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DEBURRING: TECHNICAL CAPABILITIES
AND COST-EFFECTIVE APPROACHES

LESSONS 1 AND 2

By L. K. Gillespie

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DEBURRING: TECHNICAL CAPABILITIES AND COST-EFFECTIVE APPROACHES,
Lessons 1 and 2

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Prepared by L. K. Gillespie

This two-lesson text on deburring provides engineers and production supervisors with an overall understanding of deburring economics and capabilities. The subject matter includes economics, side effects, process selection techniques, product design influences, standards, plant-wide approaches, and burr formation and prevention. Deburring methods discussed include barrel, centrifugal barrel, vibratory, spindle, manual, electrochemical, electropolish, brush, abrasive jet, abrasive flow, water jet, thermal energy, and mechanized mechanical. Lesson 1 is an introduction to burr technology; Lesson 2 discusses burr formation and properties.

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Deburring: Technical Capabilities and Cost-Effective Approaches

by LaRoux K. Gillespie

Lesson 1 Introduction to Burr Technology

SUMMARY

Deburring requires a knowledge of deburring processes, burr properties, process economics, design effects, effects of machining operations on burr size, and standards. A wealth of information is available.¹⁻⁷

A knowledge of burr sizes and properties is essential to make the best choices initially.

There are four cardinal rules for appropriate burr cost control.

- Preventing burr formation eliminates removal problem.
- Every conventional machining operation produces burrs.
- If you don't have to remove the burr, don't.
- Machining conditions affect deburring costs.

Despite these cautions, effective burr cost control demands tabulated information. The data here are realistic for much of industry.

LESSON 1

INTRODUCTION TO BURR TECHNOLOGY

Since man began cutting metal, he has had to overcome the problems of burrs and sharp edges. Although safety and aesthetics have been long-standing reasons to remove burrs and radius edges, today we remove them for these and other reasons (Figure 1). Because of this variety of reasons, the tremendous variation in quantitative edge conditions required, component serviceability, and materials involved, the economic removal of burrs has become itself a science.

This 10-part manual can provide the training and rationale required to define actual needs and appropriate solutions to burr-related problems and questions. However, limited space prohibits detailed coverage of all burr-related information. SME's Deburring Capabilities and Limitations and Advances in Deburring are required supplementary texts for use with this manual. As is common in many technological fields, up-to-date information accumulates at a much faster rate than text publishers can produce; therefore, the reader needs to be aware of reports and articles about burrs published every year.

Approaches to Reducing Burr Costs

The reduction of deburring costs involves several techniques not immediately obvious such as these:

- Burr formation can be prevented;
- Burr size can be minimized;
- Burrs can be positioned for easy removal;
- Part design can facilitate deburring;
- Dealing with burr problems on a plant-wide basis minimizes cost;
- Better deburring processes or equipment may be available.

Obviously, preventing burr formation means no removal problem. Small burrs can be removed quickly and easily without affecting critical dimensions or finishes. Figure 2 illustrates how burr location affects deburring time or cost. The parts in Figure 3 are good examples of how part design affects deburring costs. The sharp-cornered, left-hand example causes rapid die wear, which results in large burrs after only a few parts are cut. For

Figure 1. Reasons for Deburring and for Edge Radiusing

HEAVY BURRS WILL FORM
HERE, WHERE THEY ARE
EASILY ACCESSIBLE

Figure 2. Place Heavy Burrs in Proper Location

Figure 3. Use Large Radii on Blanked Parts

optimum die life and consistently small burrs, the right-hand design is preferable. In practice, the difference between these two approaches increases or decreases the deburring costs by a factor of two or three.

The impact of plant-wide analysis and solution of burr problems will be discussed in a subsequent lesson. This approach requires

- Developing in-house burr removal standards;
- Developing in-house deburring processes standards;
- Educating plant personnel about burr-related facts;
- Experimenting to verify that published approaches do minimize problems;
- Documenting observations.

Lastly, reducing deburring costs may mean seeking improved deburring processes or equipment.

A review of the 10 lesson titles in this manual indicates that half of the lessons are concerned with the basic problem of burr formation, as opposed to burr removal. It is important to realize that THE BURR IS THE PROBLEM, NOT DEBURRING.

An analysis of specific situations determines why deburring is required and whether the existing reasons are valid. For example, whether a job shop deburring facility can remove burrs more cheaply than an in-house facility, or whether changes in feedrates and speeds will make smaller, more easily removed burrs must be considered. These considerations must include the knowledge that savings gained in deburring by slowing feedrates should not exceed the additional cost increment in machining.

Changes in feeds and speeds do not imply necessarily increases in machine cycle time. Preliminary work on ultra high-speed machining of aluminum indicates that, in addition to such advantages as faster cycles, less part distortion and less end mill deflection, burrs are much smaller than in conventional machining.

The basic approaches to minimizing burr-related costs all have one common facet--they require careful consideration of facts and actual requirements.

Considerations When Selecting Deburring Processes

Consider now the simple part in Figure 4. The assignment is not to determine the best process but to define all the processes

HOLE
 DIAMETER
 ALLOWABLE STOCK LOSS
 ALLOWABLE STANDARD DEVIATION OF HOLE
 SIZE FROM DEBURRING PROCESS
 SURFACE FINISH
 ALLOWABLE EDGE RADIUS
 EXTERIOR SURFACE
 DIMENSIONS
 ALLOWABLE STOCK LOSS
 ALLOWABLE STANDARD DEVIATION OF
 EXTERNAL DIMENSIONS
 SURFACE FINISH
 ALLOWABLE EDGE RADIUS
 BURR SIZE
 HEIGHT
 THICKNESS
 WORKPIECE MATERIAL

Figure 4. Workpiece With Hole to Illustrate the Considerations for Selecting a Deburring Process

that will remove burrs and not affect part features. Although one can try the part in all processes, that is not feasible in many situations. The goal is to select the appropriate processes based on a technical knowledge of the part and without having to resort to experimentation.

The first requirement is to know the following information:

- Burr properties--thickness, height, and hardness in relation to part hardness; hole size;
- Allowable dimensional changes in the part resulting from the deburring operation--amount of stock loss from hole as result of deburring, repeatability of stock loss;
- Required edge radius at the entrance and exit of hole;
- Required final surface finish, as well as the surface finish of the part before deburring.

Although such conditions as burr location, part geometry, and part material are important, a knowledge of the preceding factors is essential for the preliminary selection of deburring processes for precision parts.

The size of the hole is important because some processes will not work well on miniature holes, and others will not work well on large holes. When precision holes are involved, both the average

stock loss and the repeatability of the stock loss must be ascertained. Although the holes can be drilled smaller to accommodate the stock loss from deburring, this action is of little help if the stock removal is not repeatable.

Similar data about the external edges of the part also are needed. The selection of deburring processes for a complex part involving many edges, surfaces, and burr sizes requires considerable thought. Although the availability of actual data is highly desirable, previous experience frequently will provide intuitively the facts needed to select the appropriate process. When the allowable stock loss must be kept below 0.0001 inch (2.54 μm), however, there is little margin for error.

Tables 1 through 5 highlight the basic technical limitations of the more widely used processes. Consider Table 4, for example. In normal blasting or abrasive jet usage, one obtains surface finishes of 60 to 200 microinches (1.52 to 5.1 μm). By careful matching of media and part material, however, one can use this process on parts requiring finishes of 10 microinches (0.25 μm). The solid bars indicate the normal working range of a process. Dashed bars indicate feasible but not standard capabilities.

