YOUR BURR TECHNOLOGY EFFORTS CHANGED THE WORLD

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ABSTRACT

National and international leaders in burr technology have made exceptional progress on international burr related issues over the past 50 years and that reduced the problems and costs of burrs. The history timeline of burr technology shows significant individual steps as well as the larger progress. That progress affected the edge finishing technology employed today, the economics of manufacturing and the personal lives of many of our burr technology leaders. Most of the leaders in the field of burr technology are alive today and can see the results of their work. This paper documents the history of burr technology, describes the changes and their impact to our world, and projects the changes coming in the next decade.

INTRODUCTION

An amazing transformation of edge finishing has occurred over the past 50 years. It is a transformation that has largely been ignored by writers and historians, but it represents a transformation of how business is preformed when part edges are involved. Not all industry segments have risen to the transformation, but edge finishing is beginning to be a planned effort before parts hit the floor. Engineers and shop owners are incorporating the science and mathematics of edge technology in design and manufacturing. It is more than just deburring to leaders in these industries.

To illustrate the transformation a historical timeline for deburring and edge finishing will be developed and analyzed. An engineer who lived through much of this history will discuss the impact of the developments.

ANCIENT HISTORY

Deburring and edge finishing today are tightly joined topics. That was not the case in the beginning. Obtaining sharp edges was the first issue. Stone tools having sharp edges dating back 1,750,000 years have been unearthed (Pinkstone 1974). Burrs, which come from machining metal, would not appear until the Bronze Age or similar periods of metal history. Obviously producing the desired edge is old history – deburring is relatively young. Pinkstone notes that grinding wheels were used on lathes in Egypt in 2100 B.C. The first iron weapons appeared in Mesopotamia in 1600 B.C., but metal jewelry and ornaments have been found dating back to the year 3000 B.C. and possibly as early as 4000 B.C. With the advent of jewelry and metal tools, deburring began to evolve.

To place these dates in context Moses led the Israelites out of Egypt about 1250 B.C. The future King David according to legend hid from King Saul among the Philistines and learned the art of working iron and how to sharpen it (Pinkstone 1974). In the Bible 1 Samuel 13:19-21 notes, "Now, there was no smith to be found in the land of Israel….. but all the Israelites went down to the Philistines to sharpen every man his share, and his coulter, and his axe and his mattock. Yet theyhad a file for their mattocks, and for the coulters, and for the forks, and for the axes, and to sharpen the goads." (King James version Holy Bible).

Ancient Chinese and Egyptians used tumbling barrels with natural stones as media to achieve smooth finishes on weapons and jewelry. The process was known as *barreling*, *rattling*, or *tubbing*. Stories were reported in 1948 that chain type armor in the medieval years of jousting (1100s and 1200s) required tumbling, as indicated by the statement, “Ye apprentice was required to place the parts in a cask along with small jagged stone fragments and tend to roll the cask about upon the ground until all the parts were smooth” (Beaver 1948a). Edmunds in England was the modern developer of the process in 1885 (Beaver 1948a). Grinding wheels (Pinkstone 1974), hand stones and files were the common tools in existence then for 3500 years to deburr. Grindstones were used to produce sharp cutlery. Woodgravings show English guild members grinding knives and scissors (Norton Co. wood engraving “Grinder at Work” by Jost Amman, 1568). The Pilgrims reportedly brought the first grinding wheel to America in 1620 (Pinkstone 1974).

In 1225 Chinese experimenters took paper, coated it with a natural gum, and worked crushed seashells into it (Pinkstone 1974). Coated abrasive paper or sandpaper as it is generally called today was born. The first known use of abrasive paper in Europe (Paris) is documented in 1769, and in 1808 the details of preparing coated abrasive papers were described in an English article (Pinkstone 1974). U.S. production of sandpaper began in 1828 and emery cloth was invented in 1831. Van Verquem, a Belgian, made the first diamond coated cutting or polishing wheel in 1456 (Pinkstone 1974).

The existence of files of prehistoric origin is documented as noted before. They are simple flint rasps having serrations along one edge used to smooth wood, bone or horn. One metal file dates back to 600-650 B.C. Romans used files and had names for different uses of them (Simons 1947). Egyptians used three-sided rasps made of flint, and “the Celts had iron files with tangs, as well as rasps and knife-shaped files dating from 666 B.C. (Simons 1947). The watchmakers developed the Swiss files for their use as they built watches in the 1500s (Jaquet and Chapus 1953)[1]. Clockmakers probably used larger files for the large clocks found on the outside of buildings in the 1200’s. Files were in common use for making musical instruments, gold inlay slots for knives and by cabinetmakers in the 1700s[2]. The rotary files or rotary burs began in the 1700’s.

In 1798 Eli Whitney’s development of mass production began major manufacturing innovations that required more effective edge finishing and detail. The 1800s were filled with machinery innovations and manufacturing technology that changed our world to what it is today.

MODERN HISTORY

Scythes and other “edge (cutting) tools were produced in the U.S. in 1738 (Benes 1996). Musket parts were produced in the U.S. in 1748 and each of those parts had to be burr free. In 1798 Eli Whitney received an order for 10,000 muskets – more burr free parts. The first American lathe was patented in 1794. Burrs appeared regularly afterwards as parts came off these and other machines (Benes 1996). A knife grinder appears in an 1880 American Machinist article as a new type of machine and the first non-manual sanding machine appears in 1880 as well. (Anonymous 1880b).

As noted above barrel tumbling was in commercial use at the turn of the 20th century. Filing, sanding and manual buffing lathes were all commonly in use in 1880. Filing on the lathe was a craftsman standard in 1916. That was part of the expected performance of a machinist. So, hand deburring was also a standard process at the turn of the century. Hand finishing using buffing and brushing machines was common in 1880. A wide variety of such machines existed at that time. An “emery belting machine” (belt sanding

[1] Jaquet notes that the gear teeth of watches were filed out by hand in 1700. Four main categories and several subcategories of workers were required to make watches, of which the “maker of ébauches” produced the escapement mechanisms and rounded gear teeth and the ‘finisher’ who finished any part edges needed to assure freedom of movement and finished the assembly. As the division of labor increased the ‘wheel finisher’ filed up the rim and the arms, and formed the ‘angles’; he was of necessity a good filer, and the work was done with special small files called ‘crossing files’. The fourth worker was the ‘tooth maker’; he rounded up each tooth and gave it a shape something approaching epicycloidal….. The fifth worker was the ‘polisher’ who, as the name suggests, polished the wheel.”

