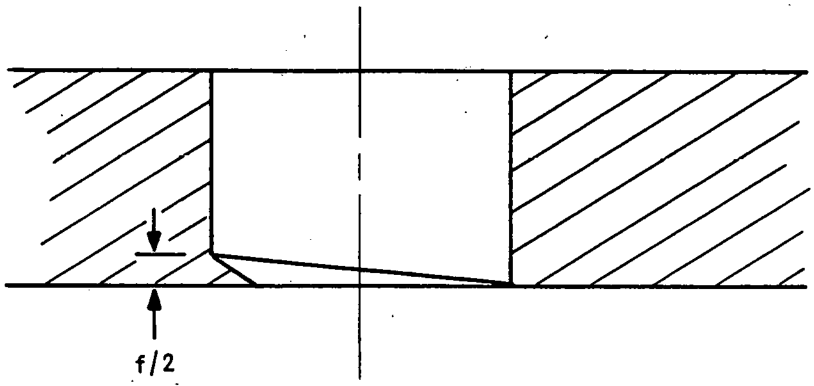

Figure 13. Material Remaining in Hole When Drill Corner Exits From Workpiece

the hole so that in one-half revolution, no stock remains. In this condition, the corners of the drill are at the very bottom of and completely through the hole (Figure 14). The only way that the remaining material can be removed is for the drill margins to shear it. With a sharp tool, the shearing force created by the leading edge of the margin will have an upward direction (Figure 15). In this situation, a burr can be formed only by a lateral extrusion of the metal (Path b in Figure 15). With a sharp leading-edge and proper clearances, a noticeable burr (greater than 0.0005 inch or 12.7 μm) cannot be produced by lateral extrusion.

If, however, the drill is worn at the corners, it may have a downward cutting-force component which will push down on the material; even the horizontal component of force will cause metal to flow downward because the material is pushed rather than cut (Figure 16). This latter force is predominant in determining the exit-burr size.

The plastic flow produced by a worn drill corner determines the thickness of the exit burr. This same plastic flow is the secondary factor that determines whether a stretchy material will produce a long burr. If there is no plastic flow (i.e. the drill corners are sharp), the long wedges of material shown in Figure 13 will be clipped off as the drill corners exit from the part. Dull corners push material out of the way. They, in essence, are pushing the root of the burr to one side rather than shearing it.

Because feedrates vary from 0.001 to 0.020 inch per revolution (25.4 to 508 μm/rev), a wear land (f/2) at the drill corners of only 0.0005 to 0.010 inch (12.7 to 254 μm) will cause movement

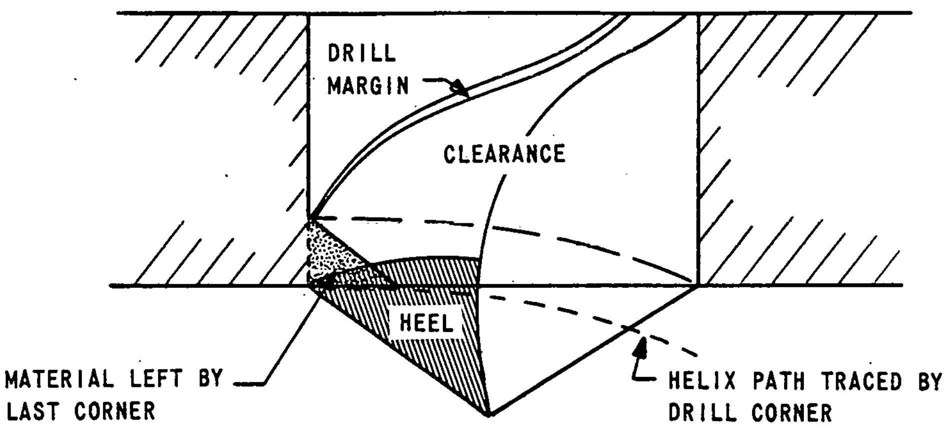

Figure 14. Drill Corners at Hole Exit

rather than cutting of the metal (Figure 17). It is relatively easy to see that a drill having dull corners would begin forming the exit burr approximately one-half revolution before the condition shown in Figure 13. In that case, the large burr would occur on the right side of the hole shown and, depending upon the size of the corner wear land, the material shown on the left side of Figure 13 probably would be sheared off by the margin (Figure 17). As in the case of the entrance burr, both the burr length and thickness would vary around the diameter of the hole.

Changes in Material Hardness and Structure

For most materials, any deformation produces an increase in hardness. As a result, the hardness of most burrs is greater than that of the workpiece. The theory for explaining this phenomenon and the equations for predicting the burr hardness have previously been described.[2,5] A typical average hardness change for 6061-T6 aluminum is from Brinnell 125 to Brinnell 150. For brass, a slightly smaller change occurs. For 303Se stainless steel, the burr is typically Rockwell C30, while the parent material is Rockwell C24.

With some materials, a change in grain structure also accompanies the machining operation. In 303Se stainless steel, for example, the material changes from austenitic to martensitic during cold-working. Structural changes such as these facilitate the removal of some burrs; however, not enough change occurs in most materials, including 303Se stainless steel, to have a noticeable effect on burr removal. Figures 18 and 19 show the severe deformation that occurs as the drill exits from the workpiece. The thin flanges of material shown in those photographs are cross sections of drill-exit burrs.

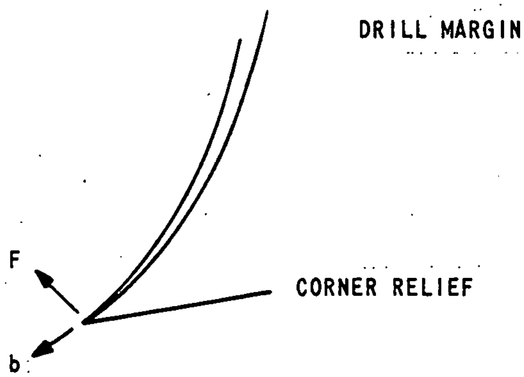

Figure 15. Typical Cutting Force of Drill Margin

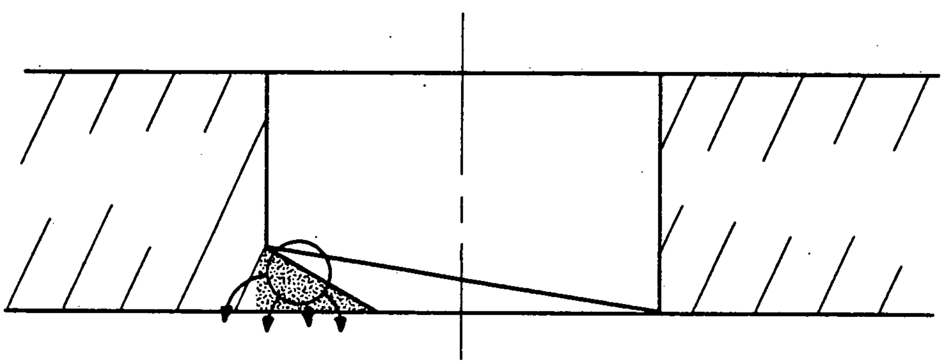

Figure 16. Material Flow Paths Produced by Hemisphere Indenting a Ring of Material

Effect of Feedrate, Workpiece Thickness, and Drill Geometry

The initial study in this investigation was designed to determine how drilling feedrate, workpiece thickness, and drill geometry affect burr properties. Sixty-four drilling combinations were studied. Workpiece materials included 303Se stainless steel (cold drawn), 17-4PH stainless steel (H900), 6061-T6 aluminum, and 1018 steel; test specimens were either 0.032 or 0.188 inch (0.81 or 4.77 mm) in thickness. The four drill geometries studied included 1/8-inch-diameter (3.17 mm) eight-facet, four-facet, radial-lip, and BT drills (Figure 20). Feedrates of 0.0005 and 0.0015 ipr (12.7 and 38.1 μm/rev) were used.

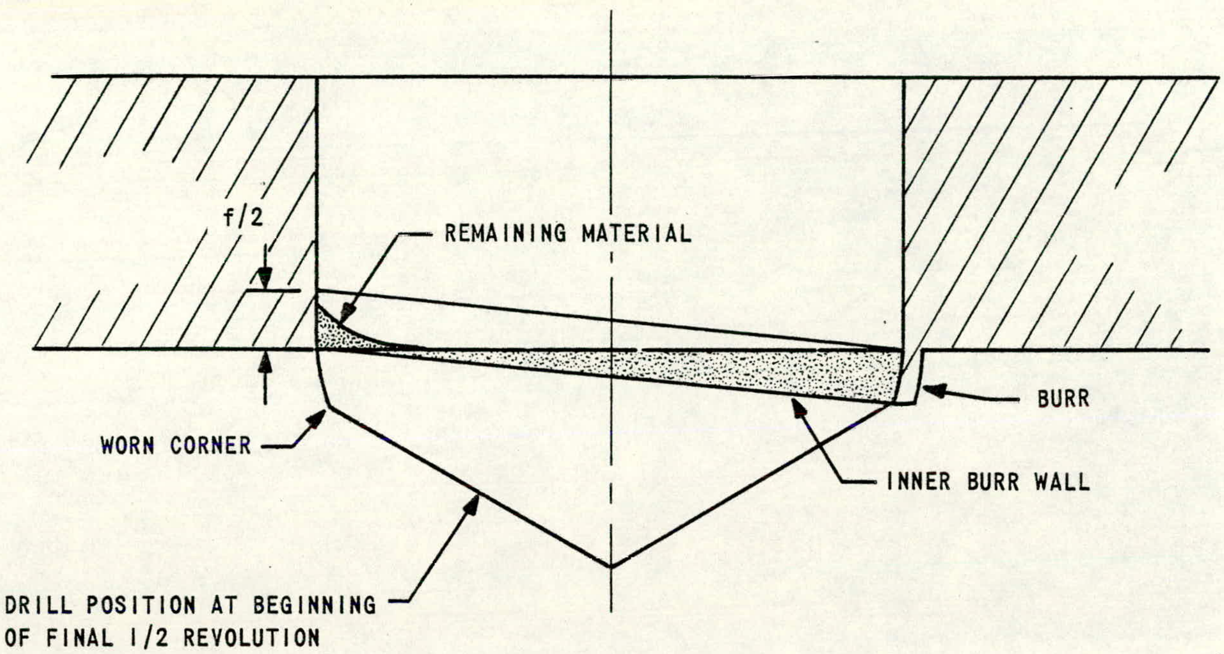

Figure 17. Material Left in Hole and Burr Produced When Worn Corner Exits From Workpiece

An analysis of variance (ANOVA) indicated that the BT drill consistently produced much larger burrs (up to ten times larger) than the conventional drills. Because the primary intent of the study was to define conditions which produce small burrs, the data for the BT drill was excluded from subsequent analyses. Test data and codes are presented in Table A-1 through A-4 of the Appendix. Since the 17-4PH stainless-steel samples were drilled at a slower spindle speed than the other specimens, the data had to be analyzed as two tests in order to be mathematically correct.

All specimens were drilled on a Hardinge chucker lathe using power feed. The spindle speed was 3000 rpm for all materials except 17-4PH stainless steel which was drilled at 750 rpm. A different spindle speed was used for 17-4PH stainless steel since any speed above 750 rpm immediately causes the drill to soften and seize.

Holes were drilled through all specimens using a water-soluble coolant. Each drill used was conditioned by drilling four holes through 0.188-inch-thick (4.77 mm) 303Se stainless steel before testing began. The collet which held the workpieces had a 0.135-inch-clearance (3.43 mm) hole so that no material supported the drill as it exited from the workpiece. The drills were HSS (Cleveland #967) with the exception of the solid carbide beryllium-copper point (BT) tools. One hole was produced for each of the 64 combinations studied.

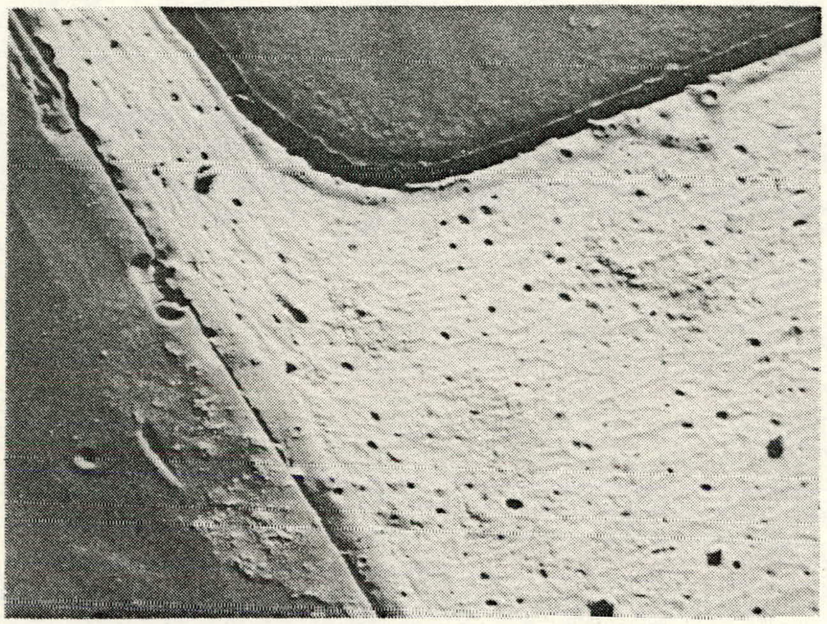

Figure 18. Workpiece Grain-Flow Lines and Burr in Drilled 6061-T6 Aluminum (Magnification 150X)

Figure 19. Workpiece Grain Structure and Burr in Alloy 6 Brass (Magnification 150X)

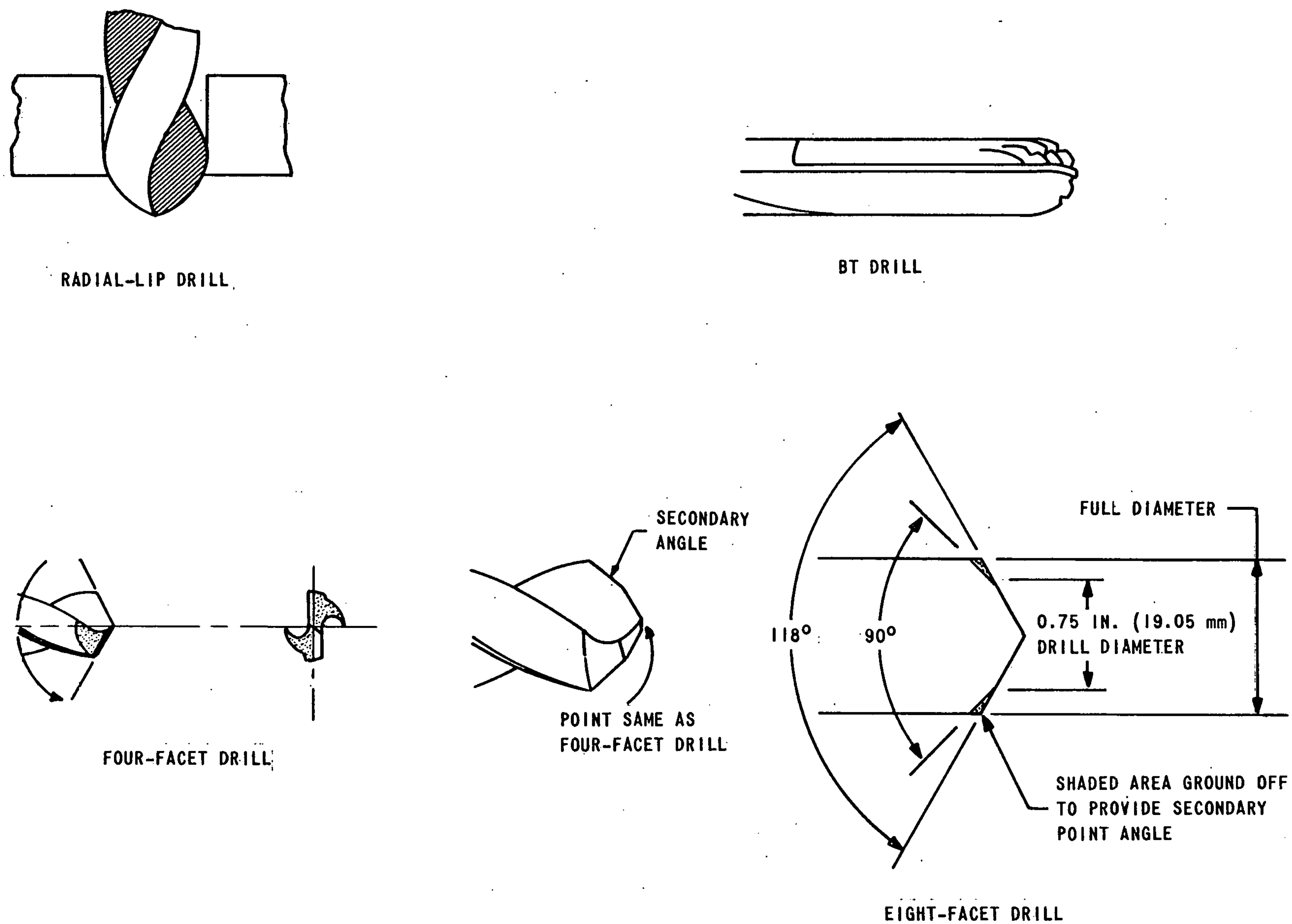

Figure 20. Geometry of Drills Studied

The four-facet point drill is essentially a standard chisel-edge drill which has been ground to produce a true point at the center. The eight-facet drill is a four-facet drill with the corners ground to provide a more gentle introduction of the drill corner into the workpiece. The radial-lip drill has a smooth radius which connects the drill lips to the margin, thus eliminating the drill corner and theoretically minimizing the drill-exit burr. The BT drill was included in this study since it also eliminates the drill corner.

In general, the results of this test varied with the workpiece materials; five results, however, were independent of the material (Table 2). The thickness and length of the entrance burrs were influenced by the thickness of the workpiece; thicker and longer entrance burrs occurred on the thin workpieces. On the thick specimens, the radial-lip drill produced the thinnest entrance burr (Figure 21).

Exit-burr lengths were a function of drill geometry, workpiece thickness, and feedrate. Contrary to expectation, the radial-lip drills produced the longest burrs, while the four-facet drills produced the shortest; however, except for 1018 steel and 303Se stainless steel, the differences were small. Higher feedrates resulted in longer burrs. Except for specific materials, exit-burr thickness was unaffected by any of the variables.

For 303Se stainless steel, the radial-lip drill produced a much thinner and shorter entrance burr than did the other drills (Figures 22 and 23). In general, the feedrate did not affect the length of the entrance burrs (Figure 24). Increasing the feedrate by 0.001 ipr (25.4 μm/rev) doubled the thickness of the exit burr (Figure 25). The radial-lip drill produced slightly thinner exit burrs than did the other drills. The exit-burr length also increased with the feedrate (Figure 26); in this instance, however, the radial-lip drill appeared to produce a smaller burr at the higher feedrate. While this is possible, results from the other materials indicated that the radial-lip drill tended to produce longer burrs at any feedrate.

For 17-4PH stainless steel, the only variable that influenced the burr size was the thickness of the workpiece. In this case, a longer entrance burr was produced from the thick specimen; a 0.0007-inch-long (17.8 μm) burr was found on the thin specimen, while a 0.0016-inch (40.6 μm) burr was found on the thick specimen. In an analysis similar to that shown in Table 2, no other relationships were found to be significant for 17-4PH stainless steel.