Consider Tables 7 and 8 (Table 6 indicates the code used in Tables 7 and 8). Table 7 indicates capabilities for a stainless steel part with a 32 microinch finish (0.81 μm) requirement, and an initial burr size of 0.003 inch thickness by 0.003 inch high (76.2 μm x 76.2 μm). Assuming that total burr removal is required from readily accessible edges, one will find that coded processes A through K and M will remove the burr, not remove more than 0.001 inch (25.4 μm) from part diameters, and not radius edges more than 0.010 inch (254 μm). When the requirement is to not break edges more than 0.002 inch (50.8 μm) and not remove more than 0.000050 inch (1.27 μm) stock from diameters, no single process will meet all these restraints.

In this case, the initial burr size is too large to meet the radius and stock loss drawing limitations. To deburr such parts, one must find some combination of two or more deburring processes that first reduce burr size and then break edges. Sanding, for example, might be used to reduce burr size; then, a tumbling-type process could radius the edge in a very short cycle. The alternative is to make the burr smaller initially.

The right-hand side of Table 7 addresses itself to the degree a repeatable size change is required. A process may be of little use, if, on the average, it removes only 0.0001 inch (2.54 μm) stock; but because of process variability, this thickness repeatability capability is as wide as ± 0.0001 inch.

Table 1. Basic Capabilities of Deburring Processes--Stock Loss*

Deburring Process	Typical Working Range, Surface Finish (mm) (μ in.)			
	0.25 (0.00001)	2.54 (0.0001)	25.40 (0.001)	254.00 (0.010)
ABRASIVE				
Abrasive Jet				
Abrasive Flow				
Semisolid Carriers				
Water Jet				
Loose Abrasive Barrel				
Centrifugal Barrel				
Spindle Finishing				
Vibratory				
Orboresonant				
Sanding (Edges Only)				
MECHANICAL				
Mechanized				
Hand				
Brushing				
THERMAL				
Flame				
Thermal Energy (TEM)				
CHEMICAL				
Chemical				
Ultrasonic				

Table 1 Continued. Basic Capabilities of Deburring Processes--
Stock Loss*

Deburring Process	Typical Working Range, Surface Finish (mm) (μin.)			
	0.25 (0.00001)	2.54 (0.0001)	25.40 (0.001)	254.00 (0.010)
ELECTROCHEMICAL				
Electrochemical	-----■-----			
Electropolish			-----■-----	

*Based on the removal of 76.2-μm-thick (0.003 in.) burrs from 303Se stainless steel edges directly exposed to the deburring process. These capability estimates assume that surface finishes of 0.81 μm (32 μin.) exist on the workpiece before deburring. Stock losses are defined as size changes occurring on exposed surfaces; the values are overall size changes of diameters or thicknesses. These estimates assume a maximum allowable edge break of 254 μm (0.010 in.). Less stock loss occurs if smaller burrs are present.

Table 2. Basic Capabilities of Deburring Processes--Part Size

Deburring Process	Typical Working Range, Workpiece Outside Dimensions (mm) (Inch)				
	0.25 (0.010)	2.54 (0.100)	25.4 (1.00)	254.0 (10.00)	2540.00 (100.00)
ABRASIVE					
Abrasive Jet					
Abrasive Flow					
Semisolid Carriers					
Water Jet					
Loose Abrasive					
Barrel					
Centrifugal Barrel					
Spindle Finishing					
Vibratory					
Orboresonant					
Sanding (Edges Only)					
MECHANICAL					
Mechanized					
Hand					
Brushing					
THERMAL					
Flame					
Thermal Energy (TEM)					
CHEMICAL					
Chemical					
Ultrasonic					

Table 2 Continued. Basic Capabilities of Deburring Processes--
Part Size

Deburring Process	Typical Working Range, Workpiece Outside Dimensions (mm) (Inch)				
	0.25 (0.010)	2.54 (0.100)	25.4 (1.00)	254.0 (10.00)	2540.00 (100.00)
ELECTROCHEMICAL					
Electrochemical					
Electropolish					

Table 3. Basic Capabilities of Deburring Processes--Feature Size*

Deburring Process	Typical Working Range, Feature Size (mm) (Inch)					
	0.025 (0.001)	0.25 (0.010)	2.54 (0.100)	25.4 (1.00)	254.0 (10.00)	2540.00 (100.00)
ABRASIVE						
Abrasive Jet	████████████████████	-----	████████████████████	-----	-----	-----
Abrasive Flow	████████████████████	-----	████████████████████	-----	-----	-----
Semisolid Carriers	████████████████████	████████████████████	-----	-----	-----	-----
Water Jet	████████████████████	-----	████████████████████	-----	-----	-----
Loose Abrasive Barrel	████████████████████	-----	████████████████████	-----	-----	-----
Centrifugal Barrel	████████████████████	████████████████████	-----	-----	-----	-----
Spindle Finishing	████████████████████	-----	████████████████████	-----	-----	-----
Vibratory	████████████████████	-----	████████████████████	-----	-----	-----
Orboresonant	████████████████████	-----	████████████████████	-----	-----	-----
Sanding (Edges Only)	████████████████████	-----	████████████████████	-----	-----	-----
MECHANICAL						
Mechanized	████████████████████	-----	████████████████████	-----	-----	-----
Hand	████████████████████	-----	████████████████████	-----	-----	-----
Brushing	████████████████████	-----	████████████████████	-----	-----	-----
THERMAL						
Flame	████████████████████	-----	████████████████████	-----	-----	-----
Thermal Energy (TEM)	████████████████████	-----	████████████████████	-----	-----	-----
CHEMICAL						
Chemical	████████████████████	-----	████████████████████	-----	-----	-----
Ultrasonic	████████████████████	-----	████████████████████	-----	-----	-----

Table 3 Continued. Basic Capabilities of Deburring Processes--
Feature Size*

Deburring Process	Typical Working Range, Feature Size (mm) (Inch)					
	0.025 (0.001)	0.25 (0.010)	2.54 (0.100)	25.4 (1.00)	254.0 (10.00)	2540.00 (100.00)
ELECTROCHEMICAL						
Electrochemical		----	=====			
Electropolish	=====	=====	=====	=====		

*Feature size indicates the size of holes, slots, and related features that can be deburred by a process without special effort.

Table 4. Basic Capabilities of Deburring Processes--Surface Finish*

Deburring Process	Typical Working Range, Surface Finish (μm), ($\mu\text{in.}$)			
	0.02 (1)	0.25 (10)	2.54 (100)	25.40 (1000)
ABRASIVE				
Abrasive Jet				
Abrasive Flow				
Semisolid Carriers				
Water Jet				
Loose Abrasive				
Barrel				
Centrifugal Barrel				
Spindle Finishing				
Vibratory				
Sanding (Edges Only)				
MECHANICAL				
Mechanized				
Hand				
Brushing				
THERMAL				
Flame				
Thermal Energy (TEM)				
CHEMICAL				
Chemical				
Ultrasonic				

Table 4 Continued. Basic Capabilities of Deburring Processes--
Surface Finish*

Deburring Process	Typical Working Range, Surface Finish (μm), ($\mu\text{in.}$)			
	0.02 (1)	0.25 (10)	2.54 (100)	25.40 (1000)
ELECTROCHEMICAL				
Electrochemical				
Electropolish				

*Based on the removal of 76.2- μm -thick (0.003 in.) burrs from 303Se stainless steel edges directly exposed to the deburring process. These capability estimates assume that surface finishes of 0.81 μm (32 $\mu\text{in.}$) exist on the workpiece before deburring. Surface finish effects are defined as changes occurring on exposed surfaces adjacent to the burr-laden areas. Small squares indicate the process does not affect surface finish.