[2] Jaquet notes that Swiss watchmakers also invented the ‘migroscopes’ (watchmakers’ eye glasses) that are still used today for precision deburring and finishing.

machine) was developed in 1881 (Anonymous 1881). Mechanized machines that did not need an operator holding the part would not appear for many years. As we will see in the next paragraph the word "deburring" did not appear until later. "Filing" was the common word for working on edges and surfaces until the early 1900's. "Finishing" was used occasionally, but "filing" was the word used at least from 1880 to 1916. In the casting houses and yards, "cleaning," meant to remove sand, black dust and flakes as well as deflashing the castings, by hammering, sawing, filing, grinding or chipping. Barrel tumbling was widely used in the casting houses as well (Estep 1916)[3]. In 1916 the barrels processed castings weighing several hundred pounds each. Cranes and hoists were used to move the larger pieces into the barrels. To accommodate these large parts one barrel was 36 feet long, but only 28 inches in diameter. Sand blasting was also ranked as the first or second most used process to "clean" castings. Water blasting was just beginning to be used for cleaning these castings in 1916. B.C. Tilghman's 1870 patent for sand blasting represented the start of blasting, but its use specifically for deburring and deflashing can better be defined as the start of the Wheelabrator machines that threw material at parts (1935). Even this may be predating its use for deburring. It was 1961 before Wheelabrator introduced a deflashing machine for rubber. By the mid-1960's many shops had small blasting cabinets used for deburring, cleaning and providing uniform surface texture. Despite the use of water blasting for cleaning castings it was Centri-spray's 1964 high-pressure water system that marked the start of water jet deburring. Flexible shaft electric motors with hand pieces for buffing were introduced in 1916, although flexible shaft machines existed in 1880 for portable drilling (Stow Flexible Shaft Co. 1880c). The Robbins & Lawrence 1880 edging machine appears to be one of the first machines to put chamfer edges other than holes (Anonymous 1924).

Terminology

The word "deburring " first appeared apparently in 1943 in the U.S. The following entries are found and provided by the author in the format used by the Oxford English Dictionary, which in the year 2005 did not even list "deburring" as a word. The examples shown list the source of the sentence that first uses the word, then the sentence that contains it.

> **Reference: 1943** anonymous *Iron Age* v. 152 These are just a few of the factors which make hand de-burring inherently non-uniform and a headache. **1944** R. Sizelove Metal Finishing v. 54 Prior to the present emergency, deburring of metal products was confined to the removal of casting fins from zinc, brass and iron castings, and several lesser applications; like the removal of extension burrs from stamped objects, and tool burrs from brass screw machine products. **1944** anonymous *Steel* v. 115 Liquid honing, the direction of a high-pressure stream of fine abrasive mixed with a chemical emulsion against parts to be deburred, finished, or polished, has indicated …….. **1944** G.O. Rowland *Iron Age* v. 153 DeBurring Aluminum and Light Steel Parts (article title). **1945** J.E. Hyler *Mill and Factory* v. 56 Deburring cutters suitable for use on tubes or shafting may be used in different kinds of machinery and are always of interest. **1953** W.J. Hobday *Automotive Industries* v. 108 When deburring was done with hand tools, the time required per disk was 15 min, and even the most skillful operator could not hold uniformity. **1953** W.G. Patton *Iron Age* v. 172 Deburring and cleaning the rifled gun barrel of a 90 mm tank cannon is accomplished in 45 min at Oldsmobile Div., General Motors Corp., by liquid honing.

While "deburring" was not coined until 1943 "burr" and "burring" were used earlier to describe deburring actions. Note that today "burring" also refers to the act of making burrs on edges. The following are also the author's submissions to the Oxford English Dictionary for the word "burring," and thus the first known uses of the words "burr" and "burring" in metal work.

[3] In 1916 Baird Machine Co., J.M. Betton, Globe Machine and Stamping Co., Northern Engineering Works, J.W. Paxson Co., Royersford Foundry and Machining and Whiting Foundry Equipment Co. all produced barrels for tumbling (Anonymous 1916b).

Burr
Reference: 1916 Anonymous *Machinery* v.5 Operation 12: File and burr. – This is a hand operation, consisting in removing the burrs and sharp edges.1928 M.G. Farrell *Mill & Factory Ilustrated* v. 1 Files are used for the removal of burrs from pipe, rods, or rails, which have been cut by saws or rotary cutters. 1928 *American Machinist* v.69 The next opertaion is to remove the burrs from the teeth and smooth of the file marks.

Burring
Reference: 1911 Anonymous *Machinery* (NY) v. 17 These attachments are used for performing various second operations on a piece of work, such as slotting, milling, cross-drilling and burring at the same time that another piece is being operated on by the cross-slide and turret tools. 1930 Anonymous *Machinery* (London) v. 36 … pressing one side of the work against the point of the rapidly moving drill and burring the opposite side in a similar manner. 1943 Anonymous *Iron Age v.* 152 The hand burring time was 1 1/2 hr per piece and the job was not uniform. 1943 H.J. McAleer *Metal Finishing v.* 4 Tedious hand-filing work has been entirely eliminated by the selection of the proper buffing wheel and burring compound. 1944 Anonymous *Iron Age v.* 154 Mr. Himmelright stated that a battery of such tumbling barrels fitted into their postwar view as compared with extensive hand labor involved in conventional burring. 1945 J.E. Hyler *Mill and Factory v.* 56 ...this is a class of work that must so often be burred, and this occurs in such large quantities in so many places, that special equipment for burring has been devised.

The description for burr technology began as “filing”, went to “finishing”, and then “benchworking”, split into “surface finishing” and “deburring.” Then “deburring” moved to “edge finishing” and “edge technology” and “burr technology”. At times as noted above the function was stated as “file and burr” (Anonymous 1916d). Today in addition to these burr technology includes surface integrity, surface metrology, micro burrs and nano technology. As noted later, proposed standards include a wide assortment of terminology dedicated just to identifying the types of burrs and their location.

PROGRESS OVER THE PAST 50 YEARS

John Kittredge’s 1980 one-page Historical Highlights in Mass Finishing (Figure 1) is one of the best summaries of progress in mass finishing. It concentrates on deburring and ignores the existence of tumbling barrels used for foundry cleaning of castings.

In addition to Kittredge’s paper the author has provided six brief summaries on burr progress (Gillespie 1974c, 1975a; 1976a, 1977c; 1990; 2000c) and his 2004 paper summarized the key people who have changed burr technology (Gillespie 2004). Takazawa and Kinoshita also have provided a brief history of grinding and surface finishing (Takazawa and Kinoshita 1984). Scheider provides a two-page summary of brushing technology advancements through 1990 (Scheider 1990). Table A1 at the end of this paper provides a four page capsule view of modern edge finishing history. The most significant of those issues are captured in the following paragraphs along with drivers and results that are not shown in the table.