In 1018 steel, the radial-lip drill produced an entrance burr that was longer and twice as thick as that produced by other drills (Figures 22 and 23). The exit-burr thickness on the 0.188-inch-thick (4.78 mm) specimen was approximately half of that produced

Table 2. ANOVA Results for Eight-Facet, Four-Facet, and Radial-Lip Drills in 303Se Stainless Steel, 1018 Steel, and 6061-T6 Aluminum

Source		Entrance Burr Thickness	Entrance Burr Length	Exit Burr Thickness	Exit Burr Length
A	Drill				√
B	Material		√	√√	√√
C	Thickness	√	√√		√√
D	Feedrate				√√
AB	Interaction	√√	√√		
AC	Interaction	√			√
AD	Interaction				√
BC	Interaction		√	√√	
BD	Interaction			√	√
CD	Interaction				√
ABC	Interaction				
ABD	Interaction		√		
ACD	Interaction				√√
BCD	Interaction				
ABCD	Interaction				

√Indicates significance at the 95-percent confidence level.
√√Indicates significance at the 99-percent confidence level.

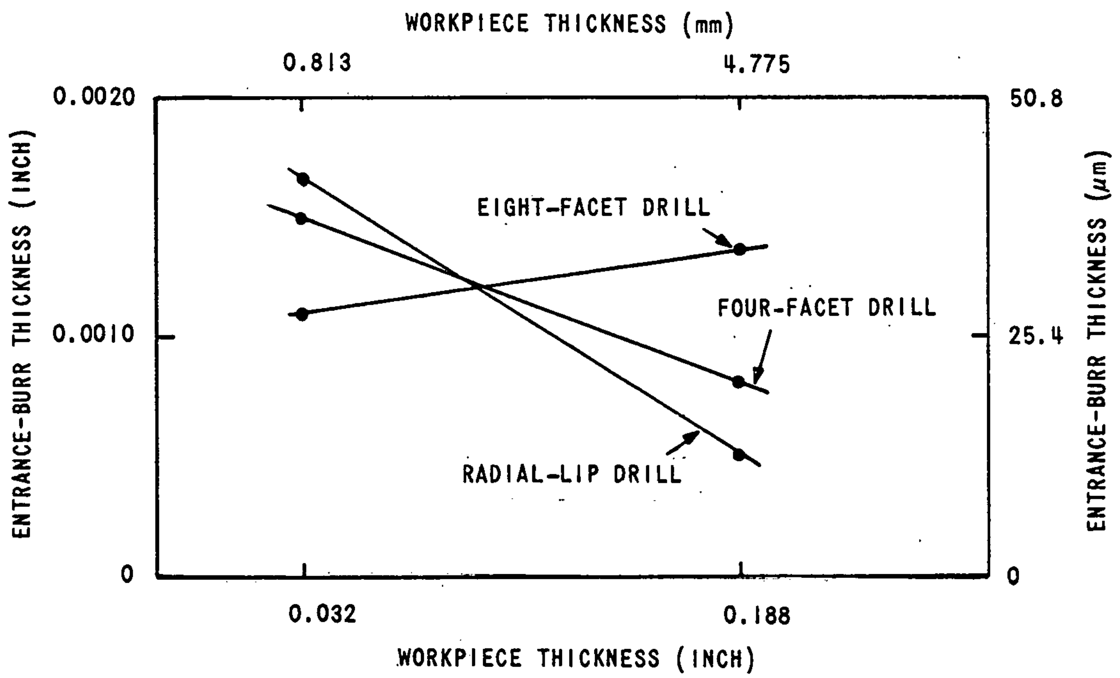

Figure 21. Effect of Drill Geometry and Workpiece Thickness on Entrance-Burr Thickness

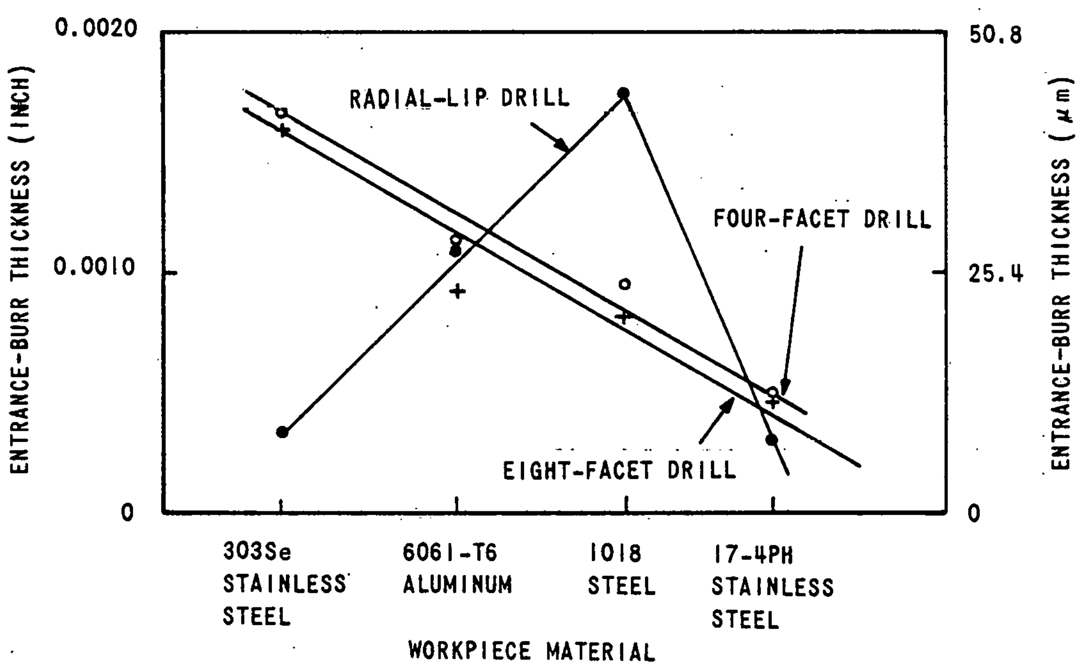

Figure 22. Effect of Drill Geometry and Workpiece Material on Entrance-Burr Thickness

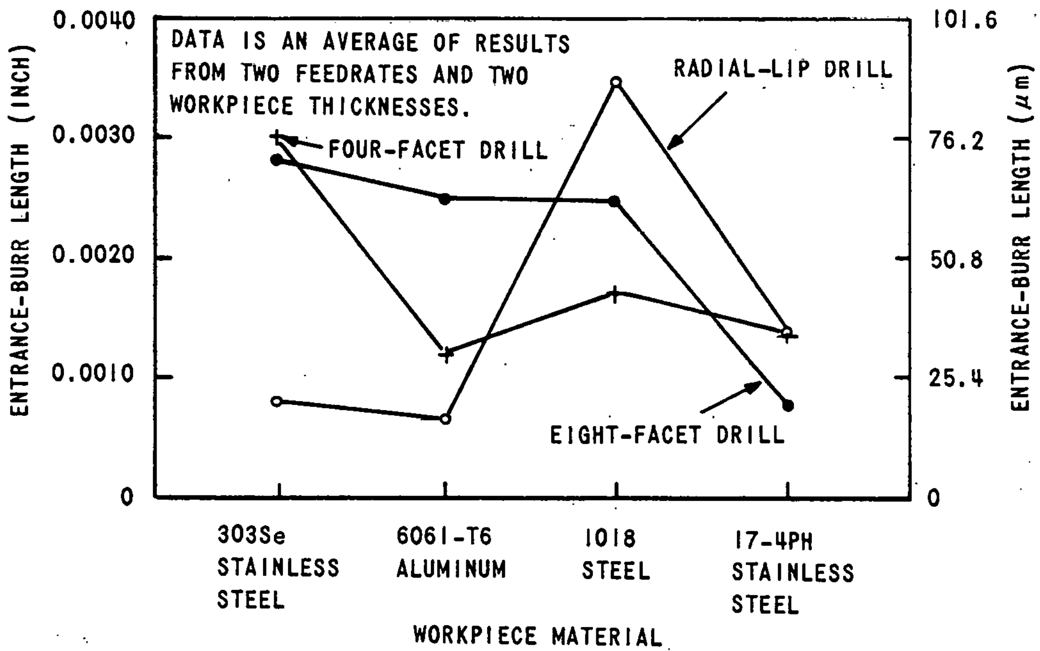

Figure 23. Effect of Drill Geometry and Workpiece Material on Entrance-Burr Length

from the thinner workpieces; the thickness from the thick specimen was 0.0008 inch (20.3 μm). The exit-burr length was doubled by increasing the feedrate to 0.0015 ipr (38.1 μm/rev); at 0.0015 ipr it was 0.0102 inch (259.1 μm).

In drilling 6061-T6 aluminum, the radial-lip drill produced a shorter entrance burr than did the other drills (Figure 23). No other relationship was observed between the test variables and the burr size.

A comparison of the results obtained from the different workpiece materials indicates that the smallest and thinnest burrs occurred from 17-4PH stainless steel (Figure 27). As a rule, the largest burrs occurred from 1018 steel and 303Se stainless steel. Fast feedrates dramatically increased the length of the exit burrs from both 1018 steel and 303Se stainless steel (Figure 28), but the feedrate did not noticeably affect the size of burrs from either 17-4PH stainless steel or 6061-T6 aluminum. In general, the radial-lip drill produced longer exit burrs than did the other drills (Figure 29).

Both the measurement of the burrs and the standard deviation of the results require further discussion: although only one hole was produced for each of the 64 combinations studied, cross-sectioning of the holes provided two views of each burr and

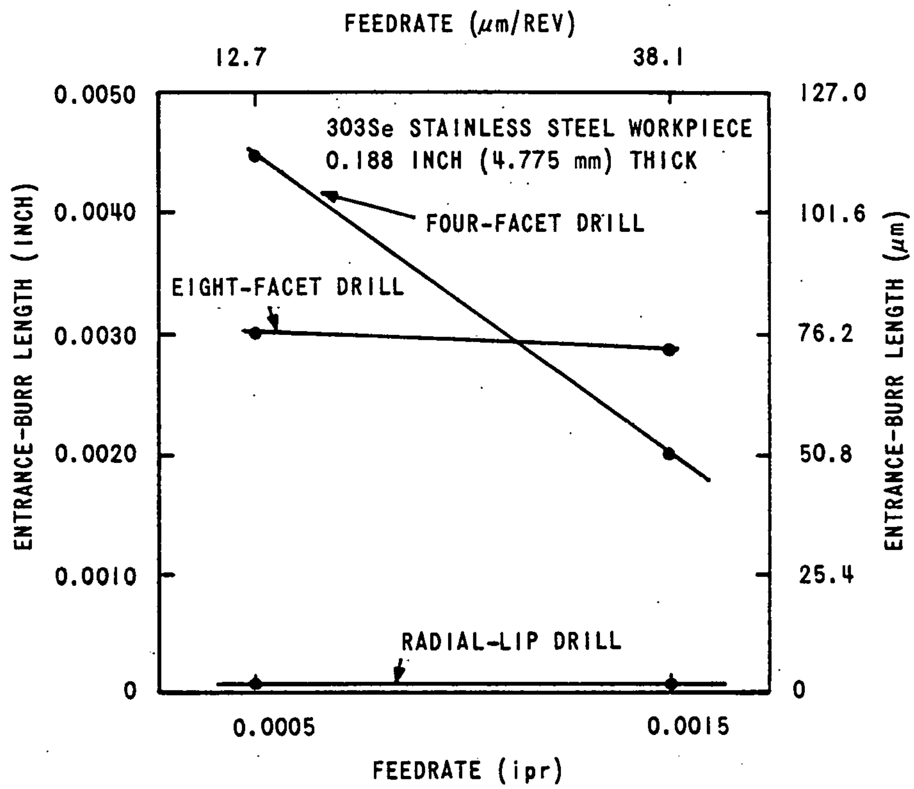

Figure 24. Effect of Feedrate and Drill Geometry on Entrance-Burr Length for 303Se Stainless Steel

therefore two measurements of each property. While this method is a reasonable approach for factorial-design tests, it also can mask some subtle, yet significant, trends and produce misleading data because of variations around the circumference of the holes. However, as noted by reviewing the data and performing three additional analyses of it, no condition produced grossly smaller burrs. Thus the approach used was adequate to fulfill the objectives of the test.

As compared to the size of the burrs, the standard deviation of the burr measurements can be quite large. For example, as shown in Figure 27, the exit-burr length of 303Se stainless steel was 0.011 inch (279.4 μm), while the standard deviation was 0.013 inch (330.2 μm). For entrance-burr thickness also, the standard deviation was approximately equal to the average burr size. This high variability is partly the reason that mechanized deburring is not always successful; repeatability of burrs must be improved if precision deburring is to be accomplished.

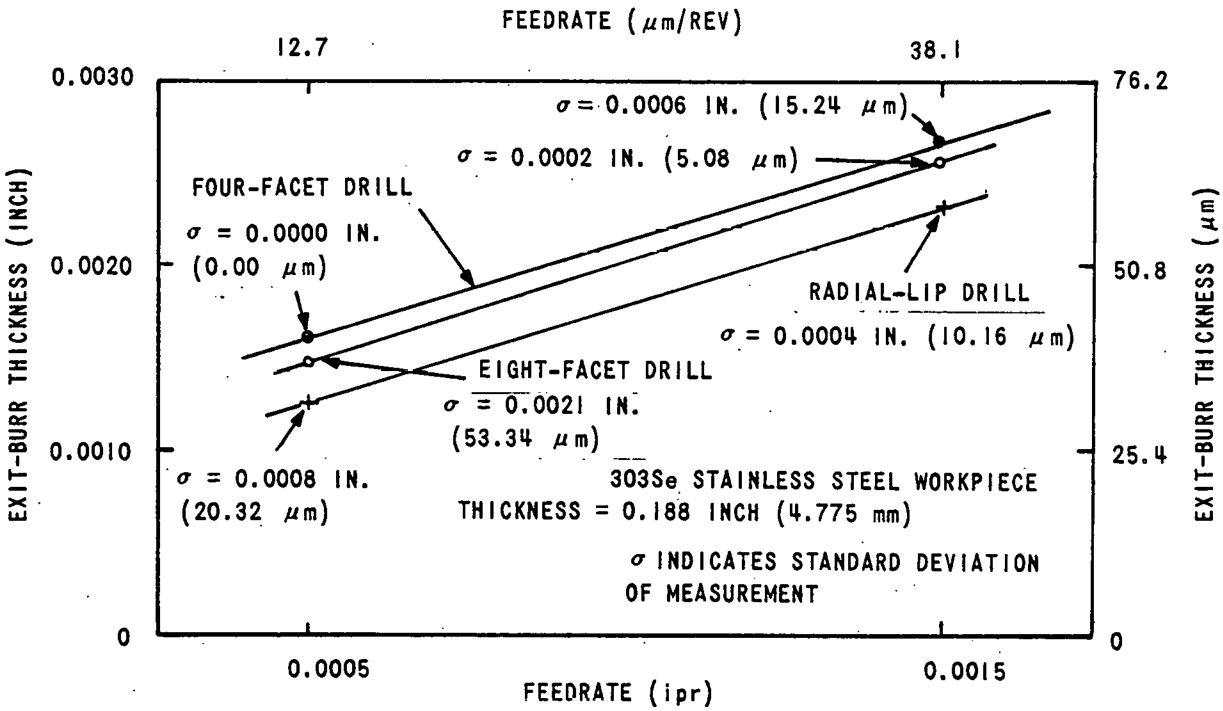

Figure 25. Effect of Drill Geometry and Feedrate on Exit-Burr Thickness

Effect of Drill Wear

The effect of drill wear on burr properties was studied in the second test. Except for BT drills, which were excluded from this and all subsequent tests, the materials and drills used in the initial test were used. Two analyses were made of the data. The first indicated that the properties of burrs produced by drilling follow typical wear-pattern curves, at least for 17-4PH stainless steel. In the second analysis, the exit-burr thickness for stainless-steel specimens was shown to be proportional to the exit-burr length. No such relationship was found for 1018 steel or 6061-T6 aluminum. For 17-4PH stainless steel, the thickness of the entrance burr was also proportional to its length.

In this test, the speeds were varied with each material to duplicate typical production practices; Table 3 indicates the conditions used. The holes were made with an N/C machining center, using a water-soluble flood coolant. All holes were drilled through 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.

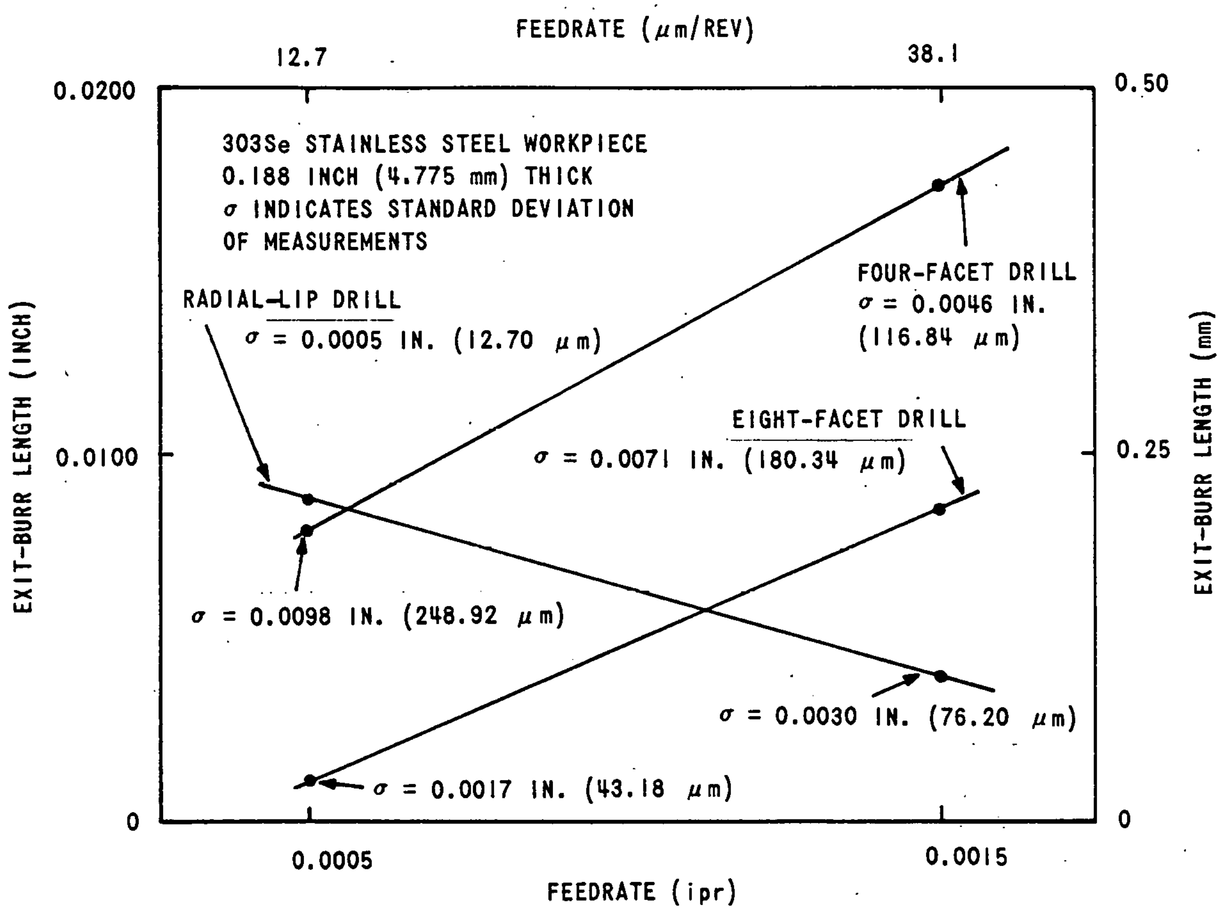

Figure 26. Effect of Drill Geometry and Feedrate on Exit-Burr Length

Both entrance and exit burrs were measured from metallurgical mounts. Prior to measuring the length, loose burr fragments were removed by wiping a hand over the burrs. Thus the burr lengths obtained represented only the burrs that were significant in deburring efforts. Four readings were taken of each burr (Appendix, Table A-5).