Table 5. Basic Capabilities of Deburring Processes--
Applicable Workpiece Materials*

Deburring Process	Steels	Stainless Steels	Copper Alloys	Aluminum	Space Age Metals
ABRASIVE					
Abrasive Jet	x	x	x		x
Abrasive Flow	x	x	x	x	x
Semisolid Carriers	x	x	x	x	x
Water Jet	x		x	x	
Loose Abrasive					
Barrel	x	x	x	x	x
Centrifugal Barrel	x	x	x	x	x
Spindle Finishing	x	x	x	x	x
Vibratory	x	x	x	x	x
Orboresonant	x	x	x	x	x
Sanding (Edges Only)	x	x	x	x	x
MECHANICAL					
Mechanized	x	x	x	x	x
Hand	x	x	x	x	x
Brushing	x	x	x	x	x
THERMAL					
Flame	x	x	x	x	x
Thermal Energy (TEM)	x	Some	Some		x
CHEMICAL					
Chemical	x	x	x	x	
Ultrasonic	x	x	x		

Table 5 Continued. Basic Capabilities of Deburring Processes--Applicable Workpiece Materials*

Deburring Process	Steels	Stainless Steels	Copper Alloys	Aluminum	Space Age Metals
ELECTROCHEMICAL					
Electrochemical	x	x		Some	x
Electropolish	x	x	x	Some	Some
*Plastics use all processes except chemical, electrochemical and some in thermal energy (TEM).					

Table 6. Codes Used in Tables 7 and 8
for Deburring Processes

Code	Deburring Process
A	Vibratory
B	Barrel Tumbling
C	Spindle Finishing
D	Centrifugal Barrel Finishing
E	Abrasive Jet
F	Sanding
G	Brushing
H	Hand
I	Abrasive Flow
J	Mechanized Mechanical
K	Thermal Energy
L	Chemical
M	Electrochemical
N	Electropolish
O	Ultrasonic
P	Torch or Flame Melting
Q	Water Jet
T	Chemical Vibratory

Table 7. Typical Processes for Precision Deburring of External Edges

Maximum Edge Break (μm) (Inch)	Allowable Size Change*				Thickness-Change-Repeatability Standard Deviation		
	Thickness Change on External Surfaces				(μm) ($\mu\text{in.}$)		
	(μm) ($\mu\text{in.}$)	(μm) ($\mu\text{in.}$)	(μm) ($\mu\text{in.}$)	(μm) ($\mu\text{in.}$)	(μm) ($\mu\text{in.}$)	(μm) ($\mu\text{in.}$)	(μm) ($\mu\text{in.}$)
	1.27 (50)	2.54 (100)	25.4 (1000)	127 (5000)	0.508 (20)	5.08 (200)	50.8 (2000)
2.54 (0.0001)	--**	--	--	I	--	I	I
25.4 (0.001)	--	--	I	I	--	I	I
50.8 (0.002)	--	F,J,M	F,I,J, M	F,I,J, M	M	F,I,J M	F,I,J M
127 (0.005)	F-H,J, M	F-H,J, M	A-K,M	Most	F-H,J, M	A,B,D, F-K, M-O	Most
254 (0.010)	F-H,J, M	F-H,J, M	A-K,M	All	F-H,J, M	A,B,D, F-K, M-O	All

*Refer to Table 6 for definitions of deburring-process code letters. Information in this table pertains to stainless steel workpieces having a surface-finish requirement of 0.81 μm (32 microinches) or better, and holes 12.7 mm (0.5 inch) in diameter, or smaller; it is based on complete removal of burrs having an initial thickness of 76.1 μm (0.003 inch) and an initial height of 76.2 μm . Milling and many turning operations produce a burr this size.

**Dashes indicate that no process will produce the desired result for the specified burr size, surface finish, and material. In these cases, the burr must be sanded or machined until a much smaller burr is left for removal by one of these processes.

Table 8. Typical Processes for Precision Deburring of Intersecting Holes

Maximum Edge Break (μm) (Inch)	Allowable Diameter Change*				Diameter-Change Standard Deviation		
	Hole Diameter Change (μm) ($\mu\text{in.}$)				(μm) ($\mu\text{in.}$)		
	1.27 (50)	2.54 (100)	25.4 (1000)	127 (5000)	0.508 (20)	5.08 (200)	50.8 (2000)
2.54 (0.0001)	--**	--	--	--	--	--	--
25.4 (0.001)	--	--	--	--	--	--	--
50.8 (0.002)	K,M	K,M	K,M	K,M	--	K,M	K,M
127 (0.005)	K,M	H,J,K,M	H-K,M	D,H-N, T	M	H,J,K,M	Most
254 (0.010)	H,K,M	H,J,K,M	H-K,M	D,H-N, T	H,M	D,H-O	Most

*Refer to Table 6 for definitions of deburring-process code letters. Information in this table pertains to stainless steel workpieces having a surface-finish requirement of 0.81 μm (32 microinches) or better, and holes 12.7 mm (0.5 inch) in diameter, or smaller; it is based on complete removal of burrs having an initial thickness of 76.2 μm (0.003 inch) and an initial height of 76.2 μm .

**Dashes indicate that no process will produce the desired result for the specified burr size, surface finish, and material.

A quick comparison of Tables 7 and 8 indicates that meeting precise requirements for intersecting holes leaves fewer process choices. When two holes intersect, the edges at these intersections have widely varying included angles. These angles markedly affect capabilities for precision situations. Similar variations in results exist for screw machine parts, plastic deflashing, and in removing burrs from threads and many other types of products.

Stock loss, edge break limitations, and surface finish requirements are not the only considerations in selecting processes. Blasting or tumbling processes can result in poor welded, brazed, or soldered joints (Table 9). These processes also can affect electroplating adhesion and the resistivity of electrical contacts. Some processes increase residual stresses in parts, but others relieve them. Some processes distort parts or discolor them. Others leave particles impregnated in the workpiece. These processes affect subsequent tool life or wear of mating parts. Some processes leave a thin surface film or oxide that is an advantage in some instances and a disadvantage in others.

Process Economics

This lesson concludes with some information on process economics. Table 10 defines the major elements that contribute to deburring costs. Total deburring cost ranges from three to 10 percent for total piece part cost for 75 percent of U.S. companies, but for eight percent of the companies, the cost is between 20 percent and 40 percent. Thus, for a rule of thumb, one could count all plant machine operators and multiply that number by 3 to 10 percent to estimate the number of people performing deburring. Multiplying this figure by a year's salary (including overhead) for a typical machine operator will provide quick insight into potential deburring plant expenditures. Completion of Table 10, however, gives better estimates because it denotes the most costly items.

Preliminary deburring costs for specific parts can be analyzed, using the information in Table 11 and 12 and Equations 1 to 9. Assuming that conventional deburring is used, these equations should be used only to provide initial estimates or if, in fact, the conventional approach will be used. Altering the process to obtain faster or better results adds a cost term to the equation. In either case, the reader is advised to read the few articles that discuss economics in some depth.^{3,4,5}

All these equations presume that the value of each cost component and the time required to remove the burr are known. Although it is possible to use rule-of-thumb costs for media, compounds, and the like, no publications other than two on vibratory deburring and centrifugal barrel finishing provide information on required time to remove specific burr sizes. Until additional research becomes available, analogies can be drawn among other parts subjected to the same process.