TECHNOLOGICAL IMPACT OF OUR PROGRESS

Eight aspects of technology have impacted the world of edge finishing and the burr. They include:

- burr formation
- burr minimization
- burr prevention
- designing for edge quality
- eliminating waste
- better cutting tools
- higher part precision
- deburring process enhancements
- availability of edge standards

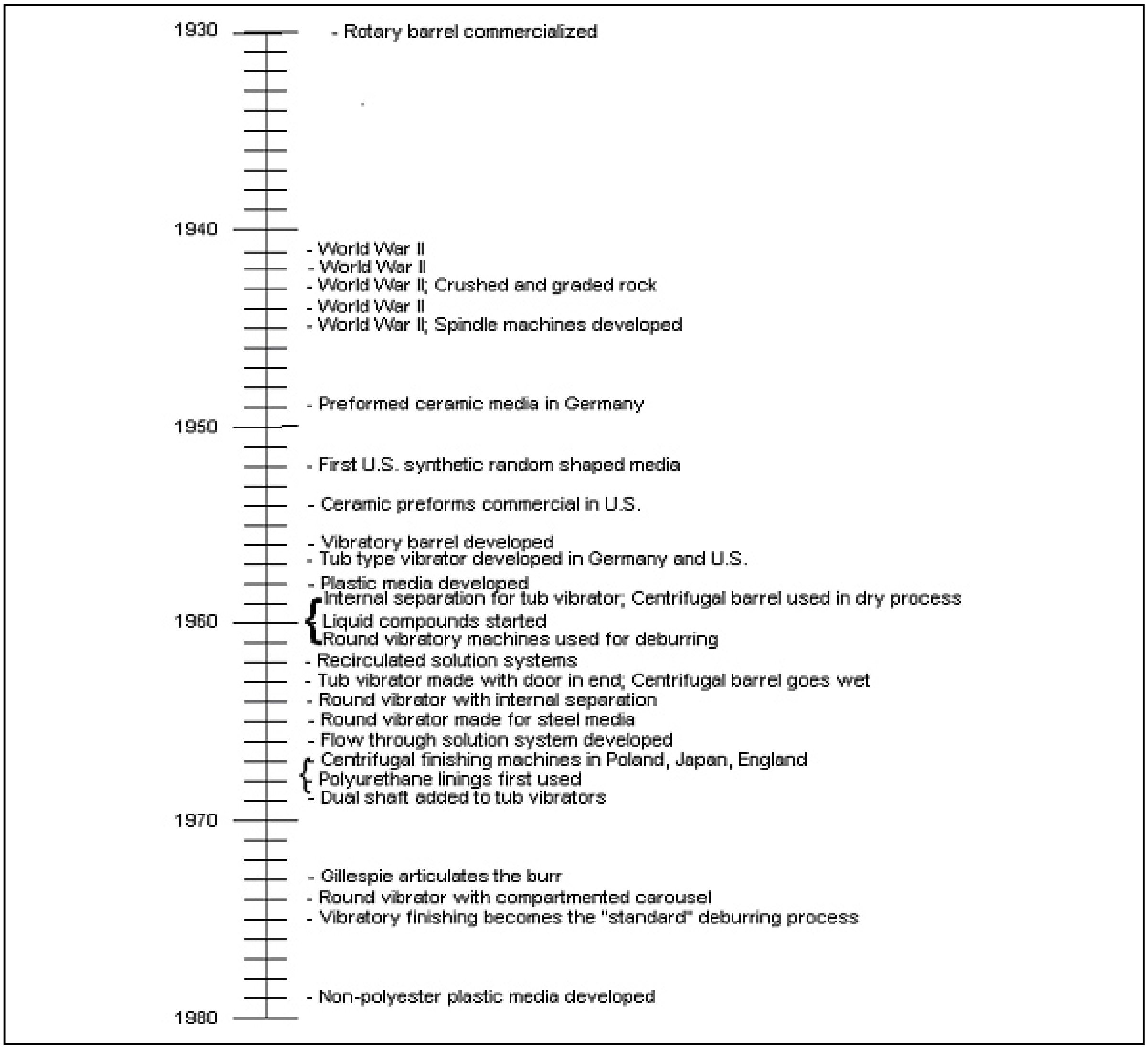

Figure 1. Kittredge Mass Finishing Timeline (Kittredge 1980).

Mathematical and Physical Understanding of Burr Formation

In the late 1950's German and U.S. researchers developed a physical understanding of burrs formed in punching. The impact of press variables and part material were known, although no mathematical theory was available to predict burr formation[4]. The understanding of the principle variables allowed die designers and floor users to change out dies before burrs became too big to foul other machines or be removed by commercial processes. In addition companies set burr size standards to monitor die wear. German innovators also developed a number of burr measuring instruments during the 1950's and 1960's to aid the pressroom in this endeavor. The punch press industry became the model of how an industry coordinating their interests could make major improvements[5].

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[4] Metallurgically based mathematical programs still do not exist for punching although numerous pressworking material flow programs have been developed.

[5] Fine-Blanking, which typically results in minimizing burrs was reportedly in production use in Switzerland by Fritz Schiess in the 1930s (Anonymous 1972). It was not until the 1950s, however, that this process and an understanding of its mechanics became widely known.

In 1972 there were no analyses of burr formation that allowed users to predict what burrs would form in machining, and the author decided that would be an appropriate Master's degree thesis. He developed three different mathematical models of burr formation, documented the variety of burr properties produced at different edges in milling, turning, drilling and grinding, and used statistical design of experiments to define empirical relationships between cutting conditions and part edges (Gillespie 1973a;Gillespie and Blotter 1975). From that he began a series of follow-up research studies on burrs from several manufacturing processes that were made available to the general public through the National Technical Information System (NTIS) and the smaller studies through the Society of Manufacturing Engineers (SME). While 18 of his publications dealt with burr formation, industry had not yet matured to the point of taking active interest in implementing the findings[6]. In contrast articles and reports on deburring appeared to generate more interest than burr prevention and formation.