In analyzing the results of the test, it is significant to note that only the tools used to drill 17-4PH stainless steel failed; apparently, all other drills could have produced many more holes. The data obtained from the other materials therefore was not representative of the total drill-life.

The data for 17-4PH stainless steel followed a typical wear-life pattern (Figure 30). The burr length and thickness at both the entrance and exit of the hole followed the pattern. The longest

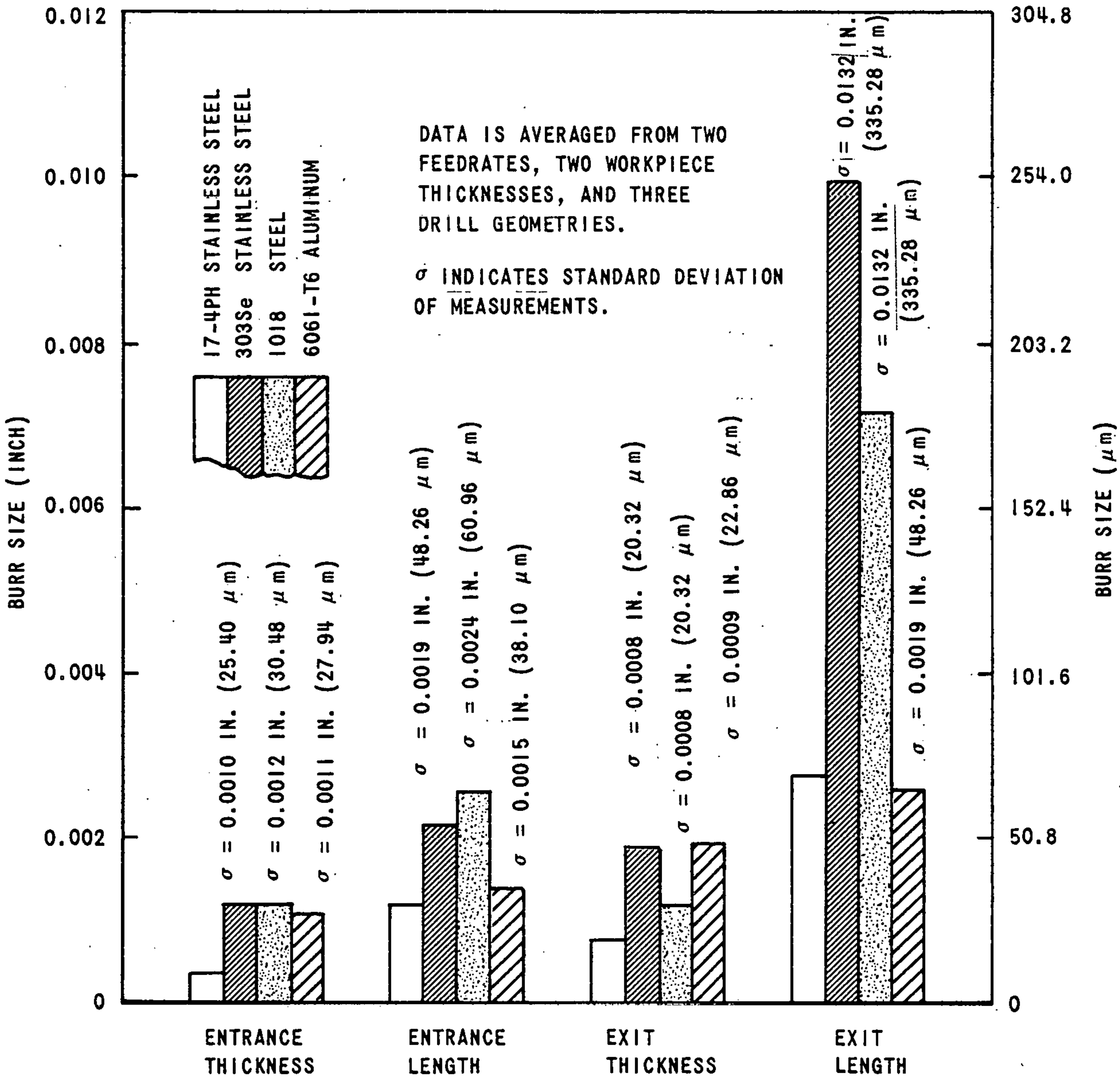

Figure 27. Typical Burr Properties of the Workpiece Materials Studied

burr length obtained was 29 percent greater than the drill radius, which agrees well with the previous discussion in this report on the maximum possible burr length.

One obvious difference between the data for 17-4PH stainless steel and that for the other materials is the repeatability of the burr properties. As shown in Figure 30, the burr-length measurements for 17-4PH stainless steel vary only 0.006 inch (152 μm)

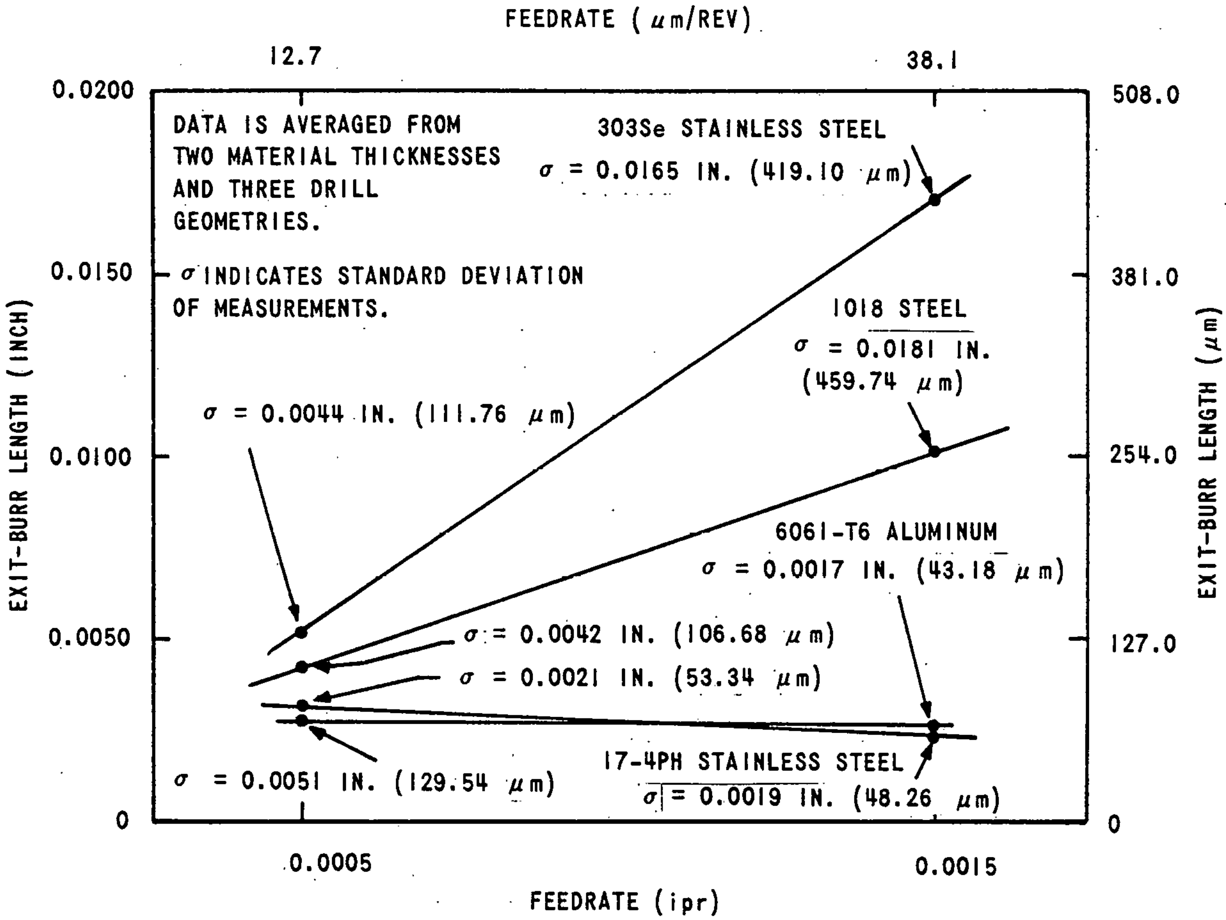

Figure 28. Effect of Feedrate and Workpiece Material on Exit-Burr Length

in the normal-wear portion of the curve. For 303Se stainless steel (Figure 31) however, the exit-burr length varies as much as 0.020 inch (508 μm). This difference in repeatability has been observed repeatedly under production conditions and in other tests.

Part of the reason for the difference is that because 17-4PH stainless steel has a low elongation value, it normally does not form long burrs; the variability in burr length therefore must be low. For each of the other materials studied, the material elongation value is quite large; because of numerous heterogeneous areas within these metals, failure can occur anywhere. (By analogy, a 6-inch tensile specimen can only fail somewhere within its 6-inch length, but a 36-inch specimen can fail anywhere within the 36-inch length.) Variability in burr properties therefore is approximately proportional to the plasticity of the material. As a consequence, the variability of the data obtained is at least partly a function of the workpiece material and geometry.

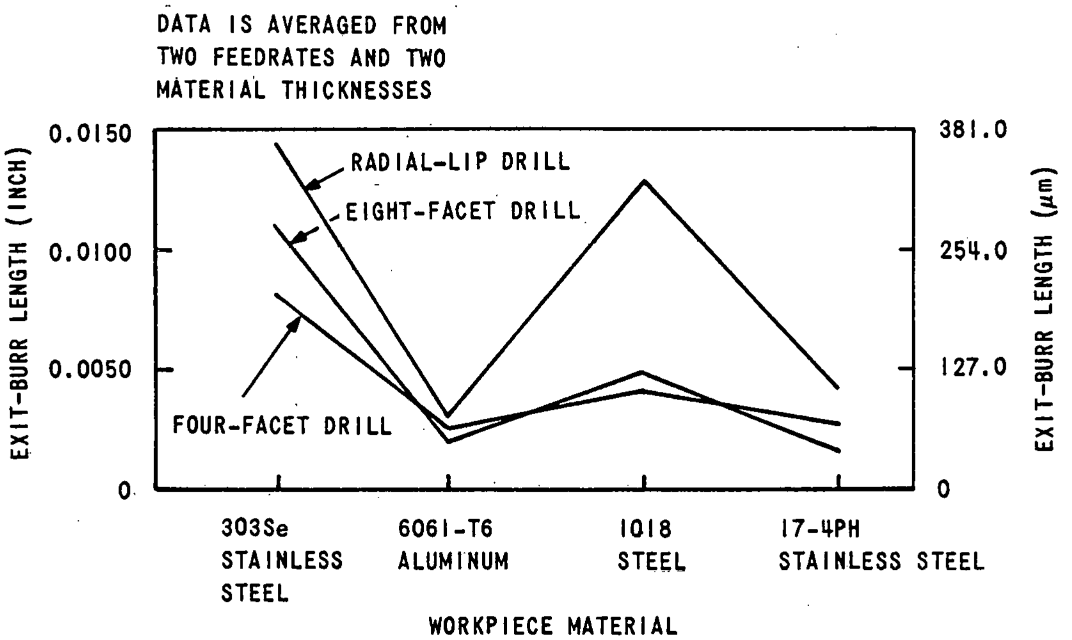

Figure 29. Effect of Drill Geometry and Workpiece Material on Exit-Burr Length

Relationships between exit-burr length and thickness were established for stainless-steel workpieces; no relationship was found for the other materials. Only data from three of the 12 drill-geometry and workpiece-material combinations analyzed exhibited a relationship between the entrance-burr length and thickness. The equations that were developed are presented in Table 4.

In this analysis, the four burr properties of each hole (Appendix, Table A-5) were evaluated as a linear function of each of the other variables. Thus exit-burr length was compared to exit-burr thickness, entrance-burr length, and entrance-burr thickness. For 1018 steel, the highest correlation coefficient from these analyses was 0.51, which indicates that only 25 percent (0.51^2) of the variation in data was explained by such a relationship. For aluminum, using the eight-facet drill, a correlation coefficient of -0.736 was obtained between entrance-burr length and thickness. Thus one-half of the data variability can be explained by a relationship in which entrance-burr thickness decreases as entrance-burr length increases.

As shown by the data in each of the tables in the Appendix, the entrance-burr length and thickness are, for all practical purposes, the same. Exit-burr lengths vary from 2 to 10 times the exit-burr thickness, depending upon the material, drill geometry, and machining conditions.

Table 3. Spindle Speeds and Feedrates Used in Wear Test

Workpiece Material	Spindle Speed (rpm)	Feedrate (ipr)	(μm/rev)
1018 Steel	2000	0.003	76
303Se Stainless Steel	3000	0.003	76
17-4PH Stainless Steel	750	0.003	76
6061-T6 Aluminum	4000	0.003	76

The equations presented in Table 4 are based on the average properties of 12 holes. Because the data used to construct the equations were obtained from a relatively small number of holes, these equations should be considered only as guidelines. (Greater accuracy would require the measurement of burrs from approximately 100 holes.) The major significant results of the analysis are that, for the conditions studied, exit-burr length was directly proportional to exit-burr thickness for stainless steel, and no similar relationship could be found for 1018 steel or aluminum.

In this test, the radial-lip drill produced thinner, shorter, and more consistent exit burrs in 303Se stainless steel than did the other two drill geometries (Appendix, Table A-5). The radial-lip drill produced exit burrs having typical thicknesses of 0.0017 inch (43.2 μm) and lengths of 0.0044 inch (111.8 μm). Under the same conditions, the four-facet drills produced 0.0028-inch-thick by 0.0089-inch-long (71.1 by 226.1 μm) burrs. There were no significant differences in the results between drills used on other materials.

The observation that the radial-lip drill produced a shorter exit burr is in direct opposition to the conclusion drawn from the first test. There are two possible reasons for this anomaly. First, the effectiveness of the radial-lip drills may be dependent upon the feedrate; at higher feedrates, the cutting forces may be more effectively distributed. Second, the failure to make multiple samples at each condition may have affected this one variable in the first test. Eight measurements for each drill-material combination were used in the first test, while 48 were involved in the life test. Because of the high repeatability level observed in the second test, and because of the nature of such statistical factorial designs as were used in the first test, the first explanation seems more plausible.

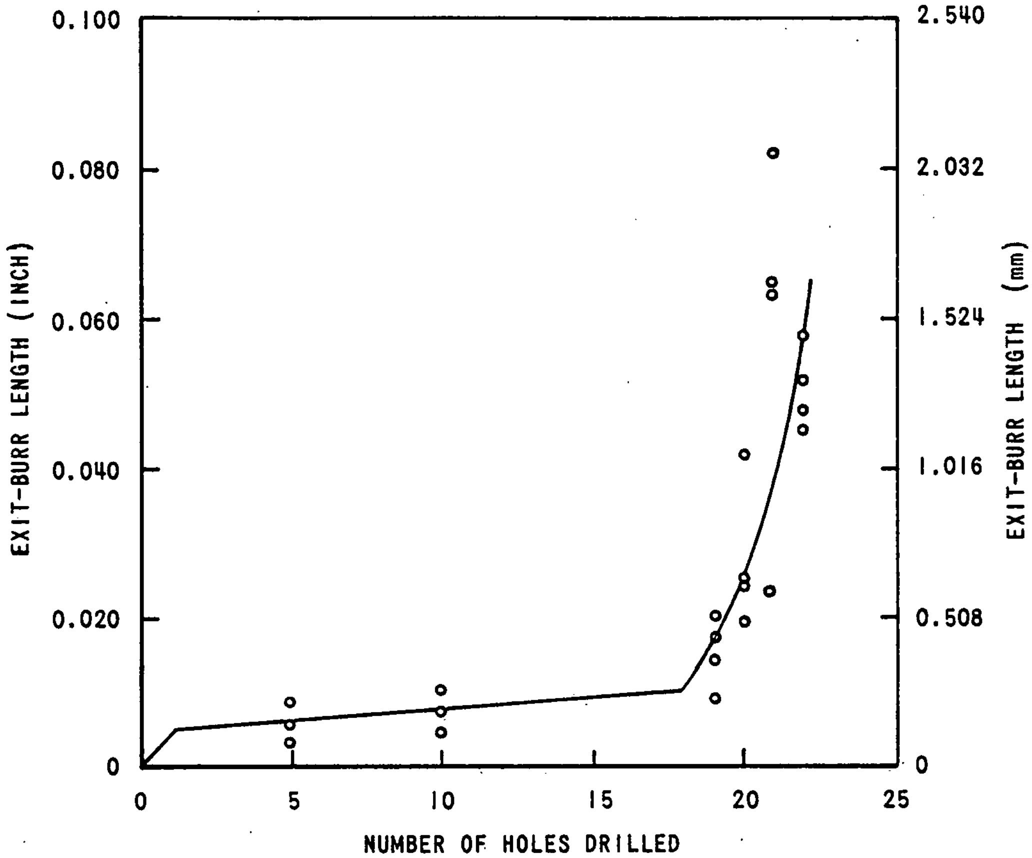

Figure 30. Burr Size for 17-4PH Stainless Steel With Four-Facet Drill

Effect of Reaming After Drilling

A study was made to determine whether reaming after drilling would result in a significantly smaller burr. While the data from this test were inconclusive, reaming appears to result in thinner and shorter burrs. The size of burrs produced by reamers apparently varies considerably among different workpiece materials. As previously described, reaming burrs are a function of stock-removal and reamer-geometry.[3] Also, the size of the drilling burr likely influences the size of the reaming burr.

This study utilized the four workpiece materials previously described. Each specimen was 0.450 inch (11.43 mm) in diameter and 0.250 inch (6.35 mm) thick. Thirty specimens of each material were drilled, and 15 of each were reamed. Five samples each from the drilled and reamed specimens then were randomly selected for measurement of the burrs.

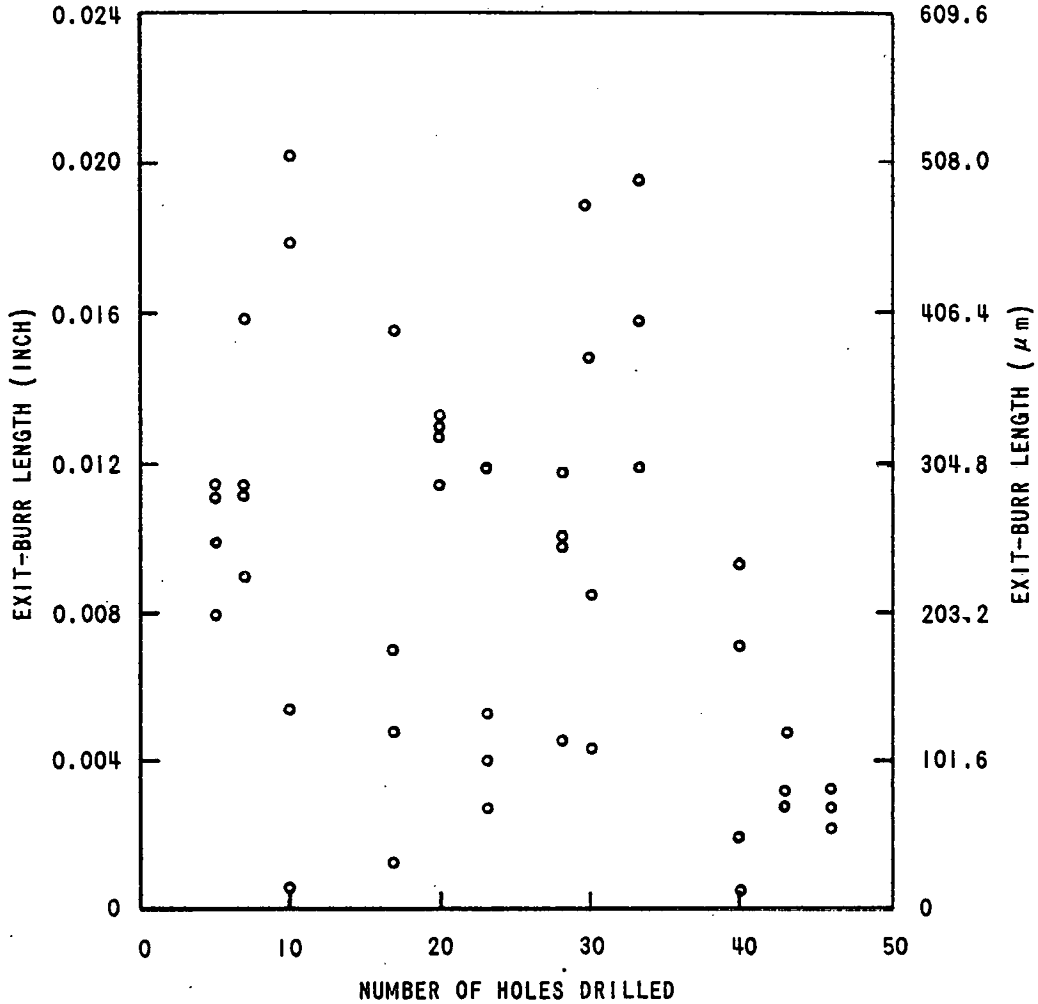

Figure 31. Burr Size for 303Se Stainless Steel With Four-Facet Drill

A Hardinge HLV lathe was used to provide the power feed and speed. Table 5 indicates the conditions under which the holes were produced. No backup material was used to support the drill at the exit.