Table 9. Overview of Deburring Side Effects*

Deburring Processes	Legend							
	1	2	3	4	5	6	7	8
ABRASIVE PROCESSES								
Abrasive Jet	X	X	X	X	X	X	X	X
Abrasive Flow								
Semisolid Carriers	X	M	Q		X			
Water Jet	Q	M						
Loose Abrasive Processes								
Barrel	X	X	X	X	X	X	X	X
Centrifugal Barrel	X	X	X	X	X	X	X	X
Spindle Finishing	X	X	X	X	X	X	X	X
Vibratory	X	X	X	X	X	X	X	X
Orboresonant	X	X	X	X	X	X	X	X
Sanding	M							
MECHANICAL PROCESSES								
Mechanized or Tooled Mechanical Methods								
Hand (Manual)								
Brushing and Buffing	M		M		X	M		
THERMAL PROCESSES								
Conventional Heat Flame								
Thermal Energy Method (TEM)	P	M	X		X			
CHEMICAL PROCESSES								
Chemical Deburring	X		X					
Ultrasonic Deburring	P		P					

Table 9 Continued. Overview of Deburring Side Effects*

Deburring Processes	Legend							
	1	2	3	4	5	6	7	8
ELECTROCHEMICAL PROCESSES								
Electrochemical								
Electropolish	X		X		X			

*Assumes normal cleaning is used before subsequent machining or manufacturing processes.

Blank = No, no effect

M = Depends on approach

P = Probably

Q = Probably Not

X = Yes

1. Affects Residual Stresses
2. Forces Can Distort Parts
3. Affects Surface Color
4. Impregnates Particles
5. Leaves Film or Oxide
6. Can Degrade Machining
7. Can Degrade Thermal Joining
8. Can Degrade Electroplated Adhesion

Table 10. Elements Contributing to In-house Deburring Costs

Source of Cost	Estimated Hrs/Yr (on Deburring)	Salary (Hour)	Overhead (Hour)	Yearly Cost
Hand deburr personnel	_____	_____	_____	_____
Deburring machine operators	_____	_____	_____	_____
Deburr foremen	_____	_____	_____	_____
Other engineering or management	_____	_____	_____	_____
Inspection personnel	_____	_____	_____	_____
Deburr equipment depreciation	_____	_____	_____	_____
Maintenance of equipment	_____	_____	_____	_____
Sharpening of deburr tools	_____	_____	_____	_____
Deburr supplies	_____	_____	_____	_____
Energy costs	_____	_____	_____	_____
Deburr on machine cycle	_____	_____	_____	_____
Warranty work caused by burrs	_____	_____	_____	_____
Scrap caused by inadequate deburr	_____	_____	_____	_____
Space costs	_____	_____	_____	_____
TOTAL				_____

Table 11. Formulas for Calculating Deburring Costs

Loose Abrasive Processes

$$C = [C_D + C_M + WC_P + C_B + C_E + C_C + C_W]/N + C_L \frac{(1 + D_O) (K_1 + K_2)}{N}$$

Thermal Energy Method

$$C = [C_D + C_M + C_L (1 + D_O) + WC_P + C_A] \frac{1}{N} + \frac{C_g}{n} + \frac{C_t}{N_p}$$

Brush Deburring

$$C = [C_D + C_M + C_L (1 + D_O) + WC_P + C_A] \frac{1}{N} + \frac{C_b}{N_{pl}}$$

Flame Deburring

$$C = [C_D + C_M + C_L (1 + D_O) + WC_P + C_A] \frac{1}{N} + \frac{C_g}{n}$$

Manual Deburring

$$C = [C_L (1 + D_O) + C_A] \frac{1}{N} + \frac{C_t}{N_p}$$

Mechanical Deburring

$$C = [C_D + C_M + C_L (1 + D_O) + WC_P + C_A] \frac{1}{N} + \frac{C_t}{N_p}$$

Chemical Deburring

$$C = [C_D + C_M + C_L (1 + D_O) + WC_P + C_A] \frac{1}{N} + \frac{C_s}{N_p}$$

ECD Deburring

$$C = [C_D + C_M + C_L (1 + D_O) + WC_P + C_A] \frac{1}{N} + \frac{C_t}{N_p} + \frac{C_s}{N_{pl}}$$

Electropolish Deburring

$$C = [C_D + C_M + C_L (1 + D_O) + WC_P + C_A] \frac{1}{N} + \frac{C_t}{N_p} + \frac{C_s}{N_{pl}}$$

where:

- C = Deburring cost each part.
- C_D = Depreciation cost each hour = machine cost each operating hour.
- C_M = Maintenance cost each hour of operation.
- C_L = Labor cost an hour to run machine.
- C_P = Cost of power used (\$ per kilowatt hour).
- C_A = Cost of cleaning each hour after deburring (labor and material).
- C_E = Cost of media an hour = media cost times percent hourly attrition.
- C_C = Cost of compound each hour.
- C_W = Cost of water each hour.
- D_O = Overhead as percentage of labor rate.
- N = Number of parts run each hour = n/t .
- n = Number of parts run each cycle.
- t = Time (hours) each cycle.
- C_g = Cost of gas each cycle.
- C_b = Cost of brush.
- C_B = Cost of cleaning materials an hour.
- N_p = Total number of parts run.
- N_{pl} = Number of parts run for a given quantity of solution or tool life.
- C_t = Total tool cost.
- C_s = Total cost of solution.

- W = Power used, in kilowatts (1 hp = 0.75 kW).
- k_1 = Percentage of cycle time that operator actually spends controlling deburring operations.
- k_2 = Percent of cycle time that operator spends cleaning parts.

These equations do not account for costs of floor space, area heating, lighting, maintenance, insurance, and supervision. These costs can add one to two dollars more for each hour than indicated by Equations 1 through 9.

For example, assume that 400,000 parts are to be deburred on a machine having a life that will accommodate that many parts. Assume that the values shown in Table 12 are representative.

For the values shown, the thermal energy method (TEM) would be the least expensive process (\$0.018 per part), but manual deburring is obviously an undesirable approach (\$1.20 per part). The calculations have been predicated on the basis that these processes will remove the burrs without adversely affecting parts.

The data shown in Table 12 represent a reasonable cost estimate for precision aerospace components, but, before decisions are made, the values should be discussed with knowledgeable vendors or users. The number of parts per cycle and the cycle duration are, of course, functions of the part size, burr size, and other variables.

Vibratory deburring is typically one of the least expensive usable processes if burrs are accessible. In this example comparison, three factors result in a high vibratory deburring cost.

- After deburring, special cleaning is required to remove traces of compound and loose particles (common procedure for precision aerospace parts but not for many commercial parts).
- A relatively long run time and small quantity of parts per cycle limit the output.
- The TEM and chemical processes basically are automated; the vibratory example uses a nonautomated machine.

In most cases these three factors would not be so pronounced. All equations except the first assume that the operator devotes full time to the deburring operation.

Deburring and deflashing can be performed on a mass production basis, as well as on an initial lot of prototype parts. Only six of the deburring processes require any tooling and the cost of tools, if required, ranges from \$150 to \$500. Highly automated processes will cost more because several sets of tools are used.