Two unrelated efforts evolved from the 1972 work. In 1975 Koya Takazawa and a group from Japan came to the U.S. and participated in SME conferences from which they took back many ideas that they similarly promoted throughout Japan. The researchers in Japan appeared to have as much interest in burr formation and prevention as in deburring. Numerous burr property studies have been reported since. The second thrust came from a young University of Wisconsin Ph.D. graduate who saw the potential for useful academic research in manufacturing by preventing burrs. Dave Dornfeld began his Consortia on Deburring and Edge Finishing (CODEF) at Berkeley in 1993 and has become the world leader in developing burr formation mechanics. Under his leadership graduate students from around the world have developed mechanistic models of burr formation for many different conditions.

Developing Burr Minimization Principles and Practices

One often overlooked aspect of burr minimization is the work performed in the printed circuit board industry in the mid-1960's followed by multilayer and then hybrid microcircuits. The holes are tiny in this industry and a burr when plated over causes a host of unfriendly conditions. Because literally millions of holes were drilled daily it was important to minimize burrs. Drill manufacturers and drilling equipment producers worked closely with users and the Institute of Printed Circuits to develop edge standards and better tools and practices for this product line (Wetherald 1966; Anonymous 1966). Circuit boards represented a real challenge for tool makers since a board consisted of a prepreg plastic, an adhesive, copper layers, backup sheets and a variety of heat resistant abrasive laminates and paper. Spindle speeds moved up from the 5,000-6,000 rpm to 60,000 rpm (and even higher today) – to give speeds that matched feedrate needs. By 1970 most of the issues had been resolved satisfactorily, although new materials required continued studies on drill wear and burr formation. Some new work was still being reported in the mid-1980's (Coombs 1988).

In April, 1974, the author began SME's International Burr Technology Committee which later became SME's Burr Edge and Surface Technology Committee. This group became the world leader in burr technology dissemination. As a result of several conferences and seminars SME was able to identify a variety of practical burr minimization principles and examples of practice. Very small burrs are much more economically removed than traditional burrs - a situation that is almost as good as preventing burrs. Neither SME nor the author developed the ideas – they merely put a accumulation of such practices in front of an international audience. Stated differently they made it easy for users to see practical ideas. The majority of this work happened in the 1970's.

At that same time (late 1960's/early 1970's) The University of Stuttgart's Institut fur Produktionstechnik und Automation (IPA) began a decade long study of burr formation and deburring. Guided by Dr. H. -J. Warnecke, Frederich Schäfer developed the earliest and some of the most important insights into burrs formed in milling and other operations. This work led to examples of product geometry influences and how manufacturing engineers could apply burr minimization on the production floor. German industry seemed

[6] Many plants were seeking to reduce drilling burr issues and did implement changes when the data was available to shops. LaRoux' reports were often published in government publications and only large companies bothered to look there for burr technology. The impact of this work is discussed in the next section on burr minimization.

to be the first to utilize burr minimization other than for drilling. Schäfer's 1975 book was the first and is still one of the finest available on the broad spectrum of burr technology (Schäfer 1975b). Schäfer's work and that of fellow colleagues represent one of the most significant advances in burr technology. It was performed for direct industry use. It is significant to note that one reason this work was incorporated into German industry so readily is the close cooperation between German industries and the universities there. Ph.D. students work on problems requested by, monitored by and funded by industry.

As noted above Dornfeld and his CODEF students from the 1990's to today have developed burr minimization models that now are in use in automotive companies in the U.S. and Europe. After extensive theoretical and empirical analysis of how burrs form CODEF is (for milling) able to provide cutter paths and conditions which minimize burrs and put them at locations that are easier to remove. The software that supports this minimization represents yet another advance in the field of burr technology. There was no software in the 1960's, 1970's, 1980's or early 1990's. Dornfeld's group developed it and the companies supporting CODEF put it to production floor use. While still limited in use to primarily automotive applications involving millions of machined castings, the software and principles are not limited to any industry. Like the other leaders in burr technology their many advances in burr minimization are published in a variety of locations for the world to read. A recent publication summarizes most of the CODEF works published through 2001 (Dornfeld 2001). The application of the minimization work is appearing in both the U.S. and Germany.

Minimizing drilling burrs probably began as soon as drills were invented, but understanding the mechanics of how they form and how that leads to minimization began as a science in 1963 (Bell and Kearsley 1963)[7]. Drill manufacturers have apparently never published reports on burrs from drilling, although they obviously have tried to improve burr reduction through better tools. As one manufacturer (who does not report all the insight) notes,

> "Burr reduction has received particular attention in recent years……… Solid carbide drills run at high speeds and feeds that generate high pressure on the workpiece material; conventional drill designs or point angles would generate large burrs at the exit of through holes. The easiest way to overcome this is typically to increase the point angle to 135-145 degrees. With a point angle in this range, the drill generates a disk at the end of the hole and keeps the work material under tensile stress, making it easier to cut instead of just pushing it out of the workpiece. Edge preparation, corner chamfers, and other geometry factors also play a major role in reducing burrs (Parzick 2006)".

The material in the bottom of a through hole has four displacement opportunities: (1) be removed as chips, (2) be formed as a disk that falls off or is brushed off, (3) become a typically ragged and long burr extension of the hole, or (4) be largely removed as chips or disk, but leave some short burrs. The third choice is of course highly objectionable to every user. The first is the goal, but the fourth is the typical result. The desire mentioned above of producing disk shaped material is a good choice for some manufacturers, but a major problem for others because the disks get caught in the flutes, under fixtures and locating devices, and sometimes are lost in the part where it will cause undesirable problems later.

Today over 3300 pages of knowledge is available for users to apply on burr formation, minimization and prevention[8] – all of it generated since 1970. More than 95% of all knowledge of burr formation, prevention and minimization has been generated since 1970. Over 90% have been generated since 1989. Burr minimization work is not limited to the U.S. or Europe. Today researchers in Japan, Korea, Russia and China have contributed to the technology of how burrs form and how they can be minimized. The work is not finished.

[7] This study involved metal parts. The first published printed circuit board drilling studies also appeared at about this same time (Anonymous 1962; Weatherald 1966). By 1972 numerous PWB studies included burrs as one of the measured variables (Gillespie 1972).
[8] These 3300 pages are just university thesis and dissertations on burr formation.

Preventing Burrs

One of the early principles of burr technology was that in conventional machining it is not possible to prevent burrs because burrs are a function of a material's ductility and all metals have some elongation. With the advent of Schäfer's work on the impact of edge angles it is clear that with a judicious choice of edge angles it is possible to prevent some burrs from occurring. Brass cartridge cases when indented with a ball indenter prior to drilling the primer hole also will not produce burrs when the right ball geometry and pressing characteristics are chosen. Dornfeld's group of researchers has also shown that when cutter teeth do not exit over an edge while cutting the exit burr will not form. That is the principle which the automotive companies are taking advantage of. The key issue is efficient cutter path planning to assure that exit burrs do not form or form only in isolated areas that are the best location for them. With careful path planning a sharp edge will typically result, although a slight dulled edge may also occur depending upon conditions. The difference between no burr and sharp edges can be significant for some applications particularly since it can reduce the edge smoothing time and simplify the edge finishing process. Burrs create more uncertainty in edge finishing processes than do just sharp edges.