All holes were drilled with a 0.134-inch-diameter (3.4 mm) cobalt HSS drill having a 135-degree split point, and those that were reamed utilized a 0.1406-inch-diameter (3.56 mm) HSS reamer having a normal 45-degree starting chamfer and six straight flutes (Bendix Kansas City Drill 50113305 and Reamer 50316345). A new drill and reamer were used for each material. A water-soluble coolant was used on all holes.

Table 4. Relationships Between Burr Length and Thickness

Material	Drill	Equation*	Correlation	Standard Error of Estimate
303Se SST	Radial Lip	$L_x = -0.0082 + 7.5\ T_x$	0.758	0.0015
303Se SST	Eight-Facet	$L_x = 0.0141 + 9.3\ T_x$	0.921	0.0037
17-4PH SST	Four-Facet	$L_N = -0.0001 + 1.5\ T_N$	0.939	0.0012
17-4PH SST	Four-Facet	$L_x = 0.0051 + 3.8\ T_x$	0.939	0.0085
17-4PH SST	Radial Lip	$L_N = -0.0006 + 1.4\ T_N$	0.831	0.0010
17-4PH SST	Radial Lip	$L_x = -0.0016 + 4.3\ T_x$	0.981	0.0053
6061-T6 Al	Eight-Facet	$L_N = 0.0033 - 0.7\ T_N$	-0.736	0.0005

*These equations are valid for burr thicknesses of 0.001 inch (25.4 μm), or larger.
L_x = burr length at hole exit,
T_x = burr thickness at hole exit,
L_N = burr length at hole entrance, and
T_N = burr thickness at hole entrance.

Table 5. Spindle Speeds and Feedrates Used in Drilling-Reaming Study

Workpiece Material	Spindle Speed		Feedrate			
	Drilling	Reaming	Drilling		Reaming	
	(rpm)	(rpm)	(ipr)	(μm/rev)	(ipr)	(μm/rev)
1018 Steel	1200	3000	0.001	25.4	0.003	76.2
303Se SST	1200	3000	0.001	25.4	0.003	76.2
17-4PH SST	1200	750	0.001	25.4	0.003	76.2
6061-T6 Al	1200	3000	0.001	25.4	0.003	76.2

For steel workpieces, both the entrance-burr length and thickness appear to be proportional to the hardness and strain-hardenability of the material. The hard workpiece (17-4PH stainless steel) had the shortest and thinnest entrance burr (Figure 32), while the soft 1018 steel had the longest and thickest. The aluminum burrs fell midway between those of the low-carbon steel and the 303Se stainless steel.

In most cases, the entrance burr created by reaming would be expected to be equal to or smaller than that produced by drilling; this generally was true. The marked exception, indicated by the 17-4PH stainless steel, is believed to be the result of improper drilling-speed selection. The drill broke down after the first 15 holes and produced large burrs on the remaining 15 holes. Rather than taking random samples from all of the specimens, the operator then reamed all of the specimens having the large drilling burrs. Under normal conditions, reaming does not produce gross burrs or brown heat stains such as those which occurred in this study.

As a general rule, entrance-burr properties in steel workpieces are inversely proportional to the workpiece hardness. The relationship, however, appears to be exponential rather than linear. For all practical purposes, both drilling and reaming produce entrance burrs having thicknesses equal to the burr length (Figure 32). As also shown in Figure 32, the thickness of the entrance burr produced by reaming 1018 steel and 303Se stainless steel was approximately half the thickness of that produced by drilling. The entrance-burr length, after reaming, was approximately 75 percent of that produced by drilling these two materials. These ratios, however, are significant only for the reaming conditions used in this study.

Reaming made little difference in the exit-burr length for either aluminum or 303Se stainless steel. In fact, the aluminum burr became longer. In 1018 steel, reaming produced a notably thinner and shorter burr than did drilling.

The length of the exit burrs produced by reaming showed no detectable pattern (Figure 33). Again, part of this variability was the result of the initial burr size and the reaming conditions chosen. Because a reamer has basically the same corner geometry as a drill, it could be expected to produce a similar-size burr provided that the feedrate and the corner angle are the same and the burr produced by drilling is not gross. Since reamer feedrates are typically much lower than drill feedrates, and the corner angle is larger, a shorter and thinner burr should be produced. Thus, although the data from this test does not confirm that reaming burrs are smaller, production experience and previously published data[3] indicate that reaming can be used to minimize burrs.

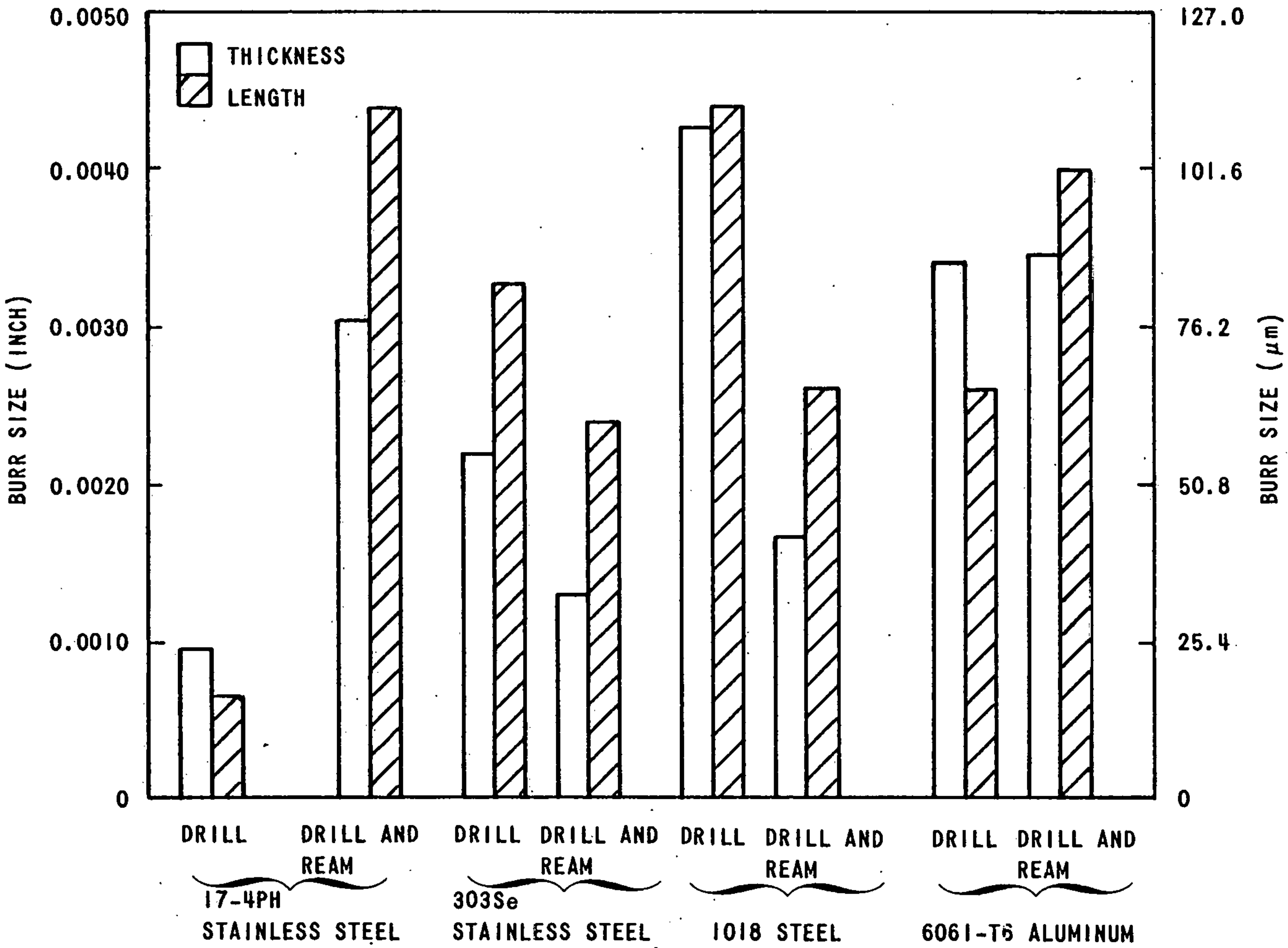

Figure 32. Entrance-Burr Properties

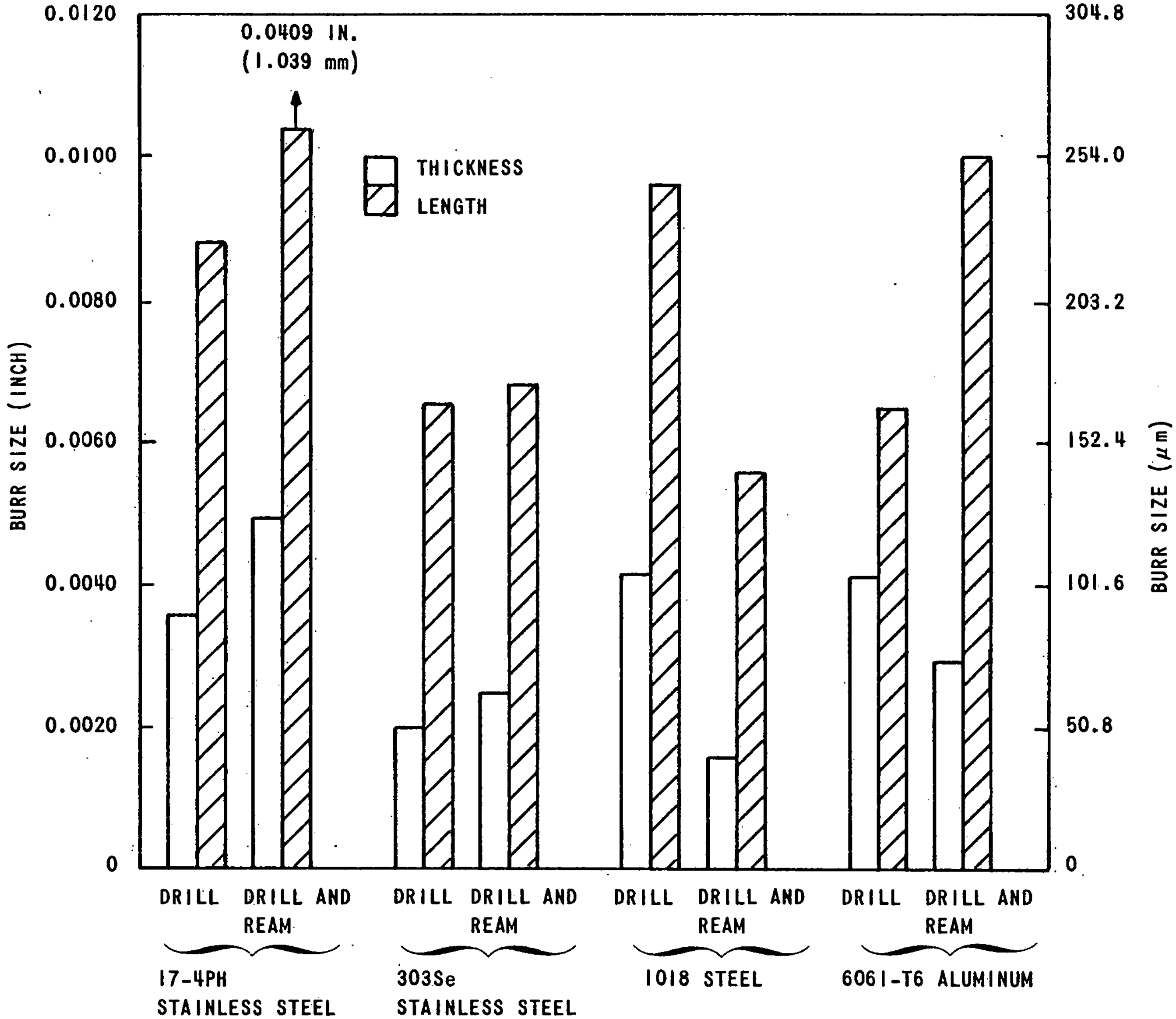

Figure 33. Exit-Burr Properties

One advantage of reaming which was demonstrated in this study is that it results in a more repeatable burr (Table 6). The burrs produced by reaming are roughly twice as repeatable as those produced by drilling.

Effect of Backup Material

In the test to determine the effect of a backup material, 303Se stainless steel specimens were drilled using ten different arrangements for supporting the drill as it exited from the hole. As shown in Table 7, three sets of backup materials consisted of solid discs, while the remaining sets had a hole drilled in them. Brass, 17-4PH (H900) stainless steel, and 303Se stainless steel were used as the backup materials to provide hardnesses which were less than, equal to, and greater than those of the workpiece.

A standard 0.125-inch (3.18 mm) cobalt HSS drill (Bendix Kansas City Tool 50112305) with a 135-degree split point was used in a Hardinge HLV lathe to produce the holes at a spindle-speed of 2800 rpm and a feedrate of 0.0016 ipr (40.6 μm/rev). Two drills were used in the study to minimize the effects of drill wear. Each drill was broken-in prior to the test by drilling three holes through 0.250-inch-thick (6.35 mm) 303Se stainless steel.

For the test, three specimens were drilled at each condition. New backup material was used with each specimen and a water-soluble coolant was applied to the drill. The drilling was randomized, insofar as possible, with the three replications being drilled in sequence.

Each sample was cut in half and potted in a plastic matrix. Two measurements both of the burr length and burr thickness were made on each specimen (Table A-6). To determine whether effects were significant, the average of the two readings was used to provide an average burr size for each hole.

A solid piece of material placed below the workpiece will minimize the size of the burr produced as the drill breaks through the bottom of the workpiece; the harder the backup material, the smaller the exit burr will be (Figure 34). In this test, both the exit-burr thickness and length decreased with hardness. When no backup material was used, a 0.0027-inch-thick (68.6 μm) burr occurred (Figure 35, value for 0.005-inch shim). By using a brass backup, the burr thickness was reduced to 0.0012 inch (30.5 μm); 17-4PH (H900) stainless steel, having a Rockwell C hardness of 42, further reduced the burr thickness to 0.0004 inch (10.2 μm). The burr length was reduced from 0.0080 to 0.0030 inch (76.2 to 203.2 μm) by using a brass backup, and to 0.0012 inch (30.5 μm) by using 17-4PH stainless steel.

Table 6. Repeatability of Drilling and Reaming Burrs

Workpiece Material	Process	Entrance Burr* Thickness (Inch) (μm)	Entrance Burr* Length (Inch) (μm)	Exit Burr* Thickness (Inch) (μm)	Exit Burr* Length (Inch) (μm)
303Se SST	Drilling	0.00124 (31.5)	0.00169 (42.9)	0.00038 (9.6)	0.00400 (101.6)
	Reaming	0.00049 (12.5)	0.00094 (23.9)	0.00127 (32.2)	0.00017 (43.2)
17-4PH SST	Drilling	0.00097 (24.6)	0.00074 (18.8)	0.00176 (44.7)	0.00409 (103.9)
	Reaming**	0.00049 (12.5)	0.00259 (65.8)	0.00085 (21.5)	0.00886 (225.0)
1018 Steel	Drilling	0.00239 (60.7)	0.00170 (43.2)	0.00100 (25.4)	0.00230 (58.4)
	Reaming	0.00026 (6.6)	0.00031 (7.9)	0.00013 (33.0)	0.00109 (27.7)
6061-T6 Al	Drilling	0.00087 (22.1)	0.00092 (23.4)	0.00200 (50.8)	0.00232 (58.9)
	Reaming	0.00112 (28.4)	0.00293 (74.4)	0.00051 (13.0)	0.00557 (141.5)

*Values shown are standard deviation.
**Data for these reaming burrs probably are higher than those that would be found under production circumstances.

Table 7. Backup Material Configuration

Code	Backup Material	Backup Material Thickness (Inch)	(mm)	Clearance Hole in Backup (Inch)	(mm)
A	303Se SST	0.250	6.35	0.125	6.35
B	303Se SST	0.250	6.35	0.127	3.23
C	303Se SST	0.250	6.35	0.135	3.43
D	303Se SST	0.250	6.35	0.145	3.68
E	303Se SST	0.001*	0.025	0.145	3.68
F	303Se SST	0.003*	0.076	0.145	3.68
G	303Se SST	0.005*	0.127	0.145	3.68
H	303Se SST	0.250	6.35	None	None
I	Brass	0.250	6.35	None	None
J	17-4PH SST	0.250	6.35	None	None

*These shims, which had clearance holes, were placed over 0.250-inch-thick (6.35 mm) solid 303Se stainless steel backups to determine the effect of small gaps upon burr size.

These reductions in burr size are significant because of their impact on deburring costs. A burr which is not more than 0.0005 inch (12.7 μm) thick can be readily removed by most deburring processes, while a 0.0030-inch-thick (76.2 μm) burr requires considerably more time for removal from precision parts.

The disadvantage in using a backup material is that it adds to the manufacturing cost for producing each hole. When a hard material such as 17-4PH stainless steel is used for a backup material, the drill wear increases rapidly.