Deburring costs for commercial parts represents from one to five percent of total fabrication costs. Deflashing cast parts requires up to 35 percent of total part cost. Deburring costs for precision aerospace components often approaches 50 percent. Vibratory

Table 12. Example Data for Use with Equations 1 to 9

Cost Item*	Vibratory	TEM**	Manual	Chemical
C_D	0.40	5.00	---	0.20
C_M	0.04	1.00	---	0.02
C_L	5.00	5.00	5.00	5.00
C_P	0.04	0.04	0.04	0.04
C_A		5.80	5.50	5.50
C_E	0.60	---	---	---
C_C	0.30	---	---	---
C_W	0.15	---	---	---
D_O	0.8	0.8	0.8	0.8
N	50	1500	12	400
n	100	6	1	100
t	2	.004	0.08	0.25
C_g	---	.024	---	---
W	4	4	---	---
C_t	---	1000	1000	---
N_p	400,000	400,000	400,000	400,000
C_s	---	---	---	6,000
k_1	0.17	---	---	---
k_2	0.17	---	---	---
C_B	0.60	0.80	0.80	0.50
Calculated C	0.109	0.018	1.202	0.038

*Assume that no automatic load/unload is used.

**Thermal Energy Method.

deburring is generally the most economical when burrs are on exposed edges. In large quantities, deburring costs for these processes range from \$0.001 to \$0.060 per part.

Comments on the Use of Tabled Data

Tables 1 through 12 provide convenient quantitative comparison between processes. Use of such tables requires knowledge of the conditions under which information was obtained and whether data are current.

Because burr technology is a relatively new scientific field, little quantitative data are available. The material in these tables is from research performed on basically small parts made to very close tolerances. Although the tables are based on considerable production experience and more than 50,000 measurements, neither they nor other tables can fully define capabilities. As reported elsewhere², many of these processes have four or five basic variations, and each variation has its own limitation and capabilities. In addition, economical alteration of a basic process can vary capabilities from that shown in the tabled data.

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Deburring: Technical Capabilities and Cost-Effective Approaches

by LaRoux K. Gillespie

Lesson 2 Burr Formation and Properties

SUMMARY

Burrs are actually a family of six different protrusions. True burrs (as opposed to cut-off projections, flash, and recast projections) are the result of plastic deformation in a chip-producing process. Burrs can exist on the entrance as well as on the tool exit side of a part. Burr properties vary considerably; a single cut can produce eight edges, each edge having burrs of different thicknesses, heights, and hardnesses. In all cases, minimizing cutting forces reduces burr size. Using sharp tools, reducing feedrates, and using high angles are ways to reduce forces. Material properties such as the yield strength, the unit horsepower, ductility, and the strain-hardening exponent play a major role in determining burr size. A very quick estimate of materials having the largest burrs can be made by finding materials having high ductility (large values of elongation). Burr thickness is the one property that most influences deburring efforts.

LESSON 2

BURR FORMATION AND PROPERTIES

No analysis about reducing deburring costs would be complete without a basic understanding of burr formation and size. This lesson and Lessons 3 and 4 provide an in-depth picture and guideline for reducing the size of and problems created by burrs. This lesson discusses these topics:

- The theories of burr formation;
- Predicting burr size;
- Burr measurement;
- Typical burr sizes.

Burr Formation

Basic Mechanisms

The formation of burrs, flash, and related protrusions occurs by six physical principles. Of the six, three represent basic mechanisms that form burrs. The remaining three are responsible for burr-like protrusions, also described as burrs by many people. For completeness, all six are discussed in this chapter.

Physical Principle of Formation

Name of Protrusion

Lateral flow of material

Poisson Burr

Bending of material (such as chip
roll-over)

Roll-Over
Burr

Tearing of chip from workpiece*

Tear Burr

Redeposition of material

Recast Projection

Incomplete cutoff

Cutoff Projection

Flow of material into cracks

Flash

*A tear burr also forms in stamping operations when the punch tears the part from the stock.

True burrs form by one of the first three principles listed, which involve plastic deformation of the workpiece material. Solidification of material on the working edges, the fourth

principle of formation, forms a burr-like projection. The fifth type of projection occurs as the workpiece falls from the part before the cut is completed. Flash forms as pressure on molten molding material forces it between two halves of a die.

Poisson Burr

The Poisson burr occurs as the cutting edge extends past a workpiece edge (Figure 1). It is the lateral deformation that occurs as any solid is compressed. The term "Poisson Burr" is derived from its relationship to Poisson's ratio, discussed in all elementary stress analysis texts. The extent of this deformation is a function of the workpiece material, the size and shape of the contacting body, and the applied load. In the case of a cutting tool in which no rubbing occurs on clearance surfaces, the effective shape of the indenter (cutting edge) is a cylinder (Figure 2). Because cutting tools have cutting edge radii of 0.0002-0.0050 inch (5.08-127.0 μm), the extent of the lateral deformation (burr size) is also relatively small. Actual burr size is proportional to cutting edge radius and the applied pressure.

Theoretical analyses based on the cylinder analogy indicate burr size is also a complex function of several material variables (Equations 1 to 3).

$$b_L = \left[\frac{t(1+\nu)\sigma_e e^{-\sqrt{3} \phi_a}}{3 E} \right] \quad (1)$$

$$\left[- \frac{\sin \phi}{2(\sqrt{3} \cos \phi + \sin \phi)} \right],$$

$$b_t = r \left[e^{-3 \phi_a \cos \phi_a} - 1 \right], \text{ and} \quad (2)$$

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

where

b_L = burr length;

b_t = burr thickness;

t = depth of cut (feedrate in turning);

ν = Poisson's ratio for elastic stresses;

Figure 1. Poisson Burr Formed Where Tool Cutting Edge Extends Beyond Workpiece Surface

Figure 2. Location of Poisson and Entrance Burrs, Using Cylinder Analogy for Cutting Edge

σ_e = yield stress of a perfectly plastic material;

E = modulus of elasticity;

r = cutting edge radius;

P = pressure on cutting edge;

ϕ = angle defining state of plastic flow.

In practice these equations underpredict burr size significantly, because they ignore the effect of the wear scar on cutting tools. A direct correlation exists, since the burr forms in the immediate vicinity of this wear scar (Figure 3). On a face and turning operation, however, the tip of the tool will cut away the scar-formed burr (Figure 4). Since a large wear scar is representative of high tool wear, it follows that, in general, high tool wear results in larger burrs. Tool wear, however, includes dull tools having large cutting edge radii, in contrast to large wear lands. Although Equations 1 and 2 illustrate that dull tools will produce bigger burrs, equations do not exist to account for wear scar effects. Any factor that increases the cutting force or pressure on the cutting edge will increase burr size (Equations 1 to 3). Thus, a built-up-edge (BUE) as well as a lack of lubricant will increase burr size.

As indicated in Figure 5, a dull tool causes a larger, downward force into the workpiece that causes the Poisson burr to squirt out the sides of the cut (Figure 1). The material in front of the cutting tool is actually compressed below the tool, then partially expands after the tool has passed over the cut surface (Figure 6). Another estimate of burr thickness uses a simplified analysis based on Boussinesq's solution to concentrated forces acting on infinitely large plates.

$$b_t = \frac{F_a}{3\sqrt{3}b\sigma_e} \quad (4)$$

where

F_a = component of force acting perpendicular to the direction of feed; (pounds)(see Figure 5)

b = depth of tool engagement (inch); (see Figure 1)

σ_e = yield strength of the material (psi) and the factor "3" is an empirically determined factor related to burr size.