Nontraditional Machining Processes

Many nontraditional metal removal processes do not produce burrs. Table 1 lists a few of the more common nontraditional processes. Water jet, laser and EDM cutting can leave sharp edges, slightly dulled edges at one end of the cut or some fine recast material at edges. As these processes were first introduced to production machining their edge quality had significant limitations. Since their introduction in the 1960's these processes have matured to the extent that they consistently produce high quality burr free edges, and edges largely free of objectionable recast material. These particular processes have become major forces in high production. They not only produce near sharp edges, but they can hold much tighter tolerances than when they were first introduced into production. More precision, finer edge control, better control of surface integrity, faster cut rates and automated operation have resulted in processes in widespread application today. As a result their use has reduced the number of edges produced that have burrs. The history of edge quality improvements of these three processes would make an interesting study by themselves. The impact is ten of thousands of hours of deburring eliminated from work requirements.

The electrochemical processes like ECM absolutely do not produce burrs, but their use has never reached significant quantities to impact production. Environmental and precision issues have prevented them from achieving widespread use.

Table 1. Nontraditional machining processes

Process	Typically makes burr?*	Typical edge radii produced (in./mm)	Typical machining tolerance (in./mm)
Abrasive jet machining (AJM)	No	.003/0.08	Unknown
Chemical machining (CHM)	No	Unknown	±.002/0.05
Photchemcial machining (PCM)	No	.001/0.03	±.002/0.05
Electron beam machining (EBM)	Yes	Unknown	±.001/0.03
Electrochemical discharge (ECD)	Unknown	Unknown	±Unknown
Electrochemical grinding (ECG)	No	.003/0.08	±.002/0.05
Electrochemical machining (ECM)	No	.001/0.03	±.002/0.05
Electrochemical honing (ECH)	No	.0005/0.013	±.0002/0.005
Electrical discharge machining (EDM)	Yes	Unknown	±.00006/0.015
Electropolishing (ELP)	No	.001/0.03	±.0005/0.013
Electrostream machining (ESM)	No	.002/0.05	±.001/0.03
Hot chlorine gas (HCG)	No	.002/0.05	±.003/0.08

Ion beam machining (IBM)	No	.00005/0.0013	±.0001/0.003
Laser beam machining (LBM)	Recast material	Unknown	±.001/0.03
Plasma arc machining (PAM)	Recast material	Unknown	±.003/0.08
Ultrasonic machining (USM)	No	.001/0.03	±.001/0.03
Water jet machining (WJM)	No	Unknown	±.003/0.08

* Where burr is visiible under 30X magnification.

Designing for Edge Quality

Knife manufacturers have always designed to produce a sharp knife and a blade that stays sharp under hard use. The design of part edges to perform well in machines, however, has not always been a subject of renown. In the 1960s the topic of surface integrity became a beacon of design concern for aircraft engine makers and aircraft body manufacturers. Typical machine part edges, however, did not receive the same attention to performance. Takazawa describes his work in the 1960's on the edge quality of automotive air conditioner parts (Takazawa 1998). By reducing edge radii from 0.2 mm to 0.05 mm he was able to show a 6 percent improvement in volumetric efficiency. Like all these improvements it began by generating data on burrs and edges.

Designing for edge quality begins by:
1. defining what the edges, **all the edges** require, to perform as desired,
2. providing product designs that minimize the burr and edge issues
3. providing designs that minimize the burr and edge manufacturing issues.

Bralla introduced his *Handbook of Product Design for Manufacturing* in 1986 and it incorporates a lengthy section on designing to reduce edge finishing costs (Bralla 1986). Frederich Schäfer's several publications on product design aspects and Dornfeld's many research publications on burr formation and prevention have established themselves as equally significant works for product designers to use in their design (Dornfeld 2001). The literature tells designers what to consider. The literature tells the manufacturing engineers what to tell the designers and how to make simple impacting changes.

Designing for edge quality is not in its infancy anymore. It has not been embraced as fully as it should be and will be in the next decade. The ready existence and retrievability of edge quality design principles combined with the growth of the Toyota Production System (Lean Manufacturing) will accelerate the incorporation of edge quality in design.

Eliminating Waste through Lean and Six Sigma

Over the past decade Japanese production practices defined by many related aspects have made inroads even into deburring. Shiego Shingo through his Single Minute Exchange of Die system (SMED) revealed the principle that any process can be improved through very simple means. The Toyota Production System, JIT and Lean Manufacturing brought a "plant wide, every employee involved" premise to manufacturing that changed and is changing the very nature of how improvements are made. It has not eliminated all the burr related issues that face industry and U.S. industry particularly is just beginning to use these tools in a manner that optimize production. The Toyota Production System is not associated with deburring per se, but the Toyota System drives the changes that solve the burr related issues. The initiatives have started, and their goal is to deliver just what the product needs at the point it needs it or is most economical to provide it. Edge quality needs is being addressed at the worker level in cells as well on plant levels.

The issue of what the parts must have to reach the desired performance is in part a subject for designers to identify. At the same time, the individuals who make and assemble the parts also have great insight into what happens if all the performance issues are not addressed in design. They see what is happening in machines and tools and basic suggestions about improvements are easily made on the floor with proper management leadership.

Better Cutting Tools

Of all the improvements over the past 50 years the single most important one is the use of replaceable carbide inserted tools. In 1965, high speed steel was the single most widely used tool material. Carbide tools were either solid carbide or brazed carbide tips. Tool change was slow because the entire tool had to be removed, replaced and reset. Machinists were reluctant to change tools just because the burrs were getting big. As a result many parts had abnormally large burrs on them which required extensive manual finishing. This also was occurring at a time when the aerospace industry was introducing many more parts made of nickel and other hard to machine materials. Short tool life, long change over times, and an attitude that the burr bench will take care of it all contributed to large finishing costs in the 1960's. The advent of easy to change tool tips meant that machinists had no reason not to change out dull tips. Change outs became rapid and did not require additional tool setup. The tools were always sharp. Materials could be cut at feeds and speeds that were better choices in some cases for burr minimization. With replaceable carbide inserts users could predict when change outs would be needed. In short the right tool at the right cutting conditions resulted in normal burrs all the time.