When a small gap is present between the workpiece and the backup material, a noticeable burr will form (Figure 36). In production situations, the gaps are caused by the material not being flat, and by deflections produced by clamping pressures. The thicker the gap, the longer and thicker will be the burr. A 0.005-inch (127.0 μm) gap, for example, allowed an 0.008-inch-long (203.2 μm) burr to form (Figure 35), while a 0.001-inch (25.4 μm) gap

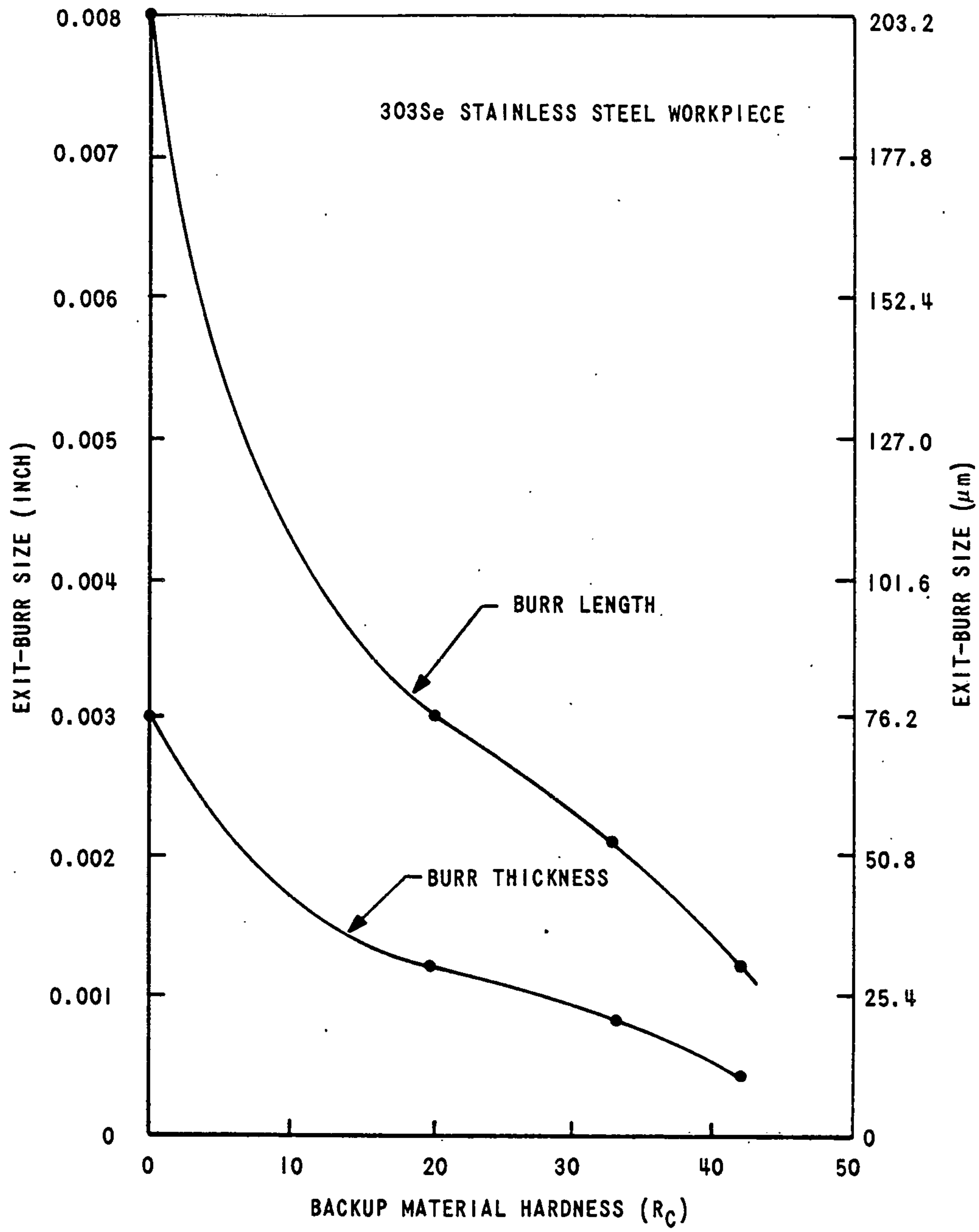

Figure 34. Effect of Backup-Material Hardness on Exit-Burr Size

allowed a 0.0042-inch (106.7 μm) burr to form. Although burr thickness was affected less dramatically, the difference was significant.

An obvious question at this point is, "How can a 0.0042-inch-long burr form in a space which is only 0.001 inch long?" This can

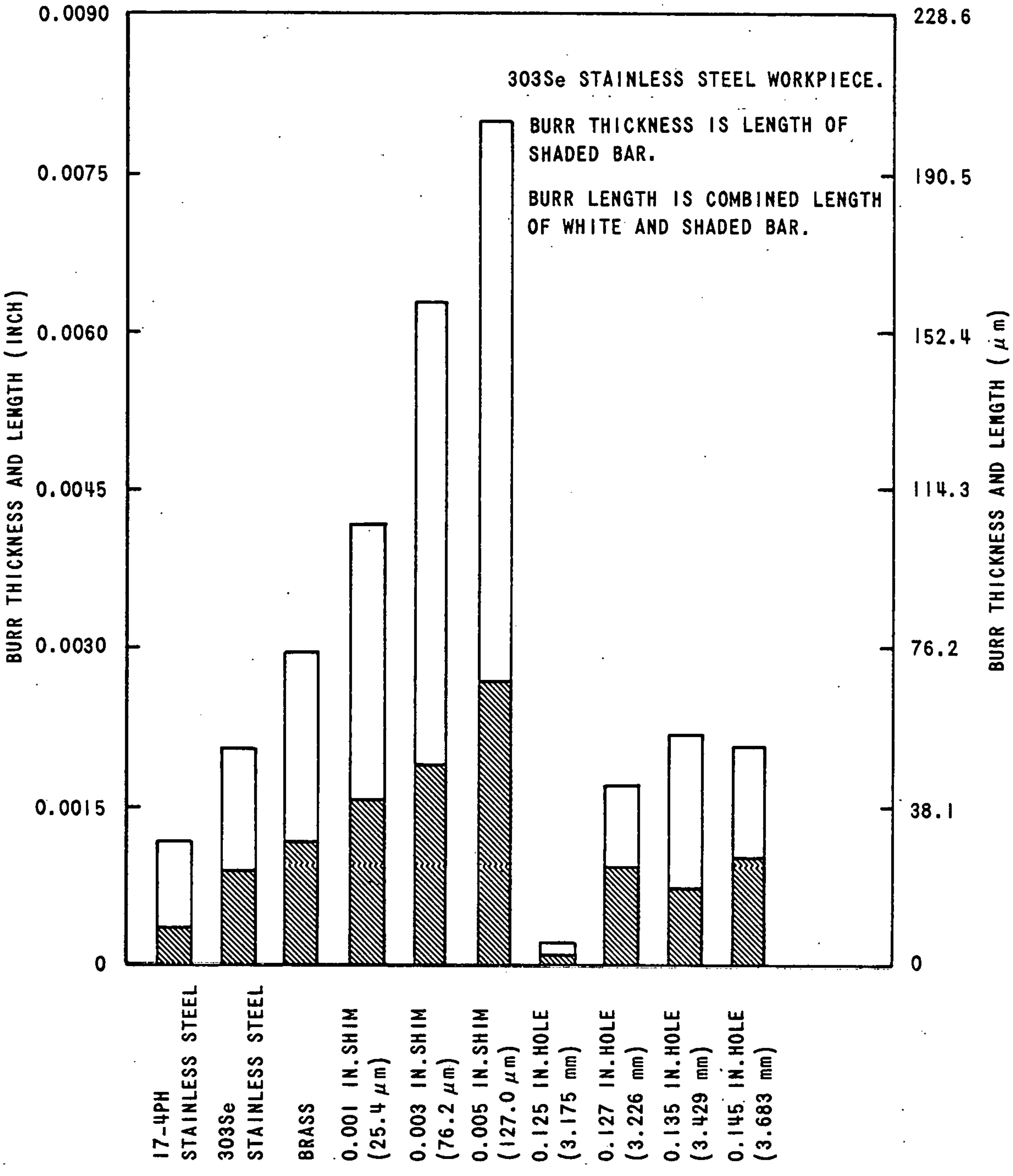

Figure 35. Effect of Various Backups on Burr Properties

happen in two ways. In the first case, when the drill corners break through the part, the part lifts away from the backup material and widens the actual gap. This is particularly obvious on long, thin panels which are clamped only at the edges. In the second case, material "smearing" occurs when the cutters exit

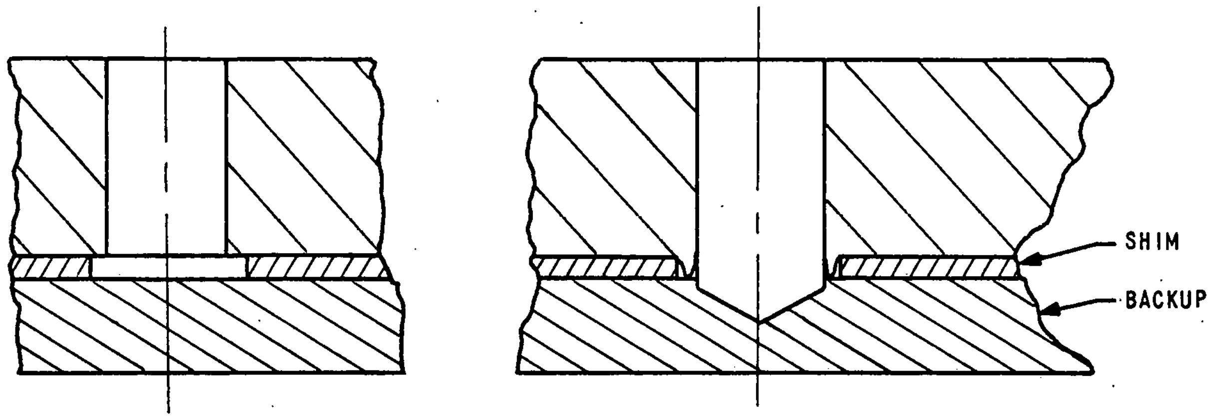

Figure 36. Effect of Small Backup-Material Gap on Burr Formation

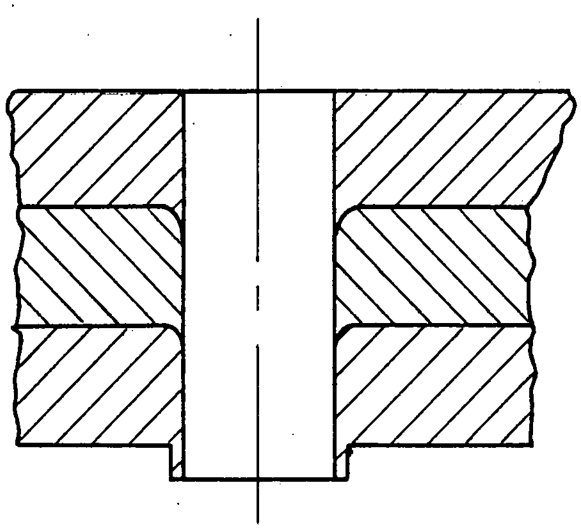

Figure 37. Smearing of Workpiece Material Into Backup Material

into the backup material (Figure 37). Even when the workpiece and backup are perfectly flat and squeezed tightly together, a burr will form. This is particularly noticeable in gear-hobbing operations involving 303Se stainless steel and brass workpieces. The smearing effect apparently is a function of the strain-hardenability of the workpiece material.

A method which frequently is used to back up the drill without using new backup material for every hole consists of placing a bushing below the workpiece (Figure 38). Idealistically, this would not allow burrs to form; practically, however, some burr will always form because of small differences in size between the drill and the bushing, and because a lead-in radius will form on the bushing (if it is not present initially) to create a gap (Figure 39). In addition, the drill will deflect and break anytime it is not exactly on the centerline of the bushing.

The observation was made during this study that a bushing which was 0.002 inch (50.8 μm) larger in diameter than the drill resulted in no improvement in the burrs produced. When the bushing size was exactly equal to the drill size, only an extremely small burr formed (Figure 35). In the latter case, the bushing consisted of a predrilled hole in the same type of material as that of the workpiece, rather than a hardened bushing. This allowed the drill to cut the bushing if it was off center without breaking the drill or accelerating the tool wear.

Although a 0.0003- by 0.0001-inch (7.6 by 2.5 μm) burr can be readily removed by all deburring processes, the drilling procedure just described could be made to produce even smaller burrs. This, of course, would require extreme accuracy in both the size and positioning of the backup bushing.

Based on the tests performed, the most effective approach to minimizing drill-exit burrs would be to use a backup bushing having a diameter within 0.0002 to 0.0004 inch (5.1 to 10.2 μm) that of the drill. To minimize drill wear, the bushing should be readily replaceable and should be made from the same material as the workpiece.

Miscellaneous Tests

At the beginning of this development program, a brief test was performed to determine the variation of burr size in three common materials. The results of the test are shown in Table 8. A 0.025-inch-diameter (0.635 mm), 118-degree-point, HSS drill was used at a feedrate of 0.0005 ipr (12.7 μm/rev) and a spindle speed of 2000 rpm. Each drill was changed when the operator decided that it was dull.

A comparison of these test results with those shown in Figure 33 indicates that the smaller drill produced shorter exit burrs. Equally significant, the standard deviations also are much smaller than those shown in Table 6 for the 0.125-inch (3.175 mm) drills.

A random sample in brass and 302 stainless steel of 2500 holes having diameters of 0.025 or 0.082 inch (0.635 or 2.083 mm)

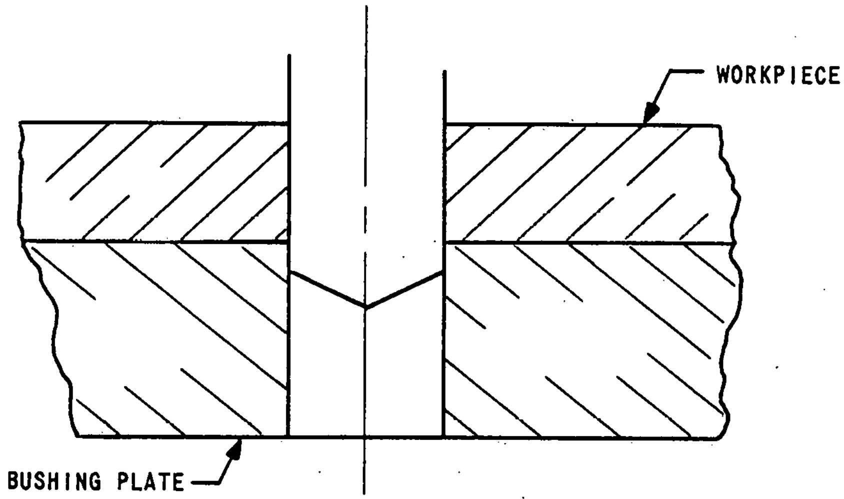

Figure 38. Use of Bushing as a Backup

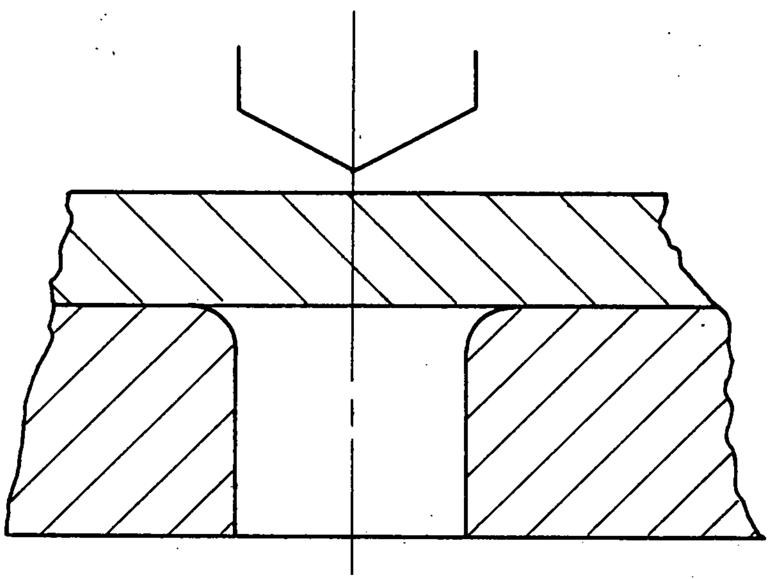

Figure 39. Lead-In Radius on Bushing Provides Space for Burr Formation

revealed the burr sizes shown in Table 9. The holes were part of a production run in which each drill produced approximately 100 holes. Solid carbide drills having 118-degree, four-facet points were used, and no control was maintained on feeds or speeds. The drills were changed only when they broke.

Table 8. Exit-Burr Properties as a Function of Workpiece Material

Material	Burr Thickness (Inch) (μm)*	Burr Length (Inch) (μm)**	Burr Hardness (Knoop)***	Parent Hardness (Knoop)
6061-T6 Al	$\bar{w}$ = 0.0014 ($\bar{w}$ = 35.6)	$\bar{L}$ = 0.0013 ($\bar{L}$ = 33.0)	$\bar{h}$ = 164	$\bar{h}$ = 140
	σ = 0.0002 (σ = 5.1)	σ = 0.0003 (σ = 7.6)		
Brass, 1/2 H (Alloy 6)	$\bar{w}$ = 0.0021 ($\bar{w}$ = 53.3)	$\bar{L}$ = 0.0037 ($\bar{L}$ = 94.0)	$\bar{h}$ = 162	$\bar{h}$ = 148
	σ = 0.0004 (σ = 10.2)	σ = 0.0009 (σ = 22.9)		
302 SST (Cold Drawn)	$\bar{w}$ = 0.0021 ($\bar{w}$ = 53.3)	$\bar{L}$ = 0.0040 ($\bar{L}$ = 101.6)	$\bar{h}$ = 305	$\bar{h}$ = 256
	σ = 0.0003 (σ = 7.6)	σ = 0.0011 (σ = 27.9)		

*$\bar{w}$ = average thickness; σ = standard deviation.
**$\bar{L}$ = average length.
***$\bar{h}$ = average hardness.

Table 9. Exit-Burr Properties Observed in a Large Production Run of Holes

Material	Hole Size (Inch) (mm)	Burr Thickness (Inch) (μm)*	Burr Length (Inch) (μm)**	Hardness Increase (Knoop)
Brass, 1/2 H	0.025 (0.635)	$\bar{w}$ = 0.0003 ($\bar{w}$ = 7.6)	$\bar{L}$ = 0.0012 ($\bar{L}$ = 30.5)	+7
		σ = 0.0002 (σ = 5.1)	σ = 0.0011 (σ = 27.9)	4
	0.082 (2.083)	$\bar{w}$ = 0.0012 ($\bar{w}$ = 30.5)	$\bar{L}$ = 0.0045 ($\bar{L}$ = 114.3)	+8
		σ = 0.0003 (σ = 7.6)	σ = 0.0017 (σ = 43.2)	5
302 SST	0.025 (0.635)	$\bar{w}$ = 0.0012 ($\bar{w}$ = 30.5)	$\bar{L}$ = 0.0031 ($\bar{L}$ = 78.7)	+39
		σ = 0.0005 (σ = 12.7)	σ = 0.0010 (σ = 25.4)	14
	0.082 (2.083)	$\bar{w}$ = 0.0012 ($\bar{w}$ = 30.5)	$\bar{L}$ = 0.0060 ($\bar{L}$ = 152.4)	+35
		σ = 0.0005 (σ = 12.7)	σ = 0.0041 (σ = 104.1)	9

*$\bar{w}$ = average thickness; σ = standard deviation.
**$\bar{L}$ = average length.

The data obtained is significant because it represents the full range of burr sizes that could be expected to occur if production runs were not monitored to limit the burr size. As anticipated, the repeatability of these burrs was less than it was for the controlled tests.

Burr Shape and Hardness

As shown in Figure 40, the entrance burrs produced by drilling during this investigation were basically triangular in shape, and, as previously mentioned, the burr length and thickness were almost identical. The exit burr, however, had a basically rectangular cross section.

Although these observations held true for the several hundred specimens studied, work done by another investigator indicates that workpiece geometry can play an important role in determining the burr shape.[29] For example, when one hole breaks into the edge of another hole, a nonrectangular burr might form on the side near the hole wall. While little is known about the influence of burr shape on burr removal, the fact that the shape can be a significant variable should be noted.

Whenever metals are strained, they tend to become harder in the strained area. Since both entrance and exit burrs are the result of displaced (strained) material, the assumption logically can be made that they will be harder than the rest of the workpiece. This, in fact, is the case (Tables 8 and 9). As shown in Figure 41, even the walls of the holes can be strained enough to produce significant changes in hardness.

Occasionally, this work-hardening of the material will make the burrs brittle and thus easier to remove; however, this is seldom true. As a rule, work-hardening is a disadvantage since hard materials react slower to abrasion than do softer materials. When burr knives are used to remove the burrs, a greater force is required to cut the harder material.