The term F_a can be estimated by the following formula, if it is not known:

Figure 3. Wearland Exists at Point of Burr Formation

$$F_a = (0.5)(396000)bfW_N \quad (5)$$

where

f = feedrate (inch/rev) or depth of cut t for the operation shown in Figure 1 and

W_N = unit horsepower = horsepower/in³/min.

Values for W_N for several metals are given in many tables.¹

For example, assume a tool engagement length of b of 0.025 inch (0.635 mm), a yield strength of 150,000 psi (1034.2 MPa), a W_N of 1.5 hp/in³/min (1.125 W/cm³s), and a feedrate of 0.005 inch/rev (127 μ m/rev). For these values the predicted burr thickness is

$$b = \frac{(0.5)(396,000)(0.025 \text{ in.})(0.005 \text{ in./rev})(1.5 \text{ hp/in.}^3/\text{min.})}{3\sqrt{3} (0.025 \text{ in.})(150,000 \text{ psi})}$$

$$b_t = 0.0019 \text{ in. (48.26 } \mu\text{m)}$$

This is a typical burr size for 17-4 PH stainless steel machined under these conditions.

Figure 4. Relation of Wear Scar to Burr For Turning, and Turning Then Facing

Entrance Burr

Another type of burr forms as the cutting edge first indents the workpiece (Figure 2). This entrance burr, essentially a Poisson burr, is material that has flowed opposite the direction of the tool. It is similar to the ridge that forms around the indentation made by a Brinnell Hardness Tester.

Whether a burr forms at this point depends on the workpiece properties and, probably, the actual shape of the cutting edge. Strain-hardening plays an important role if a cylinder indenting metal produces effects somewhat similar to those of a ball indenting metal. Based on Brinnell hardness results, a lip of material forms when the material has a low strain-hardening exponent (Figures 7 and 8). Materials having high strain-hardening exponents cause a bulge but not a sharp burr. This bulge will be wide but short, if volume is constant. In the previous case, the burr will be long but narrow. In the case of high strain-hardening exponents, the bulge will probably be short enough that it is difficult to detect.

Figure 5. The Resolving of the Resultant Tool Force F_{RES} Into Two Components: Ploughing Force F_P and Tool Face Force F_Q

The strain-hardening exponent is an empirically derived constant that defines a material's true stress. The equation for this true stress is

$$\sigma = \sigma_0 \epsilon^n \quad (6)$$

where

σ_0 = material stress at a true strain of 1.0;

ϵ = true strain of the material; and

n = strain-hardening exponent.

Values of the strain-hardening exponent can be found in several references.^{2, 3}

Roll-Over Burrs

A roll-over burr forms as a cutting edge exits from a workpiece (Figure 9), when it is easier to bend the chip than cut it. A

Figure 6. Schematic of the Cutting Edge and Flank Face of a Cutting Tool

burr thickness estimate can be made on the assumption that a roll-over burr occurs when the energy required to bend the chip is equal to or less than the energy required to cut the chip. For a perfectly plastic material, the burr thickness is

$$b_t = 1/3 \left[2F_c + \sqrt{4F_c^2 - \frac{2b\sigma_e \theta t F_c}{\tan \phi}} \right] \left[\frac{1}{b\sigma_e \theta} \right] \quad (7)$$

$$\text{for } b_t \geq \frac{t}{\tan \phi}$$

For a strain-hardening material,

Figure 7. Effect of Strain-Hardening Exponent on Ridging Burr Formation

Figure 8. Material Displacement, Using Spherical Indentors

Figure 9. Chip Deformation Modes at End of Cut

$$b_t = 1/3 \left[2F_c + \sqrt{4F_c - \frac{2b\sigma_o \epsilon_f^n t \theta F_c}{(n+1) \tan \phi}} \right] \left[\frac{n+1}{b\sigma_o \theta \epsilon_f^n} \right] \quad (8)$$

for $b_t \geq \frac{t}{\tan \phi}$

where

ϕ = shear angle in cutting;

θ = angle in radians through which the burr is bent ($\pi/2$ = rake angle);

ϵ_f = true strain at fracture;

F_c = principle cutting force = 396,000 $b_t W_N$

The shear angle ϕ is calculated from Merchant's equations and data^{4,5} as

$$\phi = \frac{C - \tau + \alpha}{2}, \quad (9)$$

where

C is a material constant;

τ = friction angle = $\arctan \mu$;

μ = coefficient of friction between chip and tool; and

α = tool rake angle.

If, for example, a 1045 carbon steel has a yield strength of 85,000 psi (586 MPa), a depth of cut of 0.050 inch (1.25 mm), a feedrate of 0.005 inch/rev (127 $\mu\text{m}/\text{rev}$), $F_c = 2F_A$, a rake angle of 15 degrees, a shear angle of 24 degrees, a specific horsepower of 1.5 (1.125 W/cm³/s), then, by Equations 5 and 7,

$$F_c = 148.5 \text{ lbs (201.1 N}\cdot\text{m)}$$

$$\text{and } b_t = 0.023 \text{ inch (0.58 mm)}$$

If the material is not ductile, however, a burr will be less thick than this equation predicts. Cast iron and fully hardened alloy steels, for example, have no ductility with which to form; thus, roll-over burrs on these materials are very small. Typically, a material must have an elongation of at least 10 percent before a roll-over burr is noticeable.

The length of a roll-over burr is a function of the cutting conditions, and the plasticity of the workpiece and cannot be longer than the total depth of cut. If, in bending, the strain exceeds the strain required to fracture, then most of the burr will break off and leave only a short burr.

If one notes that F_c is directly proportional to feedrate or depth of cut (t), then by substituting into Equation 7, burr thickness for roll-over burrs is also directly proportional to t .

Since hardness is a direct function of strength (and therefore of strain also), obviously highly strained burrs are harder than the basic workpiece. The Meyer Hardness Number (MHN), for example, is expressed as

$$MHN = 2.8 \sigma_o \epsilon^n \quad (10)$$

thus, hardness depends on the amount of strain at the root of the burr and the strain-hardening exponent. The average burr hardness at the base of the burr approaches one half the sum of the parent material hardness and the hardness of the same material in the fully work-hardened condition.

Tear Burrs

Tear burrs form as the chip is torn, rather than sheared, from the workpiece. Although this burr can form in most of the basic cutting processes, it is easiest to conceive in side milling operations. As shown in Figure 10, the cutter tooth forces the chip up and forward. As it does so, the sides of the chip are torn from the workpiece, leaving a torn portion on the workpiece, the tear burr. This burr actually can form by two mechanisms (Figure 11). The tooth can stretch the material in such a way that the burr is formed by a bending mechanism, or it can shear the metal. The predominant form appears to be a function of cutting velocity and workpiece properties. At this time, however, no quantitative theory exists for predicting tear burr properties.

The Poisson burr, the roll-over burr, and the tear burr all have one property that has not been discussed. A radius occurs on the back side of these burrs (Figures 12 and 13). For Poisson burrs this radius is actually an exponential function (Equation 2). The total shape of the burr cross section then can be expressed by length b_l , thickness b_t , and radius b_r . Although some individuals consider b_{min} as burr thickness, it is obvious that all b_t best defines thickness.