The continued improvement in cutter inserts literally took the required 30% deburring time and drove it back eventually to the more normal 3%. Unfortunately industry does not measure impact to deburring. The cutting tool manufacturers were not keeping track of their impact on deburring. Those of us who began our careers in the 1960s remember the problems before insert tools became standard practice.

Closer Part Precision Drove Resulted in Better Edges

Part tolerances have continued to tighten over the past four decades. The differences between .005 inch part tolerances and .0002 inch tolerances forced changes in manufacturing processes and sequences, These changes in turn typically result in smaller burrs. Closer tolerances also forces more care of the parts which in turn eventually results in better understanding of edge needs.

Deburring Process Enhancements

The growth in deburring processes has been staggering. When the author reported on the then known processes in 1973 only 17 processes were known. Another 7 had actually been developed but had not reached commercialization or reporting in the popular press. Figure 2 shows 20 processes commercially known in 1976. As shown in Figure 3 108 of the 117 processes have been developed since 1950 and 98 of the 117 since 1960. The era from 1960-2000 brought 82 percent of all deburring processes. Table A2 provides a capsule look at the 117 deburring processes of which 80 are significant.

Deburring equipment companies have come and gone yet in the year 2000 over 1000 companies made and supplied deburring products and services (Gillespie 2001). The product catalog defining *who makes what* is over 300 pages long and some suppliers of these items have detailed product catalogs of the same magnitude. An estimated 40,000 pages of information on burrs and deburring exists today.

Progress has come in hundreds of small steps, but four deburring processes particularly stand out as major contributors to enhanced deburring effectiveness. They are:

- on machine brush deburring
- mass finishing
- abrasive flow deburring
- robotic deburring

BRUSH DEBURRING ON MACHINE INCREASES EFFECTIVENESS

In the 1970's when mechanized brush deburring was required an old worn machine tool was often used. New machines specifically for brushing were also available for purchase. Brush deburring was a secondary operation, required handling parts another time, another set up, another person to monitor or run the

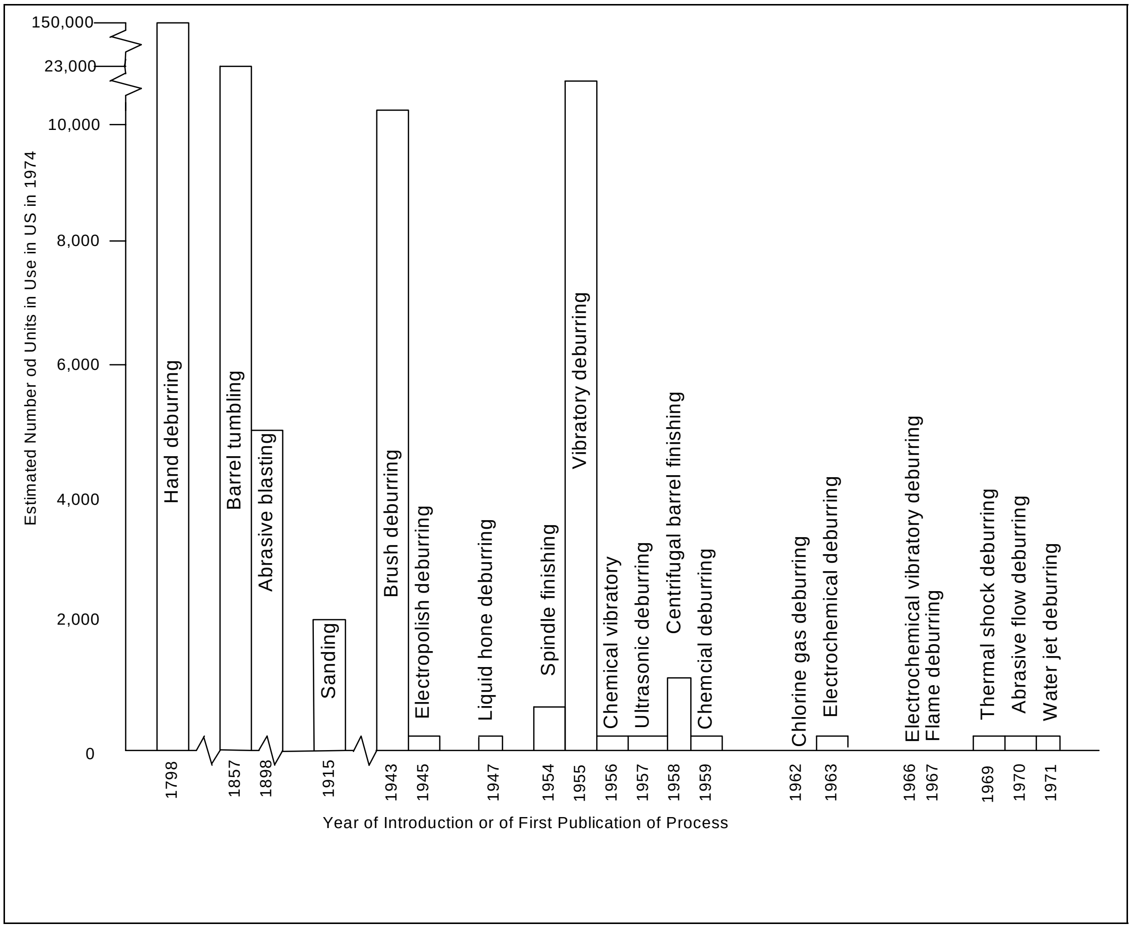

Figure 2. !975 Timeline of Deburring Development (Gillespie 1975a)