The measurement of burr hardness is somewhat of an art, since the hardness can vary considerably across the width of the burr.[30] With some materials, this difference in hardness also may indicate a change in crystal structure which, in turn, can result in improved chemical deburring.

Analysis of Published Drilling-Burr-Investigation Results

The few authors who have studied the burrs produced by drilling have limited their efforts to measuring burr lengths. While the assumption logically can be made that a distinct though unknown relationship exists between burr thickness and length for a given material, the reporting of burr length alone will not permit the defining of general trends for different materials.

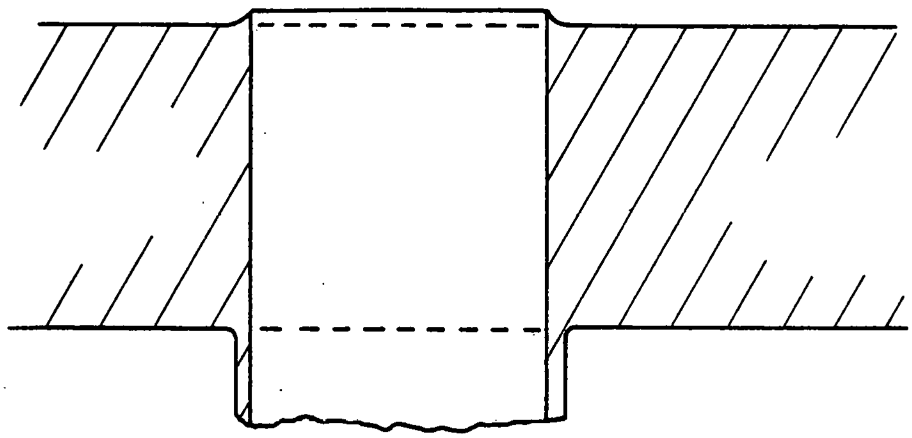

Figure 40. Shapes of Burrs Produced by Drilling

In evaluating the information which has been published on the burrs produced by drilling, the most obvious starting point is to define the areas in which little or no work has been done. The following list summarizes these areas.

- Analysis of burr formation during drilling
- Empirical relationships between burr thickness and length
- Empirical relationships between burr size and deburring costs
- Effect of BUE on burr size

In a review of 1300 published articles and reports on burrs and deburring, only eight were found to contain data on the burrs produced by drilling. Of these, four were written by the author of this report. Bell and Kearsley's report[8] investigated the effects of drill-point angle, feedrate, and spindle speed in low-carbon steel. Their brief investigation of 0.500-inch-diameter (12.7 mm) drills indicated that either slower feedrates or lower spindle speeds resulted in shorter exit burrs. Lower spindle speeds also resulted in smaller entrance burrs.

The use of a sheet-metal or fish-tail point resulted in slightly larger exit burrs than did the conventional 118-degree-point drill. The fish-tail point, however, produced a significantly longer entrance burr than did the conventional point: 0.008 versus 0.003 inch (203.2 versus 76.2 μm). The large burr was attributed to the tendency of the fish-tail point to "walk around" the hole and thereby "upset" the hole edges.

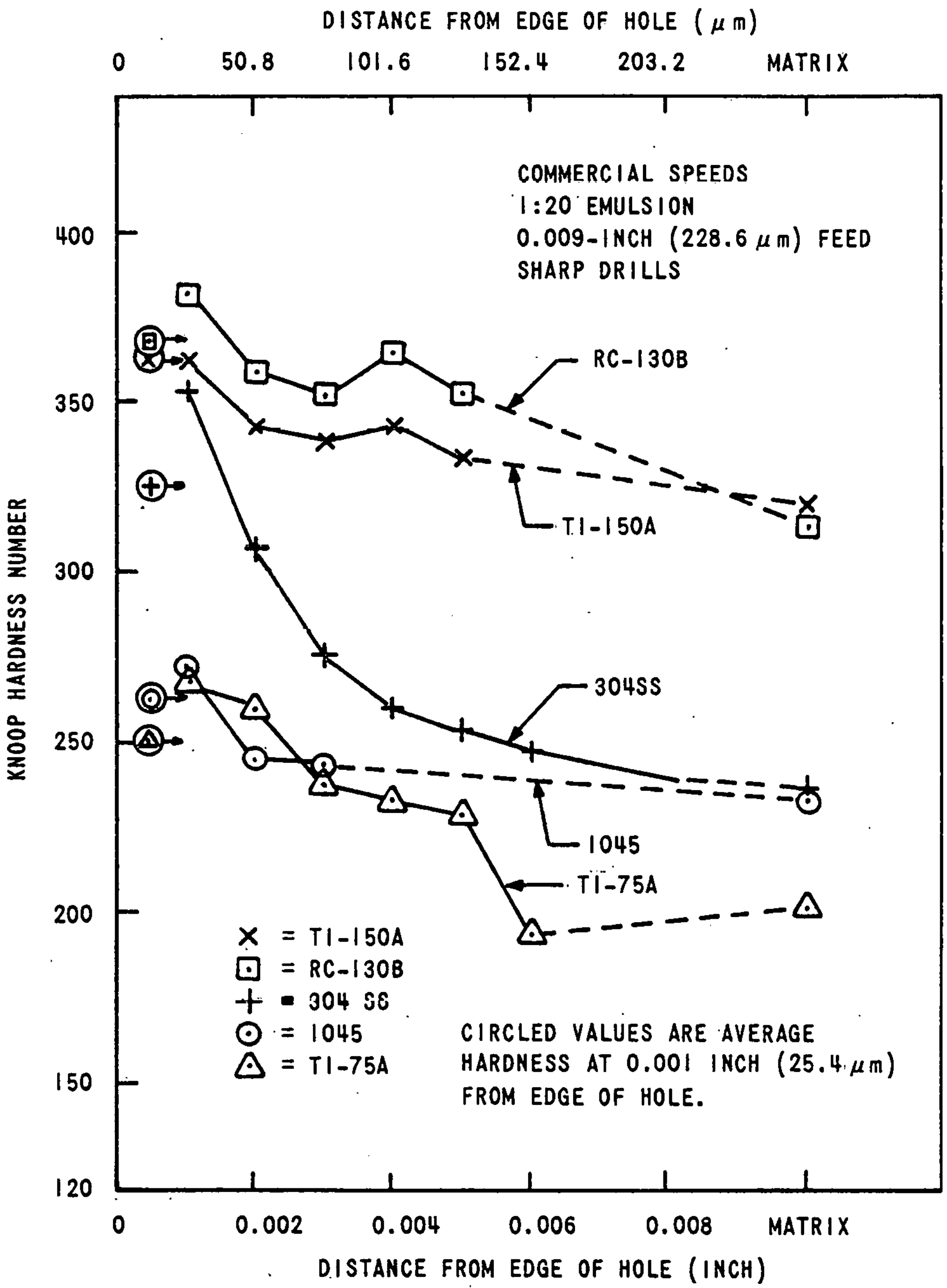

Figure 41. The Effect of Drilling on the Hardness of Material Near the Hole[31]

One particularly noteworthy aspect of Bell and Kearsley's study is their removal of the long, thin, ragged, exit-burr segments prior to making the burr measurements. While this method masks the true length of some burr particles, it provides a more realistic measurement in terms of burr removal. If these long, ragged segments can be easily broken off, their existence offers no burr-removal problems. The firmly attached burr is the one which requires special deburring efforts.

Zaima, Yuki, and Kamo's study[7] also indicated that increases in feedrate result in longer exit-burr lengths. Their study involved the use of five drill-point designs in aluminum.

Another report by Zaima, Iio, and Shirakawa[11] indicates that exit burrs were reduced when coolants were used in drilling aluminum. In this case, the coolant probably minimized the BUE on the cutting lips and corners which had been the cause of the larger burrs. In drilling deep holes in which the coolant cannot prevent the BUE, larger burrs would be expected to occur than when drilling shallow holes.

One of Saito, Sato, Saga, Ogawa, and Shozo's extensive studies[10] indicates that both feedrate and drill diameter significantly affect exit-burr length. In their study, the burr length from thin aluminum sheets increased with the drill diameter up to a 6-mm drill. The spindle speed did not significantly affect the burr length. The shortest burrs were produced by the smallest drill at the lowest feedrate.

Fleming[9] apparently has done more work than any other researcher in measuring drill-exit burrs. His extensive study involved both free, hand-fed and power-fed equipment, bushed and nonbushed holes, and drill diameters from 1/4 to 1/2 inch (6.35 to 12.7 mm). Workpiece materials included 300M steel, titanium, and aluminum. Five aircraft-style drill geometries and three reamer geometries were evaluated.

The study indicated that a drill similar to the eight-facet drill shown in Figure 20 produced the shortest burr. No relationship could be established between drill-corner wear and exit-burr length. Reaming burrs were generally as long as drilling burrs. Free, hand-fed drilling, using portable tools, resulted in larger and less consistent burr lengths than did power-fed drilling. (A recent innovation to prevent uncontrolled breakthrough of hand-fed drills is now available.[32]) Oil-hole drills provided shorter burrs than did standard drills, apparently the result of preventing a BUE.

In relating Fleming's study to the Bendix study, four factors seem significant with regard to corner wear. First, in Fleming's study, only one burr-length measurement was made at each tenth hole. As previously discussed, the failure to make multiple measurements can mask subtle, but significant, effects. Second, the maximum burr-height was chosen as the representative burr-height. Wang, Taraman, and Wu's study[17], however, indicates that an average burr-length is statistically 50 times more repeatable than a maximum burr-length. Although the latter study was of punching burrs, the same basic phenomena are involved. Third, a built-up edge frequently occurs in drilling and, if not noted and prevented, it can mask the difference between sharp and worn drills. While Fleming's study provides a practical evaluation of drill-wear effects, a more clinical evaluation is in order on the same materials. Fourth, tool wear typically has three phases; as shown in Figure 30 of this report, the uniform-wear phase often exhibits a very gradual increase which easily could be overlooked. This may be the case for burr length as a function of corner wear.

Burr height in copper-clad glass-epoxy laminates is definitely a function of the number of holes drilled.[33] In a study of some 200,000 holes, a distinct second-order relationship was observed. As in the current study data, the scatter was large. The study involved the use of four-facet-point drills in the size range from 0.029 to 0.078 inch (0.74 to 1.98 mm) in diameter.

An analysis-of-variance of helix angle, drill-point angle, and feedrate effects in 303Se stainless steel indicated that each of these variables significantly affected the burr length at both the entrance and exit of a hole.[2] A 118-degree point angle produced shorter burrs than did a 60-degree point angle, but it also resulted in a much thicker exit burr. In every case, a 35-degree helix angle resulted in much smaller burrs than did a 25-degree helix angle. A feedrate of 0.0015 ipr (38 μm/rev) resulted in a slightly shorter entrance burr and a slightly longer exit burr than did a 0.0005-ipr (12.7 μm/rev) feedrate. These tests utilized a 0.125-inch (3.175 mm) solid carbide drill. In addition to presenting some of the first published information on drilling-burr size, the report presented the first rudimentary analysis of the manner in which drilling burrs are formed.

Using aluminum, beryllium copper, and 303Se stainless steel, the following relationship was observed for the hardness of exit burrs produced by drilling.[1]

$$H_b = H_p + C\left(\frac{fSD}{\alpha}\right)^r\left(\frac{1-Ar}{100}\right)^{1/2}, \qquad (1)$$

where

H_b = hardness of burr in Knoop hardness numbers using a 0.1-kg load,

H_p = hardness of parent material in Knoop hardness numbers using a 0.1-kg load,

f = feedrate (ipr/t),

S = spindle speed (rpm),

D = drill diameter (inches),

α = K/Cp,

Ar = area reduction of standard tensile specimen,

K = thermal conductivity of workpiece (BTU/hr-ft-°F), and

Cp = specific heat of workpiece (BTU/lb-°F).

For the materials studied, the exponent r was found to be equal to 1.0 and the coefficient C was 7500.

In addition to hardness information, representative burr sizes also were given for hole sizes from 0.078 to 0.125 inch (1.98 to 3.175 mm) in diameter.

Significance of Test Results

The three "conventional" drill geometries used in this study produced reasonably equivalent results, although the radial-lip drill performed better in some materials than did the other drills. The BT drill produced extremely large burrs, and it obviously has no potential for minimizing burrs in steel or aluminum.

Experience with radial-lip drills in other unreported tests indicates that the larger-diameter drills produce significantly shorter burrs in low-carbon steel than do other conventional drill points. Although the data from these tests did not support this conclusion, the apparent reason for the lack of support was the fact that the radial-lip drills used in these tests were not ground to the correct configuration for use in 1018 steel. Each had a small chamfer similar to that of the eight-facet point rather than the smooth radial blend that is typical of the radial-lip drill. On thin workpieces that are not supported beneath the hole, the entrance burrs are small, but the exit burrs tend to be longer because of less resistance to plastic deformation of the material.

Tables 10 through 15 summarize the major factors that are significant in drilling and show their effect on burr properties. The many blank spaces in these tables indicate the scarcity of information available on drilling-burr size. As indicated, low feedrates, small drill diameters, and low values of ultimate elongation minimize the burr thickness and length. From an earlier test, a large helix angle and corner angle (small point

Text continued on page 76.

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

Variable	Effect of Increasing Variable*						
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass	All Mtls.
Feedrate		0	0		0		0
Lip Wear							↑
Corner Wear							
Corner Angle	↓						
Helix Angle	↓						
Diameter	↑				↑	↑	↑
SFPM							
Helix Direction					0**		
Workpiece Thickness	0	0	↓		0		
Number of Holes		↑					
Feedrate Consistency							
Ultimate Elongation							
Lip Relief					0**		

*↑ = larger burr when variable is increased; ↓ = smaller burr when variable is increased; 0 = burr unaffected by variable.
**From Zaima's study.

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

Variable	Effect of Increasing Variable*						
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass	All Mtls.
Feedrate	↑	0	↑		0		↑
Lip Wear							
Corner Wear							0**
Corner Angle	↑						
Helix Angle	↓						
Diameter	↑				↑	↑	
SFPM***					0†		
Helix Direction							
Workpiece Thickness	0	↑	0		0		↓
Number of Holes		↑		↓**			
Feedrate Consistency							↑
Ultimate Elongation							
Lip Relief							

*↑ = larger burr when variable is increased; ↓ = smaller burr when variable is increased; 0 = burr unaffected by variable.

**From Fleming's study.[9]

***Assuming surface velocity is maintained below that recommended for particular tool and workpiece material combination.

†From Saito's study.

Table 12. Effect of Drilling Variables on Entrance-Burr Thickness

	Effect of Increasing Variable*						
Variable	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass	All Mtls.
Feedrate	0	0	0		0		
Lip Wear							
Corner Wear							
Corner Angle							
Helix Angle							
Diameter							
SFPM							
Helix Direction							
Workpiece Thickness	↓	↓	↓		↓		↓
Number of Holes		↑					
Feedrate Consistency							
Ultimate Elongation							
Lip Relief							

*↑ = larger burr when variable is increased; ↓ = smaller burr when variable is increased; 0 = burr unaffected by variable.

Table 13. Effect of Drilling Variables on Entrance-Burr Length

Variable	Effect of Increasing Variable*						
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass	All Mtls.
Feedrate							
Lip Wear							
Corner Wear							
Corner Angle							
Helix Angle							
Diameter							
SFPM							
Helix Direction							
Workpiece Thickness	↓	↓	↓		↓		↓
Number of Holes		↑					
Feedrate Consistency							
Ultimate Elongation							
Lip Relief							

*↑ = larger burr when variable is increased; ↓ = smaller burr when variable is increased; 0 = burr unaffected by variable.

Table 14. Effect of Drilling Variables on Repeatability of Exit-Burr Thickness

Variable	Effect of Increasing Variable*						
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass	All Mtls.
Feedrate							
Lip Wear							
Corner Wear							
Corner Angle							
Helix Angle							
Diameter	↓				↓	↓	
SFPM							
Helix Direction							
Workpiece Thickness							
Number of Holes							
Feedrate Consistency							
Ultimate Elongation							
Lip Relief							

*↑ = larger burr when variable is increased; ↓ = smaller burr when variable is increased; 0 = burr unaffected by variable.

Table 15. Effect of Drilling Variables on Repeatability of Exit-Burr Length

Variable	Effect of Increasing Variable*						
	303Se SST	17-4PH SST	1018 Steel	Titanium	6061-T6 Aluminum	Brass	All Mtls.
Feedrate							
Lip Wear							
Corner Wear							
Corner Angle							
Helix Angle							
Diameter	↓				↓	↓	
SFPM							
Helix Direction							
Workpiece Thickness							
Number of Holes							
Feedrate Consistency				↓**			
Ultimate Elongation							
Lip Relief							

*↑ = larger burr when variable is increased; ↓ = smaller burr when variable is increased; 0 = burr unaffected by variable.
**From Fleming's study.[9]

angle) were found to reduce exit-burr thickness in 303Se stainless steel. However, a large corner angle produced slightly longer exit burrs in the tests shown for 303Se stainless steel.

The effective application of coolants also appears to play a major role in minimizing burr size. Most of the drills used in the life studies had a BUE welded to the lips. If the drill lips can be kept cool and lubricated, a BUE will not form. This will result in smaller and more consistent burrs.

As indicated by Fleming[9] and others, the elimination of drill surge at breakthrough also should help to minimize burrs. This may require a programmed breakthrough to reduce the elastic energy stored in the drill and the machine tool. The use of so-called "constant feed" equipment may not be adequate for minimizing burrs because of this stored elastic energy and the wear of the machine tool.

The effects of such drill-geometry features as lip-height runout, web centrality, and lip-relief angles have not been evaluated. As an after-the-fact observation, they may be as significant as drill-point shape.

The use of a backup material results in the production of much smaller burrs. Burrs are minimized by using a backup hole having the same diameter as that of the drill. When a solid backup support is used, it should be as hard as possible without affecting the drill life. Even small gaps of 0.001 inch (25.4 μm) between the backup and the workpiece will allow significant burrs to form.

Burr thickness and length follow a typical wear-failure pattern in 17-4PH stainless steel. Similar results might be expected in other materials provided that the drill is run to complete failure. Exit-burr thickness can be predicted from exit-burr length measurements for stainless steel. No relationship has been found between these properties when other materials are used.

For low-quantity, precision miniature parts, exit-burr thickness is generally the key parameter which determines whether parts must be manually deburred or whether mechanized processes can be used. The burr thickness determines the time required for a given process, and the time is proportional to the stock-loss and edge-radiusing. Parts having tolerances of 0.001 inch (25.4 μm) or less often cannot accommodate the stock-loss or edge-radiusing which accompanies the removal of a 0.002-inch-thick (50.8 μm) burr.

Thus when the objective is to minimize deburring costs for precision miniature parts, the exit-burr thickness must be minimized. With the exception of 303Se stainless steel, neither drill geometry nor feedrate significantly affected exit-burr thickness (Table 16).

Table 16. Workpiece Material and Variable Combinations to Minimize Exit-Burr Thickness

	Variable*	
Workpiece Material	Drill	Feedrate (ipr)**
303Se SST	Radial Lip	0.0005
17-4PH SST	Not Critical	0.0005 to 0.0015
1018 Steel	Not Critical	0.0005 to 0.0015
6061-T6 Al	Not Critical	0.0005 to 0.0015

*Based on drilling 50 holes or less and using feedrates and speeds compatible with the workpiece material.
**0.0001 ipr = 2.54 μm/rev.

To minimize exit-burr thickness when using 303Se stainless steel, radial-lip drills should be used. Feedrates of 0.0005 ipr (12.7 μm/rev) or less, as opposed to a commercially recommended rate of 0.0030 ipr (76.2 μm/rev), will further reduce the burr thickness. Drills having helix angles of 35 degrees should produce thinner exit burrs than those having conventional helix angles. These drills also will minimize burr length in 303Se stainless steel when commercial feedrates are used (Table 17).