Figure 10. Separation of Initial Side-Milling Chip

BENDING MODE FAILURE

SHEARING MODE FAILURE

Figure 11. Tear-Burr Modes of Failure

Figure 12. Cross Section of Typical Machining Burr

Figure 13. Cross Section of Blanking and Some Machining Burrs

Cutoff Projections

A part allowed to fall from barstock before the cutting tool has completed the cut, is often called a cutoff burr (Figure 14). Typically, this projection must be removed either by a deburring process or a secondary machining operation. In some cases, if its size can be controlled or predicted, no subsequent machining or deburring is required.

To determine the diameter of the cutoff projection, it is only necessary to realize that the workpiece falls free of the stock when the stresses in the vicinity of the cutoff projection exceed the maximum strength of the material.

The diameter of the cutoff projection can be estimated from the following equation if weight is ignored.

$$\left(\frac{\pi\sigma_{ult}}{8F_R}\right)^2 = \left(\frac{\sin\theta}{d_{cut}^2}\right)^2 + \left(\frac{w}{d_{cut}^3}\right)^2 \quad (11)$$

where

σ_{ult} = ultimate tensile strength of the material;

F_R = resultant force of radial; and primary cutting force components;

(F_r and F_c in Figure 15)

θ = the angle between F_R and F_r

(Figure 15) = $\tan^{-1}(F_c/F_r)$;

d_{cut} = diameter of cutoff burr;

w = width of the cutoff tool.

When the weight of the part is significant, then Equation 12 predicts more closely.

$$d_{cut} = \left(\frac{N}{72.3} \sqrt{\frac{WL_w^3}{E}}\right)^{1/2} \quad (12)$$

where

N = spindle speed (rpm);

w = part weight (pound);

Figure 14. Definition of Cutoff Projection

Figure 15. Cutting Conditions During Cutoff

L_w = tool width + 1/2 part length in inches (see Figure 16);

E = modulus of elasticity (psi)

Consider the following conditions. In annealed 303 Se stainless steel, a 1/16 inch wide (1.57 mm) cutoff tool at a feedrate of 0.0015 ipr (38.1 μ m per revolution) and a spindle speed of 300 rpm produced an F_r of 12 pounds (53.4 N) and an F_c of 75 pounds

Figure 16. Dimensions Used in Critical Speed Equation

(333.6 N). This material has a tensile strength of 80,000 psi (0.55 MPa). By using these figures, the following values are obtainable:

$\theta = 80.91$ degrees;

$F_R = 75.95$ pounds (337.8N);

$d_{cut} = 0.078$ inch (1.70 mm).

Similarly, for a stainless steel part turning at 300 rpm with the following properties, Equation 12 predicts the cutoff diameter to be 0.020 inch (0.5 mm):

Diameter = 1.0 inch (25.4 mm)

$L = 2$ inches (50.8 mm);

$w = 0.062$ inch (1.57 mm);

$W = 0.445$ pound (0.20 kg), and

$E = 30 \times 10^6$ psi (206.85 GPa).

Empirical results indicate that for most materials, Equation 12 predicts cutoff burr diameters more accurately than Equation 11. For gummy or ductile materials like the 300-series stainless steel and glass-sealing alloy, which have high-strain hardening exponents, cutting forces greatly influence the cutoff-projection thickness. In this case Equation 11 predicts better.

To predict cutoff-projection diameters, Equation 12 will establish what the smallest possible diameter can be; Equation 11, the largest expected diameter.

Note that Equation 12 is totally independent of workpiece strength--only the modulus of elasticity and the density are significant. Hardness, ductility, elastic limit, ultimate strength, or other related material properties are meaningless when Equation 12 is used.

As shown by Equations 11 and 12, anything increasing the cutting force F_R will increase the diameter of the projection.

Increasing the radial component (F_r) of the cutting force (F_R) decreases θ which, in turn, decreases the diameter. Similarly, as the ultimate workpiece strength increases, the diameter decreases.

From Equation 11, it is evident that if the width of cut (w) increases without any increase in F_R , d_{cut} also increases. Actually, however, a wider cut increases force F_R (Equation 9), and, as a result of both F_R and w increasing, d_{cut} also must increase.

From Equation 12, anything that increases the part weight will increase the cutoff diameter. Thus, the use of material having a high density will increase the diameter, as will an increase in the part size. Increasing the spindle speed (N) also increases the cutoff-projection diameter.

Increasing L_w has a major impact in increasing the cutoff-projection diameter. Because L_w is dependent upon both the part length and the cutoff-tool width, both of these elements should be kept as small as possible.

Increasing the modulus of elasticity will reduce the diameter of the cutoff projection.

Recast Metal

The recast metal projection, which is not a burr, forms as molten metal resolidifies on an edge of the workpiece. The most common occurrence of this burr is found on electrical discharge machined (EDM) features. A close examination of edges produced by EDM reveals hundreds of small spherical particles firmly bonded to the workpieces. Although no quantitative theory has been developed for these metal particles, McBride⁶ indicates that their size is a function of polarity, workpiece material, and frequency and amperage of the current. Figure 17 shows one such recast projection occurring in beryllium copper.

Figure 17. Recast Metal From EDM Operation:
 Lower View is Edge of EDM Slot;
 Top View is Cross Section of
 Recast Nodule

Flash

Although equations have been developed to predict the thickness and length of flash formed in casting or forging processes, these properties become obvious from a knowledge of process parameters and tooling dimensions.

If the clamping pressure between dies is adequate, flash occurs only if die halves are not perfectly matched. Flash thickness then is equal to the thickness of the voids between mold halves, and flash height is equal to or shorter than the length of these voids. The hardness of this flash is the same as the workpiece.

Burrs Produced by Specific Operations

Poisson, entrance, tear, and roll-over burrs, as well as cutoff projections can occur with any type of machining operation.

A Poisson burr typically occurs in a turning operation (Figure 18). As the tool passes over an undercut, however, a roll-over burr forms (Figure 18). In producing a groove, a tear burr forms. If sufficient rubbing occurs between the groove tool and the walls of the groove, material also will flow from a Poisson effect.

A small Poisson burr occurs at the entrance of drilled holes. The burr formed as the drill exits from the bottom of the workpiece is initially formed as chip roll-over.

In a side milling slotting operation, burrs are produced on eight edges (Figure 19). A roll-over burr occurs at edges as the cutter exits from the part. The height of the burr is equal to the depth of the cut or less. An entrance burr occurs at edge 8. A hybrid Poisson/tear burr occurs at edges 6 and 7. A tear burr occurs at edges 1, 2, 3, and 4. A cutter with a helix angle changes the properties of the burrs at each edge. Eight different sets of burr thickness, burr height, burr radius, and burr hardness are possible for such a cut, and each edge will respond differently to a single deburring process. Furthermore, the properties vary along the length of all edges, except edges 5 and 8, because the burrs are formed by many teeth.

In end milling operations Poisson burrs are formed on edges 1, 2, 4, and 10 (Figure 20). An entrance burr forms on edge 6 and roll-over burrs form on edges 3 and 9. On half of edges 5 and 8 an entrance burr forms, and a roll-over burr occurs on the other half. The height of the roll-over burr equals the radial depth of cut, until the cut exceeds 0.6 times the tool diameter. For cuts deeper than this, the height tends to remain constant at 0.6 times the tool diameter. This relationship may vary, however, with workpiece properties and tool forces.

Figure 18. Burrs Formed in Basic Turning Operations

In surface grinding, an entrance burr occurs at one edge of the workpiece. Roll-over burrs occur on the other three sides. Because of the random placement of the abrasive grains in the graining wheel, many cuts are produced in these burrs. On sides 1 and 2, these cuts are parallel to the edge (Figure 21). On sides 3 and 4, these cuts are perpendicular to the edge. These cuts make the burrs very fragile and very short.