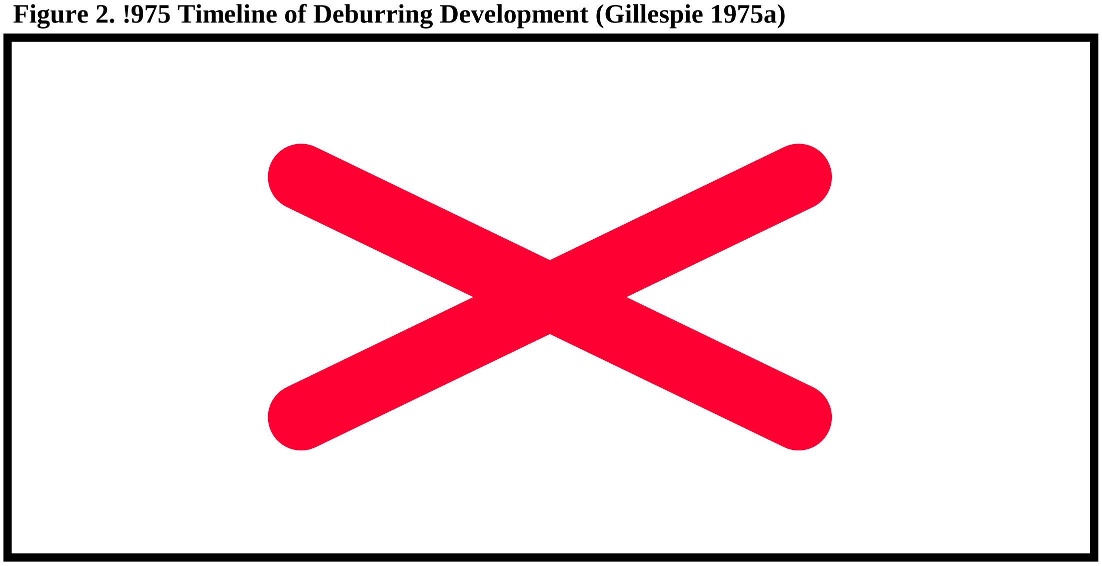

Figure 3. Number of Ddeburring Processes by Year of Introduction

machine. Capital equipment was expensive, especially precision mills or machining centers. Owners would not allocate their expensive machine tool time to deburring, “which any old machine and operator could do.”

As a result of increased pressure to eliminate unnecessary handling (wasted labor), relatively inexpensive automated machining centers, major improvements in brushing's effectiveness and continued push to use on-machine brushing by brush manufacturers and published articles many shops now incorporate brush deburring in the machine cycle that produced the part. The abrasive filament brush was developed in the 1970's and by the mid-1980's sophisticated abrasive filled nylon filament brush designs were available that out-performed wire brushes in many applications (Scheider 1990). Since the 1990's more innovative brush designs using these filaments have made the process even more efficient. Brushing is one of the most cost effective processes available for many parts. The use of these brushes on the machining centers began in the 1980's and this proliferated in the 1990's. The combination of better materials, designs, and CNC machine finishing, and simplicity of brushing has taken it out of the hands of the manual operator for many applications. Path planning is simple for this process. Edges do not have to be followed; a simple back and forth motion over the machined surfaces typically is adequate.

ENHANCEMENTS TO MASS FINISHING

As noted above barrel tumbling was already entrenched in the first half of the 1900's. Vibratory finishing appeared in the 1960s followed by centrifugal barrel, centrifugal disc in the 1980's. Other variations appeared along the way as well. Today an estimated 30,000 vibratory finishing machines are in use (Gillespie 1999), joined by 10,000 centrifugal disc machines and perhaps 2000 centrifugal barrels. These three processes deburr an estimated 30-50% of all hand size and smaller metal piece parts. Their success is in part to the 500 billion operational variations users can select from to tailor parts and edges within parts (Kittredge 1983). Manufacturers of this type of equipment have provided manually operated machines as well as fully automated systems and plants. They have provided benchtop units and machines that are 40 feet long. Very low cost machines are available as well as more durable industry ruggedized units.

The theory and operation of this equipment has been written in hundreds of articles and reports. It is simple to use and lasts for years. Operator training is minimal. Matsunaga's research defined the process variables and provided clear guidance for users (Matsunaga 1958; 1959; Matsunaga and Hagiuda 1965; 1967). Others came along after and added to the data (Robbins 1965;Gillespie 1973b; Hignett 1976; Kittredge 1981). Extensive handbooks have been produced for these processes in Japan (Matsunaga 1959:Anonymous [Sintobrator] 1980), Russia (Babichev 1968, 1974, 1981, 1984, 1994, 1999), and the U.S. (Gillespie 2006a). The IPA effort in Germany also provided a series of geometry issues for mass finishing that were put in practice in Germany and spread around the world (Schäfer 1975b).

The technology allows users to position finishing at ends of production lines. It provides smoother parts - parts easier to assemble. In some instances it adds fatigue life to the parts, perhaps hundreds of hours more to each. The technology hones the outer part dimensions. The technology allows last minute process changes that accommodate larger burrs, changes dimensional needs, different material and faster production rates. Every incremental improvement and new insight allows more products to be finished less expensively.

EXTRUDE HONE ABRASIVE FLOW DEBURRING

The abrasive flow process was commercialized in 1966. The aerospace industry was searching for effective ways to deburr and radius cooling holes in jet engine turbine blades. By the 1970's industry of all kinds was looking for better deburring approaches. The first magazine article describing this process reportedly resulted in 5000 enquiries – an extraordinary response to an article. Industry was actively looking for solutions to burrs.

Extrude Hone began an aggressive effort to educate the public, participating in almost every deburring conference and seminar held in the U.S. They publicized the applications and new approaches in technical papers and articles continuously. They led conferences and took an active leadership role in promoting burr technology in SME's Best Committee and other venues. That leadership, the publicity and extensive advancement in machine and process capability kept the process in the mainstream of reader attention. Over 3000 machines around the world have finished an estimated 500,000,000 precision parts via this process according to Bill Miller of Extrude Hone. It provides edge finishing and surface polishing capabilities that no other process can produce. It has the capability to reach areas that other processes can not. Every edge, no matter how deep, is another opportunity to excel. While it finishes molds and dies, medical and dental pieces, hydraulic components and many others, it has made numerous jet engine blade advances possible. Those advances make travel more economical, engines lighter and production faster.

ROBOTIC DEBURRING

The technology of deburring robots began in 1975 in Germany and Sweden. Frederich Schäfer reported on them as part of his research in 1976 (Schäfer 1976). By 1980 industry around the world had begun studies to apply them to their production. Deburring robots began as fettling robots. They removed the sprues, risers, gates and runners and some flash from cast metal parts and some plastics. That work did not require close tolerances. As the controllers and machines became more accurate users and machine producers moved into deburring. The challenge for using deburring robots became one of accurate and repeatable control. Following hundreds of line arcs and segments that represented every edge of a part took extensive programming. Few robots have been able to accomplish that for production use. As a practical matter many users also questioned whether it made sense to traverse every edge of a part as humans did.