Sharp drill corners are a necessity for minimizing exit-burr thickness. The maintaining of sharp corners requires positive feed and reasonable spindle speeds with no spindle vibration. In 303Se stainless steel for example, spindle speeds above 100 surface feet per minute (0.508 m/s) will cause tool softening, will increase wear, and will accelerate the formation of a built-up edge.

ACCOMPLISHMENTS

The effects of feedrate, workpiece thickness, drill geometry, workpiece material, backup techniques, and drill wear on burr size have been evaluated for 0.125-inch (3.175 mm) drills. A conceptual model of burr formation has been prepared. The results will assist manufacturing engineers in selecting a drilling technique which will produce the smallest and most easily removed burrs.

Table 17. Workpiece Material and Variable Combinations to Minimize Exit-Burr Length

Workpiece Material	Variable* Drill	Feedrate (ipr)**	Helix Angle (Degrees)
303Se SST	Eight-Facet	0.0005 to 0.0030	35
	Radial Lip	0.0005 to 0.0030	35
17-4PH SST	Not Critical	0.0005 to 0.0015	
1018 Steel	Not Critical	0.0005	
6061-T6 Al	Not Critical	0.0005 to 0.0015	

*Based on drilling 50 holes or less and using feedrates and speeds compatible with the workpiece material.
**0.0001 ipr = 2.54 μm/rev.

FUTURE WORK

An additional test will be conducted to compare the performance of properly ground radial-lip drills with that of conventional drills. Using four workpiece materials, the test will determine the effects of surface velocity and drill diameter. Drill-life tests will be continued for 303Se stainless steel, 1018 steel, and 6061-T6 aluminum.

Milling, turning, and grinding tests also will be performed along with additional burr-prevention and deburring tests.

REFERENCES

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

[2]L. K. Gillespie, *The Formation and Properties of Machining Burrs.* MS Thesis, Utah State University, Logan, Utah, 1973.

[3]L. K. Gillespie, *The Effects of Reaming Variables on Burr Properties* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-1083, April, 1974.

[4]L. K. Gillespie, *Properties of Burrs Produced by Ball Broaching* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-1084, April, 1974.

[5]L. K. Gillespie and P. T. Blotter, *The Formation and Properties of Machining Burrs,* ASME paper 75-PROD-J, 1975.

[6]L. K. Gillespie, *The Effect of Cutting Edge Radius on Poisson Burr Properties,* SME paper MR74-990, 1974.

[7]S. Zaima and others, "Drilling of Aluminum Alloy Plates with Special Type Point Drill," *Journal of Japan Institute of Light Metals,* Volume 18, Number 5, May, 1968, pp 269-276; Volume 18, Number 6, June, 1968, pp 307-313.

[8]Clarence L. Bell and Blaine Kearsley, *The Effects of Drill Point Geometry, Feed and Speed on Cutting Forces and Burrs,* Unpublished report prepared for Utah State University, Department of Manufacturing Engineering, Logan, Utah, 1963.

[9]C. M. Fleming, *Precision Hole Generation Methods,* McDonnell Aircraft Company: AFML-TR-73-135, March, 1973.

[10]Yuzo Saito and others, "Drilling Machinability for Aluminum Sheets," *Journal of Japan Institute of Light Metals, (KEI Kinzoku),* Volume 20, Number 2, February, 1970, pp 69-76.

[11]Shigeo Zaima and others, "On the Effect of Cutting Fluid on Drilling Aluminum Alloy," *Journal of Japan Institute of Light Metals, (KEI Kinzoku),* Volume 19, Number 1, January, 1969, p 8.

[12]Otto Kienzle and D. Werner Kienzle, *Tool Wear in the Cutting of Thin-Gauge Steel Sheets.* ASTME Research Report Number 22, May 1, 1959. Translation and discussion of article in *Stahl und Eisen,* Volume 78, Number 12, June 12, 1958, pp 820-828.

[13]John E. Biegel and Robert E. Holmes, *Development of a Punchability Rating Method for Electrical Steels*. ASTME Research Report Number 30, March 1, 1961.

[14]Hans Buhler and Fedor Pollmar, "The Formation of Burrs in the Cutting of Thin Sheet," *Bander-Bleche-Rohre*, Volume 12, Number 3, March, 1971, pp 105-111.

[15]Harding R. Hugo, "How to Improve Metal Stamping Die Performance," *Sheet Metal Industries*, February, 1971, pp 120-135.

[16]Frederico Strasser, "How Control of Burrs Aids Sheet Metal Stamping," *The Iron Age*. Volume 185, Number 3, January 21, 1960, pp 90-92.

[17]K. K. Wang and others, *An Analysis of Punching Variables by Two-Level Fractional Factorial Design*. ASME Paper 69-WA/Prod 27, 1969.

[18]C. S. Wukusik and R. S. Zeno, "Improving Punchability of Silicon Steel," *Tool Engineer*. Volume 41, Number 12, December, 1958, pp 63-70.

[19]James Nielson McBride, *The Magnitude of Burrs Caused by Electrical-Discharge Machining*. MS thesis, Utah State University, Logan, Utah, 1969.

[20]M. C. Shaw and C. J. Oxford, Jr., "On the Drilling of Metals 2 - The Torque and Thrust in Drilling," *Transactions of the ASME*, January, 1957, pp 139-148.

[21]R. A. Williams, *A Study of the Drilling Process*, ASME Paper 73-WA/Prod-6, 1973.

[22]W. A. Haggerty, "Effect of Point Geometry and Dimensional Symmetry on Drill Performance," *International Journal of Machine Tool Design and Research*, Volume 1, 1961, pp 41-58.

[23]Joseph Datsko, *Material Properties and Manufacturing Processes*. New York: John Wiley and Sons, 1966.

[24]Serope Kalpakjian, *Mechanical Processing of Materials*. New York: D. Van Nostrand Co., 1967.

[25]*Armco 17-4PH Precipitation-Hardening Stainless Steel Bar and Wire*, Product Data Brochure S-6b, Armco Steel Corp., Baltimore, Maryland, 1970.

[26]*Stainless Steels*, Product Technical Brochure, Universal-Cyclops Specialty Steel Division, Bridgeville, Pennsylvania, 1965.

[27]J. R. Mulkey, *Strain Hardening Exponent for 17-4PH Stainless Steel* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-577, December, 1971 (Available from NTIS).

[28]Theodore Baumeister, editor, *Mechanical Engineers' Handbook.* New York: McGraw-Hill, 1958.

[29]F. Schafer, "Entgraten in der Fertigungstechnik," *Werkstattstechnik,* Volume 63, 1973, pp 692-696.

[30]L. K. Gillespie, *The Measurement of Burrs,* SME paper MR74-993, 1974.

[31]USAF Data.

[32]"New Drill Guide Improves Efficiency in Drilling with Portable Tools," *Cutting Tool Engineering,* January/February, 1974, pp 18-19.

[33]L. K. Gillespie, *Drilling Printed Circuit Boards* (Final Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-279, January, 1972 (Available from NTIS).

Appendix

MEASUREMENTS OF BURR PROPERTIES

Table A-1. Identification of Test Conditions for Drill-Geometry Study

Level	Factor A Drill Point	B Workpiece Material	C Workpiece Thickness (Inch) (mm)	D Feedrate (ipr) (μm/rev)
1	Eight-Facet	303Se SST	0.032 (0.813)	0.0005 (12.7)
2	Radial Lip	6061-T6 Al	0.188 (4.775)	0.0015 (38.1)
3	Four-Facet	1018 Steel		
4	BT			

Table A-2. Burr Sizes Produced by Four Drills

Factor and Level A B C D	Sequence Number	Entrance Burr Thickness (0.0001 Inch)*	Entrance Burr Length (0.0001 Inch)	Exit Burr Thickness (0.0001 Inch)	Exit Burr Length (0.0001 Inch)
1 1 1 1	23	14,16	12,20	17,24	17,75
1 1 1 2	37	22,17	46,44	35,21	269,89
1 1 2 1	45	4,19	18,44	0,30	0,24
1 1 2 2	15	14,26	30,28	24,27	138,37
1 2 1 1	57	10,0	12,0	11,23	41,89
1 2 1 2	50	12,0	17,0	0,16	0,13
1 2 2 1	55	8,0	24,0	18,27	21,13
1 2 2 2	52	21,39	21,23	30,22	24,17
1 3 1 1	56	11,12	21,54	4,10	7,8
1 3 1 2	59	0,22	0,10	18,5	170,17
1 3 2 1	13	21,10	21,33	21,13	59,37
1 3 2 2	1			1,4	17,8
2 1 1 1	43	4,5	4,5	15,8	27,23
2 1 1 2	18	11,7	6,52	27,20	611,242
2 1 2 1	11	0,0	0,0	7,18	86,93
2 1 2 2	17	0,0	0,0	25,20	59,16
2 2 1 1	9	11,0	25,0	8,15	26,15
2 2 1 2	2	10,38	4,7	29,24	18,16
2 2 2 1	4	20	13	39,31	25,36
2 2 2 2	27	13	5	30,24	57,56
2 3 1 1	19	16,0	3,0	18,15	9,5
2 3 1 1	53	31,30	80,69	11,19	13,109
2 3 1 2	66	28,47	93,35	18,35	298,602
2 3 2 1	47	6,6	28,32	6,4	14,44
2 3 2 2	64	13	19	22	7

Table A-2 Continued. Burr Sizes Produced by Four Drills

Factor and Level A B C D	Sequence Number	Entrance Burr Thickness (0.0001 Inch)*	Entrance Burr Length (0.0001 Inch)	Exit Burr Thickness (0.0001 Inch)	Exit Burr Length (0.0001 Inch)
3 1 1 1	14	18,24	11,38	17,13	80,61
3 1 1 2	61	15,19	38,14	9,22	9,199
3 1 2 1	65	12,7	47,43	16,16	149,10
3 1 2 2	16	39,0	14,0	19,30	147,248
3 1 2 2	36	34,0	62,0	42,13	136,168
3 2 1 1	41	13,25	56,47	10,22	32,20
3 2 1 2	40	10,0	21,0	15,10	14,31
3 2 2 1	8	9,11	22,26	34,23	20,17
3 2 2 2	26	5	27	10,21	17,11
3 3 1 1	32	4,20	55,20	16,16	114,132
3 3 1 2	42	11,19	30,68	14,10	14,10
3 3 2 1	39			8,5	22,8
3 3 2 2	21	11	24	10,6	34,44
4 1 1 1	63	14,14	25,18	16,16	26,204
4 1 1 2	48	33,36	89,184	85,86	616,752
4 1 2 1	51	96,49	115,111	127,74	824,800
4 1 2 2	29	25,32	69,42	166,188	518,781
4 2 1 1	54	61,57	128,130	129,78	666,573
4 2 1 2	25	46,28	63,122	61,76	574,444
4 2 2 1	28	21,28	128,144	35,55	136,160
4 2 2 2	58	20,0	65,0	68,105	289,278
4 3 1 1	33	41,55	99,99	35,45	459,528
4 3 1 2	60	10,11	27,8	25,32	612,673
4 3 2 1	24	5	44	37,30	504,460
4 3 2 2	46	32,40	85,111	Drill Broke	Drill Broke

*0.0001 inch = 2.54 μm.

Table A-3. Identification of Test Conditions for Drill-Geometry Study Using 17-4PH (H900) Stainless-Steel Workpiece

	Factor				
	A	B Workpiece Thickness		C Feedrate	
Level	Drill Point	Inch	mm	ipr	μm/rev
1	Eight-Facet	0.032	0.83	0.0005	12.7
2	Radial Lip	0.188	4.775	0.0015	38.1
3	Four-Facet				
4	BT				

Table A-4. Burr Sizes Produced by Four Drills in 17-4PH Stainless Steel

Factor and Level A B C	Sequence Number	Entrance Burr Thickness (0.0001 Inch)*	Entrance Burr Length (0.0001 Inch)	Exit Burr Thickness (0.0001 Inch)	Exit Burr Length (0.0001 Inch)
1 1 1	35	2,9	2,27	5,7	14,37
1 1 2	10	7	13	16	52
1 2 1	5	12,6	20,31	12,9	12,18
1 2 2	31	5	16	12,10	45,37
2 1 1	49	4	13	9,6	7,13
2 1 2	12	10	11	6,3	7,6
2 2 1	3	4,3	19,23	8,5	214,26
2 2 2	7	3,4	18,26	18,4	43,14
3 1 1	20	4,3	4,6	4,9	5,9
3 1 2	6	6	7	14	17
3 2 1	22	2	8	6,4	16,19
3 2 2	34	17,7	17,20	8,7	11,44
4 1 1	44	3,5	2,17	6,5	9,6
4 1 2	30	3,18	6,30	11,2	357,2
4 2 1	38	7,7	41,48	10,13	50,49
4 2 2	62	3	18	15,8	97,155

*0.0001 inch = 2.54 μm.

Table A-5. Effect of Drill Wear on Burr Size

Specimen and Hole Number	Entrance Burr Thickness (0.0001 Inch)*	Entrance Burr Length (0.0001 Inch)	Exit Burr Thickness (0.0001 Inch)	Exit Burr Length (0.0001 Inch)
1018 Steel Specimen; Four-Facet Drill				
1-05	21,0,35,34	8,0,11,8	19,16,15,12	10,114,13,107
1-07	19,0,10,17	3,0,34,4	13,14,12,14	54,45,18,42
1-10	32,0,30,46	7,0,3,11	0,0,16,0	0,0,48,0
1-17	17,13,18,5	60,42,63,3	11,10,20,33	22,106,40,64
1-20	0,21,10,20	0,59,5,51	22,22,10,20	12,32,10,57
1-23	41,0,0,32	7,0,0,7	23,25,25,20	56,70,140,41
1-28	20,0,7,36	7,0,7,8	17,21,16,19	10,121,13,116
1-30	18,29,21,0	10,13,3,0	21,14,18,15	65,75,164,91
1-33	27,36,8,31	7,10,5,17	5,0,22,23	5,0,150,73
1-40	38,44,12,53	9,15,5,18	22,55,21,21	72,17,72,81
1-43	0,6,5,0	0,26,5,0	16,21,41,27	77,44,40,122
1-46	32,27,0,0	7,9,0,0	47,21,20,21	74,56,56,45
$\bar{x}$	18	12	19	57
σ	9	12	7	23
1018 Steel Specimen; Radial-Lip Drill				
2-05	22,18,19,8	7,55,8,25	21,22,27,23	85,84,80,81
2-07	0,0,21,16	0,0,8,49	16,28,20,22	53,59,64,52
2-10	35,19,21,25	16,13,51,15	18,20,25,19	18,59,15,26
2-17	46,20,31,21	16,16,23,31	25,19,29,25	34,37,40,57
2-20	20,0,16,14	20,0,54,53	16,16,13,26	51,23,12,30
2-23	20,26,11,19	12,15,41,12	19,19,15,16	61,212,60,48
2-28	16,1,26,41	49,5,9,19	28,22,28,23	61,55,51,54
2-30	0,0,18,12	0,0,11,48	12,14,24,21	27,62,107,253

Table A-5 Continued. Effect of Drill Wear on Burr Size

Specimen and Hole Number	Entrance Burr		Exit Burr	
	Thickness (0.0001 Inch)*	Length (0.0001 Inch)	Thickness (0.0001 Inch)	Length (0.0001 Inch)
2-33	12,29,28,27	5,20,13,19	18,34,10,19	10,22,19,30
2-40	32,14,8,31	20,52,32,26	12,16,17,21	56,19,17,17
2-43	36,26,16,11	13,33,12,44	16,19,21,20	69,38,19,78
2-46	13,22,13,15	43,48,10,30	14,17,17,23	7,49,37,17
$\bar{x}$	19	23	20	52
σ	7	7	3	30
1018 Steel Specimen; Eight-Facet Drill				
3-05	12,11,22,15	5,20,9,44	20,24,19,19	42,35,52,28
3-07	13,15,9,7	35,6,50,29	16,13,14,14	26,64,36,42
3-10	25,14,33,31	15,50,12,48	20,23,19,21	38,40,37,45
3-17	29,15,20,20	12,37,15,41	22,23,21,30	16,21,46,41
3-20	10,12,5,21	38,50,28,13	19,18,21,19	66,42,46,37
3-23	21,21,10,10	3,9,4,25	27,31,28,28	79,143,177,151
3-28	19,18,20,18	7,49,10,48	21,13,21,14	42,29,48,30
3-30	22,16,24,8	16,41,53,88	14,19,17,16	186,92,48,100
3-33	33,25,21,18	65,50,73,8	34,30,23,25	61,74,73,86
3-40	14,9,20,27	59,28,51,21	29,20,28,25	40,52,67,89
3-43	14,0,18,8	40,0,55,40	29,21,18,17	55,90,79,270
3-46	24,26,27,18	34,43,19,35	27,24,21,25	86,139,86,93
$\bar{x}$	18	32	22	70
σ	5	11	4	38
6061-T6 Aluminum Specimen; Four-Facet Drill				
11-05	32,11,14,14	16,10,48,22	7,42,13,7	14,14,9,40
11-07	17,8,9,10	34,48,40,43	14,19,29,19	10,31,8,36
11-10	9,12,10,10	43,43,43,7	19,20,15,30	43,5,20,45
11-17	0,9,19,11	0,30,24,44	18,11,14,8	5,9,37,13

Table A-5 Continued. Effect of Drill Wear on Burr Size

Specimen and Hole Number	Entrance Burr Thickness (0.0001 Inch)*	Entrance Burr Length (0.0001 Inch)	Exit Burr Thickness (0.0001 Inch)	Exit Burr Length (0.0001 Inch)
11-20	8,10,9,14	29,39,39,6	15,11,9,15	46,22,25,10
11-23	15,17,14,29	4,23,27,16	23,15,17,23	12,13,15,83
11-28	20,14,12,18	24,32,35,30	10,10,28,16	37,35,7,7
11-30	10,20,14,20	37,15,21,21	14,13,3,18	48,18,10,26
11-33	16,21,20,21	10,30,11,30	15,16,15,14	36,8,28,42
11-40	23,24,26,13	8,29,24,34	23,16,15,10	42,37,6,52
11-43	24,12,12,21	28,34,36,6	15,4,7,19	16,8,4,23
11-46	14,10,12,11	14,33,6,36	18,16,23,13	13,24,11,24
$\bar{x}$	15	26	16	24
σ	4	6	3	6
6061-T6 Aluminum Specimen; Radial-Lip Drill				
12-05	20,10,23,15	5,29,9,7	11,16,22,0	97,10,19,0
12-07	8,40,22,24	31,14,7,7	8,11,24,31	55,29,8,11
12-10	15,29,26,35	5,9,36,8	12,11,21,13	7,33,13,5
12-17	6,12,3,0	37,47,31,0	9,15,14,20	36,14,20,11
12-20	37,31,32,0	7,9,9,0	15,42,10,14	10,11,37,8
12-23	18,31,9,15	8,12,32,40	15,21,22,13	38,26,33,30
12-28	26,23,19,5	4,8,19,31	15,10,15,5	20,10,8,11
12-30	38,8,19,10	8,43,7,24	19,18,7,18	27,8,22,15
12-33	20,7,19,22	3,20,3,7	7,7,23,9	14,29,13,7
12-40	12,23,15,7	23,10,5,22	9,15,22,19	37,152,26,15
12-43	22,19,11,8	13,8,32,28	16,21,14,10	36,18,102,28
12-46	19,15,7,31	7,20,32,9	18,24,29,19	153,73,17,16
$\bar{x}$	18	16	16	30
σ	6	6	3	18