Figure 19. Burrs Formed by Side Milling Cutter

Figure 20. Identification of Burr Locations in End Milling-Profiling Cut

Figure 21. Burr Placement in Grinding

Figure 22. Burr Thickness as a Function of Helix Angle, Point Angle, and Feed Rate

Burr Properties

What makes a burr difficult to remove? The answer varies with each situation, but the following list is typical.

- Burr Thickness
- Burr Location
- Burr Toughness
- Burr Height (Length)
- Workpiece Tolerances
- Burr Radius

For most applications the above list is in approximately the correct order of significance. It is burr thickness at the root of the burr, not burr height, which makes a burr most difficult to remove. This is easy to see by looking at two extremes. Grind a piece of 303 Se stainless steel, then take a dull end mill and cut a channel in the same workpiece. Compare the burrs. At 0.001 inch (25.4 μm) per pass, a 0.010 inch (0.25 mm) downfeed will produce a 0.007 inch high by 0.0002 inch thick (177.8 μm x 5.1 μm) grinding burr on one edge. One of the milling burrs will be 0.003 inch thick and 0.005 inch high (76.2 μm x 127.0 μm). Experience indicates that the grinding burr can be removed readily with a fingernail. The milling burr requires considerable effort to remove, yet it is shorter. A similar comparison can be drawn between hardness and height.

For a specific machining operation, is burr height directly relatable to burr thickness? From a theoretical standpoint the answer is yes, but from a practical standpoint, the relationship is not readily evident. Nowhere in the literature has an empirical relationship yet been described. A few authors maintain that burr heights will be roughly 20 times burr thickness. However, this is by no means universally true, although for one material, one machining operation and one point in tool life, this may be true.

Burrs assume many shapes. They can be triangular, rectangular, or spherical in cross section, uniform or ragged (irregular), or feather-like in height.

Burr toughness is not measured directly. Burr hardness, however, is readily measurable and at least qualitatively can be related to burr toughness. For a given material, higher hardness indicates lower toughness.

Burr hardness by itself reveals little about deformation, but it is important to know also the hardness of the workpiece. The burr hardness can be related to workpiece hardness and the strain produced by burr formation. Since workpiece hardness can vary noticeably on a single workpiece, it is important to measure hardness in the general vicinity of the burr.

Burr properties vary considerably from part to part, and even within the same part. Consider Table 1, for example. When a dull cutter was used under somewhat abusive conditions in low-carbon steel, the Poisson burr thickness averaged 0.0049 inch (124.5 μm). The variation in thickness was considerable, however, since 95 percent of the measurements fell within the wide range of $0.0049 \pm 2\sigma$. Thus, for this 2 sigma spread the burr thicknesses were as small as 0.0009 inch (22.9 μm) and as large as 0.0089 inch (226.1 μm). Burr height is even more variable. Though the hardness of the workpiece is very consistent, the hardness of the burr is not (Table 1). The burr is consistently harder than the basic workpiece itself, however.

The equations presented thus far indicate how various machining parameters influence burr size, but because of tool geometry, using them may not be straightforward. For example, ways to apply these equations to drills or end mills are not apparent to most engineers. Because of this, researchers have developed a number of other equations based on experimental results rather than metal cutting theory. Consider drilling, for example. Equation 13 defines the exit burr thickness obtainable using a conventional 1/2 inch (12.7 mm) diameter drill in AISI 1018 steel having a Brinnell hardness of 150.

Table 1. Comparative Poisson Burr Sizes Generated by Milling Operations

Material	Condition	Burr Thickness (Inch)	Burr Height (Inch)	Hardness (Knoop)	
				Parent Material	Burr
Aluminum	Abusive Face Milling	$\bar{X}$ 0.0078	0.0138	115	129
		σ 0.0011	0.0045	4	9
	Gentle Profile Milling	$\bar{X}$ 0.0023	0.0015		
		σ 0.0003			
Low-Carbon Steel	Abusive Face Milling	$\bar{X}$ 0.0046	0.0255	230	275
		σ 0.0010	0.0191	7	17
	Gentle Profile Milling	$\bar{X}$ 0.0014	0.0024		
		σ 0.0002	0.0009		
Stainless Steel 303Se	Abusive Face Milling	$\bar{X}$ 0.0049	0.0095	305	428
		σ 0.0020	0.0053	0	56
	Gentle Profile Milling	$\bar{X}$ 0.0020	0.0013		
Beryllium Copper	Abusive Face Milling	$\bar{X}$ 0.0045	0.0189	249	268
		σ 0.0008	0.0017	7	22
	Gentle Profile Milling	$\bar{X}$ 0.0007	0.0016		
		σ 0.0005	0.0011		

Abusive Face Milling--dull cutter and 0.025 inch depth of cut.

Gentle Profile Milling--burr produced by the bottom of a 1/4-inch diameter end mill 2730 rpm, 9-3/16 ipm.

Knoop Hardness Number with 100 g load (249 = Rc 24; 115 = RB 73)

$\bar{X}$ = average measurement

σ = standard deviation of measurements

0.001 inch = 25.4 μ m

$$b_T = 4271 H_1^{-1.72} P^{0.84} L^{-0.36} f^{0.86} \quad (13)$$

where b_T is given in 0.001 inch units;

H_1 = helix angle (degrees);

P = point angle (degrees);

L = lip clearance angle (degrees); and

f = feedrate (inch/rev).

A preliminary examination of Equation 13 indicates that increasing the helix angle and lip clearance angle decreases the burr thickness. The equation is least affected by the lip clearance angle. Decreasing the point angle and feed also decrease the thickness.

Assume that the lip clearance angle is 9.2° . This allows the burr thickness to be shown as a three-dimensional model (Figure 22). Obviously, from this figure, numerous helix angle, point angle and feed combinations can produce the same burr thickness. The equation and graph also indicate that significant reductions in burr thickness are possible by correct selection of the helix angle, point angle and feed. Figure 22 or Equation 13 shows that a 0.0043 inch (109.2 μm) burr thickness could be expected when drilling with a 27° helix angle, 112° point angle and 0.006 in./rev (152.4 $\mu\text{m}/\text{rev}$) feed. By increasing the helix angle from 27° to 36° , which can be achieved by purchasing commercially available high helix drills, the burr thickness is reduced to 0.0026 inch (66.0 μm). If the feed is lowered from 0.006 to 0.0035 in./rev (152.4 to 88.9 $\mu\text{m}/\text{rev}$) and the point angle reduced from 112° to 98° , the burr thickness becomes 0.0015 inch (38.1 μm).

Note that this equation is totally unlike any of the previous equations. It is based on experimental data and is only valid for one material, although others may act similarly. Some of these equations could be in the literature for specific cutting conditions. About 50,000 measurements have been made and reported on the effects of various machining parameters on burr size.^{7,8}

Extensive use of equations in this chapter illustrates the effects of various machining parameters. This offers the most concise approach to showing relationships, but it must be recognized that equations are built on the basis of certain assumptions not always met in practice. As an example, although Equation 10 provides a reasonable estimate for F_c , the published values of W_n are average values that ignore the effects of tool sharpness and workpiece hardness. In addition, if very slow feedrates are used, the published values of W_n may be low by a factor of 2 or 3.⁹

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