Table A-5 Continued. Effect of Drill Wear on Burr Size

Specimen and Hole Number	Entrance Burr		Exit Burr	
	Thickness (0.0001 Inch)*	Length (0.0001 Inch)	Thickness (0.0001 Inch)	Length (0.0001 Inch)
6061-T6 Aluminum Specimen; Eight-Facet Drill				
13-05	6,11,6,23	20,41,36,6	16,3,13,19	16,47,20,21
13-07	8,9,26,30	6,6,6,32	9,16,14,22	3,16,23,16
13-10	40,13,5,11	3,59,18,6	12,19,15,18	153,169,19,31
13-17	14,12,5,15	8,56,9,3	19,20,9,16	23,29,35,14
13-20	22,25,53,25	6,8,16,10	18,3,26,25	11,50,21,22
13-23	8,55,7,20	22,13,18,5	14,28,17,18	43,54,21,41
13-28	8,7,10,27	25,6,47,9	21,20,28,17	28,22,19,46
13-30	4,15,6,9	20,28,33,34	17,5,11,15	39,64,21,26
13-33	11,18,5,17	52,26,30,5	13,19,19,20	41,23,47,21
13-40	4,11,30,13	28,50,7,10	29,18,27,22	10,19,17,11
13-43	7,0,13,11	28,0,37,21	18,16,25,18	40,29,32,103
13-46	9,9,15,28	32,36,46,3	21,15,11,14	19,12,21,19
$\bar{x}$	15	21	17	34
σ	6	6	3	21
303 Se Stainless-Steel Specimen; Four-Facet Drill				
21-05	0,30,3,9	0,15,3,27	30,23,25,20	115,79,114,98
21-07	13,23,14,21	5,32,27,36	27,22,32,25	90,113,159,114
21-10	25,16,0,29	22,16,0,4	23,32,26,27	55,179,7,203
21-17	10,12,20,18	7,4,26,17	39,30,28,28	49,71,156,14
21-20	10,0,31,0	36,0,15,0	23,23,30,37	127,115,130,133
21-23	4,15,19,17	3,30,9,13	24,27,23,20	40,28,52,119
21-28	32,23,35,22	14,10,23,18	23,36,28,35	118,100,46,97
21-30	19,17,17,0	15,7,8,0	29,19,36,17	43,85,148,186

Table A-5 Continued. Effect of Drill Wear on Burr Size

Specimen and Hole Number	Entrance Burr		Exit Burr	
	Thickness (0.0001 Inch)*	Length (0.0001 Inch)	Thickness (0.0001 Inch)	Length (0.0001 Inch)
21-33	27,23,0,0	18,38,0,0	37,29,29,31	195,158,118,195
21-40	0,22,29,19	0,28,75,73	28,16,19,21	92,6,20,71
21-43	24,19,0,12	17,16,0,4	22,21,28,24	31,47,27,31
21-46	25,24,13,15	11,5,19,27	40,52,52,39	22,27,32,28
$\bar{x}$	16	16	28	89
σ	5	9.8	6	42
303 Se Stainless-Steel Specimen; Radial-Lip Drill				
22-05	9,10,8,10	28,6,17,3	15,14,17,15	9,13,11,71
22-07	13,19,13,43	5,10,9,10	8,16,13,18	11,17,39,11
22-10	26,10,15,13	6,10,19,9	19,19,10,19	54,37,40,30
22-17	3,7,17,6	44,17,4,25	20,23,20,23	129,9,98,77
22-20	16,0,21,21	6,0,10,8	19,25,14,18	56,147,55,13
22-23	4,15,16,11	8,7,10,35	17,18,9,25	73,48,11,40
22-28	0,14,10,14	0,4,33,7	15,19,22,19	31,37,25,26
22-30	6,33,5,15	39,8,28,9	17,19,15,21	130,134,42,15
22-33	0,23,8,12	0,18,9,14	10,16,20,8	26,10,35,8
22-40	0,19,20,20	0,13,7,4	15,17,14,16	21,18,30,37
22-43	12,16,24,0	22,9,9,0	15,14,19,18	37,138,29,45
22-46	22,8,6,10	9,17,27,15	17,15,19,18	36,46,45,21
$\bar{x}$	13	15	17	44
σ	4	5	2	22
303 Se Stainless-Steel Specimen; Eight-Facet Drill				
23-05	3,15,5,13	9,6,15,4	25,29,32,33	87,77,98,81
23-07	12,9,19,19	9,16,5,9	30,14,19,14	30,28,51,48
23-10	19,12,18,19	3,7,6,7	24,24,27,27	56,53,54,107
23-17	11,21,19,17	5,12,12,11	52,51,51,52	283,521,517,183

Table A-5 Continued. Effect of Drill Wear on Burr Size

Specimen and Hole Number	Entrance Burr		Exit Burr	
	Thickness (0.0001 Inch)*	Length (0.0001 Inch)	Thickness (0.0001 Inch)	Length (0.0001 Inch)
23-20	9,4,22,15	28,2,8,2	26,23,19,22	60,66,45,36
23-23	4,11,0,19	4,25,0,9	32,25,33,27	105,65,115,120
23-28	20,10,18,16	3,5,10,4	21,22,28,21	75,71,71,84
23-30	11,17,3,19	9,11,9,7	31,25,19,20	34,16,68,17
23-33	13,14,14,16	4,6,6,8	22,19,19,14	76,77,87,101
23-40	2,11,2,5	2,29,2,5	19,18,19,16	31,90,90,79
23-43	10,19,22,13	43,5,23,5	28,21,17,22	82,87,85,88
23-46	9,13,21,18	37,14,13,13	27,23,21,17	69,45,76,61
$\bar{x}$	13	10	25	95
σ	4	5	9	91
17-4PH Stainless-Steel Specimen; Four-Facet Drill				
31-05	30,16,0,17	7,11,0,9	22,18,22,16	90,46,89,59
31-10	10,26,2,31	8,26,2,31	17,19,19,18	107,74,42,74
31-19	8,11,11,4	22,27,32,28	22,22,22,27	180,146,200,97
31-20	8,7,5,15	27,28,2,10	38,30,66,23	255,256,188,424
31-21	0,0,13,0	0,0,11,0	117,118,114, 105	626,238,647,821
31-22	45,75,39,71	69,138,62,85	128,152,139, 145	447,477,517,576
$\bar{x}$	19	26	59	278
σ	20	32	54	22
17-4PH Stainless-Steel Specimen; Radial-Lip Drill				
32-05	14,13,17,0	25,26,33,0	0,7,0,0	0,18,0,0
32-10	3,0,0,0	3,0,0,0	21,14,14,11	9,11,9,13
32-16	12,18,8,0	4,4,3,0	0,12,15,11	0,134,50,46
32-17	0,0,20,0	0,0,4,0	17,17,24,11	26,44,76,90

Table A-5 Continued. Effect of Drill Wear on Burr Size

Specimen and Hole Number	Entrance Burr		Exit Burr	
	Thickness (0.0001 Inch)*	Length (0.0001 Inch)	Thickness (0.0001 Inch)	Length (0.0001 Inch)
32-18	28,11,22,10	8,7,7,3	9,15,22,18	104,14,105,100
32-19	0,23,0,30	0,10,0,7	109,106,128, 122	413,670,784,331
32-20	0,43,45,34	0,77,44,52	130,142,123, 150	477,659,349,559
$\bar{x}$	13	11	45	174
σ	10	16	56	25
17-4PH Stainless-Steel Specimen; Eight-Facet Drill				
33-05	20,12,16,16	9,4,10,7	23,18,23,17	213,178,210,177
33-07	23,15,31,31	8,8,7,5	99,107,107,107	435,328,331,703

*0.0001 inch = 2.54 μm.

Table A-6. Results of Drilling-Reaming Test

Code	Entrance Burr		Exit Burr	
	Thickness (Inch)*	Length (Inch)	Thickness (Inch)	Length (Inch)
1	1018 Steel; Drill Only			
	0.0030	0.0031	0.0034	0.0096
	0.0056	0.0087	0.0035	0.0095
	0.0031	0.0017	0.0044	0.0084
	0.0073	0.0054	0.0041	0.0130
	0.0016	0.0054	0.0056	0.0135
	0.0024	0.0034	0.0041	0.0062
	0.0039	0.0020	0.0029	0.0068
	0.0035	0.0026	0.0037	0.0073
	0.0093	0.0047	0.0038	0.0126
	0.0035	0.0073	0.0061	0.0091
$\bar{x}$	0.00432	0.00443	0.00416	0.00960
σ	0.00239	0.00170	0.00100	0.00230
5	1018 Steel; Drill and Ream			
	0.0024	0.0021	0.0015	0.0049
	0.0018	0.0034	0.0013	0.0077
	0	0	0.0016	0.0047
	0.0023	0.0017	0.0017	0.0027
	0.0019	0.0019	0.0014	0.0071
	0.0017	0.0037	0.0023	0.0065
	0.0015	0.0012	0.0021	0.0054
	0.0026	0.0046	0.0015	0.0051
	0.0012	0.0036	0.0016	0.0057
	0.0013	0.0040	0.0018	0.0065
$\bar{x}$	0.00166	0.00262	0.00168	0.00563
σ	0.00026	0.00031	0.00013	0.00109

Table A-6 Continued. Results of Drilling-Reaming Test

Code	Entrance Burr Thickness (Inch)*	Entrance Burr Length (Inch)	Exit Burr Thickness (Inch)	Exit Burr Length (Inch)
2	303 Se Stainless Steel; Drill Only			
	0.0016	0.0049	0.0017	0.0053
	0	0	0.0020	0.0069
	0.0011	0.0012	0.0012	0.0024
	0.0028	0.0019	0.0022	0.0086
	0.0048	0.0034	0.0029	0.0030
	0.0024	0.0037	0.0017	0.0036
	0.0014	0.0050	0.0017	0.0068
	0.0025	0.0013	0.0022	0.0034
	0.0022	0.0036	0.0020	0.0025
	0.0034	0.0078	0.0023	0.0238
$\bar{x}$	0.00222	0.00328	0.00199	0.00663
σ	0.00124	0.00169	0.00038	0.00405
6	303 Se Stainless Steel; Drill and Ream			
	0.0006	0.0018	0.0005	0.0121
	0.0005	0.0011	0.0033	0.0079
	0.0016	0.0015	0.0023	0.0051
	0	0	0.0020	0.0044
	0	0	0.0021	0.0057
	0.0021	0.0016	0.0019	0.0074
	0.0015	0.0037	0.0021	0.0046
	0.0024	0.0062	0.0020	0.0055
	0.0014	0.0029	0.0015	0.0082
	0.0028	0.0057	0.0069	0.0074
$\bar{x}$	0.00129	0.00241	0.00246	0.00683
σ	0.00049	0.00094	0.00127	0.00170

Table A-6 Continued. Results of Drilling-Reaming Test

Code	Entrance Burr Thickness (Inch)*	Entrance Burr Length (Inch)	Exit Burr Thickness (Inch)	Exit Burr Length (Inch)
3	17-4PH Stainless Steel; Drill Only			
	0	0	0.0025	0.0104
	0.0014	0.0017	0.0066	0.0105
	0.0022	0.0015	0.0044	0.0129
	0	0	0.0019	0.0035
	0.0019	0.0008	0.0014	0.0033
	0	0	0.0037	0.0128
	0.0030	0.0014	0.0044	0.0104
	0.0009	0.0012	0.0062	0.0132
	0	0	0.0015	0.0045
	0	0	0.0029	0.0065
$\bar{x}$	0.00094	0.00066	0.00355	0.00880
σ	0.00097	0.00074	0.00176	0.00409
7	17-4PH Stainless Steel; Drill and Ream**			
	0.0025	0.0024	0.0050	0.0437
	0.0040	0.0051	0.0038	0.0364
	0.0034	0.0084	0.0072	0.0418
	0.0038	0.0029	0.0059	0.0240
	0.0032	0.0031	0.0059	0.0278
	0.0022	0.0027	0.0064	0.0234
	0.0026	0.0037	0.0036	0.0560
	0.0035	0.0094	0.0045	0.0539
	0.0032	0.0034	0.0044	0.0716
	0.0024	0.0032	0.0043	0.0307
$\bar{x}$	0.00308	0.00443	0.00510	0.04093
σ	0.00049	0.00259	0.00085	0.00886

Table A-6 Continued. Results of Drilling-Reaming Test

Code	Entrance Burr		Exit Burr	
	Thickness (Inch)*	Length (Inch)	Thickness (Inch)	Length (Inch)
4	6061-T6 Aluminum; Drill Only			
	0.0033	0.0012	0.0033	0.0068
	0.0029	0.0032	0.0031	0.0032
	0.0026	0.0013	0.0025	0.0075
	0.0039	0.0017	0.0030	0.0060
	0.0041	0.0031	0.0082	0.0093
	0.0030	0.0056	0.0035	0.0028
	0.0028	0.0041	0.0055	0.0072
	0.0024	0.0017	0.0025	0.0027
	0.0044	0.0022	0.0035	0.0078
	0.0050	0.0024	0.0070	0.0114
$\bar{x}$	0.00344	0.00265	0.00421	0.00647
σ	0.00087	0.00092	0.00200	0.00232
8	6061-T6 Aluminum; Drill and Ream			
	0.0023	0.0057	0.0023	0.0036
	0.0025	0.0013	0.0034	0.0046
	0.0019	0.0015	0.0032	0.0162
	0.0025	0.0078	0.0037	0.0238
	0.0050	0.0016	0.0018	0.0062
	0.0024	0.0067	0.0030	0.0110
	0.0047	0.0012	0.0027	0.0043
	0.0028	0.0049	0.0040	0.0042
	0.0055	0.0081	0.0028	0.0141
	0.0049	0.0016	0.0028	0.0083
$\bar{x}$	0.00345	0.00404	0.00297	0.00967
σ	0.00112	0.00293	0.00051	0.00557

Table A-6 Continued. Results of Drilling-Reaming Test

	Entrance Burr		Exit Burr	
Code	Thickness (Inch)*	Length (Inch)	Thickness (Inch)	Length (Inch)

*1.00000 inch = 25.400 mm.

**Because all of the holes in 17-4PH stainless steel that were reamed were selected from the drilled holes having the largest burrs, the holes that were only drilled should show larger burrs than those indicated in the table. Conversely, smaller burrs should be shown for the holes that were both drilled and reamed.

Table A-7. Effect of Backup Material on Burr Size

Sequence and Code	Repeat	Entrance Burr Thickness (Inch)*	Entrance Burr Length (Inch)	Exit Burr Thickness (Inch)	Exit Burr Length (Inch)
1-I	1	0.0040	0.0018	0.0019	0.0044
		0.0039	0.0020	0.0023	0.0050
	2	0.0039	0.0012	0.0009	0.0022
		0.0033	0.0049	0.0010	0.0031
	3	0.0040	0.0045	0.0007	0.0009
		0.0030	0.0044	0.0003	0.0003
	$\bar{x}$	0.00368	0.00313	0.00118	0.00265
	σ**	0.00024	0.00128	0.00082	0.00205
2-G	1	0.0036	0.0019	0.0039	0.0017
		0.0053	0.0054	0.0029	0.0100
	2	0.0068	0.0063	0.0021	0.0060
		0.0052	0.0047	0.0018	0.0047
	3	0.0078	0.0008	0.0027	0.0106
		0.0043	0.0051	0.0025	0.0052
	$\bar{x}$	0.00550	0.00403	0.00265	0.00803
	σ	0.00091	0.00132	0.00073	0.00275
3-B	1	0.0069	0.0024	0.0008	0.0006
		0.0034	0.0026	0.0003	0.0003
	2	0.0032	0.0046	0.0013	0.0009
		0.0053	0.0053	0.0011	0.0009
	3	0.0025	0.0039	0.0008	0.0031
		0.0034	0.0047	0.0016	0.0048
	$\bar{x}$	0.00412	0.00392	0.00098	0.00177
	σ	0.00111	0.00127	0.00038	0.00190

Table A-7 Continued. Effect of Backup Material on Burr Size

Sequence and Code	Repeat	Entrance Burr Thickness (Inch)*	Entrance Burr Length (Inch)	Exit Burr Thickness (Inch)	Exit Burr Length (Inch)
4-A	1	0.0045	0.0033	0	0
		0.0050	0.0046	0	0
	2	0.0018	0.0033	0.0006	0.0007
		0.0053	0.0053	0.0003	0.0003
	3	0.0010	0.0023	0	0
		0.0013	0.0038	0	0
	$\bar{x}$	0.00308	0.00377	0.00015	0.00017
	σ	0.00175	0.00064	0.00026	0.00029
5-E	1	0.0012	0.0035	0.0014	0.0067
		0.0024	0.0032	0.0013	0.0059
	2	0.0052	0.0023	0.0017	0.0029
		0.0044	0.0039	0.0010	0.0036
	3	0.0054	0.0041	0.0025	0.0027
		0.0051	0.0040	0.0021	0.0028
	$\bar{x}$	0.00395	0.00350	0.00167	0.00410
	σ	0.00188	0.00049	0.00025	0.00192
6-H***	1	0.0023	0.0024	0.0016	0.0022
		0.0020	0.0020	0.0002	0.0004
	2	0.0020	0.0052	0.0005	0.0014
		0.0020	0.0021	0.0004	0.0001
	3	0.0011	0.0036	0.0010	0.0038
		0.0043	0.0032	0.0015	0.0038
	$\bar{x}$	0.00228	0.00308	0.00087	0.00195
	σ	0.00037	0.00078	0.00040	0.00163

Table A-7 Continued. Effect of Backup Material on Burr Size

Sequence and Code	Repeat	Entrance Burr Thickness (Inch)*	Entrance Burr Length (Inch)	Exit Burr Thickness (Inch)	Exit Burr Length (Inch)
7-F	1	0.0011	0.0046	0.0023	0.0062
		0.0023	0.0024	0.0024	0.0062
	2	0.0030	0.0055	0.0014	0.0048
		0.0037	0.0024	0.0017	0.0069
	3	0.0009	0.0032	0.0022	0.0066
		0.0012	0.0047	0.0019	0.0075
	$\bar{x}$	0.00203	0.00380	0.00198	0.00637
	σ	0.00119	0.00026	0.00040	0.00062
8-D	1	0.0009	0.0020	0.0015	0.0019
		0.0014	0.0040	0.0010	0.0034
	2	0.0009	0.0034	0.0012	0.0009
		0.0046	0.0016	0.0007	0.0032
	3	0.0024	0.0045	0.0010	0.0011
		0.0042	0.0045	0.0009	0.0025
	$\bar{x}$	0.00240	0.00333	0.00105	0.00217
	σ	0.00112	0.00104	0.00017	0.00044
9-J	1	0.0031	0.0040	0.0003	0.0005
		0.0030	0.0037	0.0003	0.0003
	2	0.0020	0.0011	0.0008	0.0025
		0.0037	0.0009	0.0010	0.0039
	3	0.0009	0.0039	0	0
		0.0012	0.0013	0	0
	$\bar{x}$	0.00232	0.00248	0.00040	0.00120
	σ	0.00110	0.00143	0.00046	0.00174

Table A-7 Continued. Effect of Backup Material on Burr Size

		Entrance Burr		Exit Burr	
Sequence and Code	Repeat	Thickness (Inch)*	Length (Inch)	Thickness (Inch)	Length (Inch)
10-C	1	0.0041	0.0032	0.0006	0.0013
		0.0008	0.0045	0.0013	0.0073
	2	0.0007	0.0046	0.0004	0.0008
		0.0005	0.0046	0.0006	0.0010
	3	0.0015	0.0032	0.0007	0.0011
		0.0011	0.0044	0.0012	0.0019
	$\bar{x}$	0.00145	0.00408	0.00080	0.00223
	σ	0.00093	0.00045	0.00026	0.00181

*1.00000 inch = 25.400 mm.
**σ = the standard deviation about the mean of the average of each repeat.
***After drilling Sequences 1 through 5, a new drill was used to complete the test.

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