In the past 30 years the technology of robotic deburring has been studied and reported in 100-200 thesis, dissertations, papers, reports and articles, but the most successful applications appear to be those that use simple approaches, work on the same configuration every day, and work on non-precision part edges. Tens of millions of dollars have been spent by the most prestigious laboratories and universities and companies to replace human manual deburring with robotic efforts. Despite the limitations that still exist today the deburring robot has made significant impact on U.S. industry because it directed attention to the issue of human ergonomics and the need for better approaches for deburring and finishing. Unlike the other processes discussed above, the most significant attribute of deburring robots is not their ability, rather it is the thought processes required for edge finishing to implement such a machine and the use of robots to handle heavy, hot or otherwise ergonomic issues in production. Stated differently, the most successful benefit for this technology has been its lack of widespread use that forced in-depth thinking about best finishing methods.

Deburring robots are successfully used in many situations and they do save money and provide the consistency needed on some parts that simply is not reproduced by humans. As skilled labor gets more difficult to obtain robotic applications will become even more important. Investigating how these robots are actually used, reveals that many are used more for material handling, and surface polishing than for deburring even though they are identified as deburring robots. They are very successful in those applications, but they are not deburring, they are finishing and handling.

Availablility of Edge Standards

When deburring improvements are planned one of the first tasks companies face is deciding what edge standards are needed. Today a variety of edge standards have been publicized as models for companies to use. Japan and Germany continue to enhance their national standards in this area. Schäfer's book was one of the first to describe an effective edge condition standard for general parts (Schäfer 1975b). It was not whole-heartedly endorsed by German industry, but it provided a system that allowed users to specify what edge quality was needed. U.S. suggestions for burr definitions began in 1976 (Barnes 1976; Gillespie 1977a) and continued intermittently into the 1990's. Japan's BEST-J actively continues to promote standards there and internationally, and a series produced by the WorldWide Burr Technology Committee provides a smorgasbord selection that any company can use successfully. Berger's proposed standards for automotive use is the latest example of a sound discussion of this topic (Berger 2004).

The impact of standards is hard to measure. The impact of not having company standards is easier to portray. The author has been involved in two lawsuits stemming from a lack of standards. In each instance the companies involved did not have written definitions of what their intention of "burr", "deburred", "burr free" and related terms meant. As a result of several issues these cases were initiated with financial claims amounting to just less than 20 million dollars – all because they did not define their terms.

FINANCIAL IMPACT OF THIS PROGRESS

The enhancements in mass finishing technology affectes not only billions, but hundreds of billions of parts. Mass finishing is typically the least expensive of all the finishing processes. Even at savings of a penny a part, industry would have saved $1 billion on a hundred billion parts.

A 1976 survey of deburring costs indicated that the values in Table 2 were typical (Ham 1976). The range in costs varied from 0.005 to 30 percent of the total part cost with many spending 10% (Drozda 1977; Kerr 1977). Aerospace typically had many parts nearing the 30% value. Yet another study at that time indicated that finishing equipment represented about 6% of the capital equipment dollars being spent in 1979.

Table 2. Deburring Costs in 1976 (Gillespie 1981)

% of total make cost attributed to deburring	% of responders indicating this percentage	Weighted value (column 1 x column 2)	Weighed Average (%)
1	10	10	
2	9	18	
3	8	24	
5	15	75	
10	15	150	
Total	57		4.85%

Table 3. Deburring Costs (Drozda 1977)

% of total plant mfg $ spent for deburring	% of 377 respondents indicating this value	Weighed value (column 1 x midpoint of column 2)	Weighed average (%)
75%	Less than 10%	375	
17%	10-20%	255	
6%	20-30%	150	
2%	30-40%	70	
Total 100%		850	8.5%

From Drozda's survey sent to 2073 manufacturing engineers (Table 3) 25% indicated that their costs were higher than 10% of the make costs. Another study (Kerr 1977) indicated that deburring costs for machined Canadian aerospace parts ranged from 4 to 8 percent but when other parts are included the number may approach 12%. Individual aerospace parts ranged from 15 to 28 % and some required fully 50% of the number of hours required for machining them. Two companies had deburring costs for sheet metal parts of 10-11% of total part cost.

In 1976 Inyong Ham in conjunction with *Machine & Tool Blue Book* and others led a nationwide study of manufacturing company use of group technology. In that study he summarized the deburring data shown in Table 4. Ham's study showed the fact that a relatively high number of companies had a large group of people performing deburring. The weighed average number of employees seems large.

Table 4. Deburring employment (Ham 1976; Anonymous 1976c)

Number of full time deburring workers	% of responders having this number of deburring employees	Weighed value (column 1 x midpoint of column 2)	Weighed average (# employees)
1 to 5	35%	105	
6 to 10	22%	176	
11 to 20	9%	140	

21 to 30	7%	178	
31 to 50	3	106	
Over 50	7	350	
		1055	12.7

While a few plants today may have deburring exceeding 10% of total make costs, it is highly unlikely that many approach the 30% seen in 1976 and 1977. Apparently no surveys of deburring costs have been reported since that era. The author believes that today deburring costs tend to be in the range of 3% when averaged across all metal cutting operations. Actual data to support this or any other position just does not exist, however. If three percent were the case, then deburring costs would have fallen by 38% (4.85 to 3%).

US Department of Labor statistics document the fact that deburring labor is lower than 10% and probably much lower than 5%. Appendix Table A3 provides the raw data for the year 2005. Two classifications include deburring workers mixed with grinding and polishing workers. There is no breakdown for operators performing just deburring. As a best estimate the author assumes that less than half of these workers actually spend full time deburring. That would imply that just under 2% of the workers in metal and plastics perform manual deburring, while less than 5.5 % perform any kind of manual or machine deburring.

The author estimates that in the US there are less than 73,000 workers whose job is essentially full time deburring (using the statistics in Appendix Table A1 and estimating that less than half are deburring workers)[9]. At a rate of almost $30,000 per year that represents an annual total deburring labor *wage cost* of about $2 billion. Factoring current overhead costs for wage earners of 100% of salary this number becomes $4 billion. In 1976 the author had access to far less accurate data and estimated the US cost then at $2 billion including wages and overhead (Gillespie 1976c). International deburring costs were estimated then at $6 billion US.

The US metal cutting industry represents about 16% of the machine tool world market (Hill 2006). If the ratios for deburring workers to burr producing workers were the same as the US for all the other countries of the world, and the global machine tool market reflected the global manufacturing sector then about 456,000 deburring workers are at work throughout the world. While wage levels vary widely around the world they do not vary much in most highly industrialized economies. At the US rate of $30,000 per year, and an overhead factor of 100%, the world cost of deburring labor would approach $27 billion US.

If these numbers are somewhere near correct, then US costs for deburring rose 100% from 1976 to 2005 while the rate of inflation increased 243%. While the data presented here provides only conceptually accurate understanding, it does reinforce the observation that deburring costs as a percentage of manufacturing costs are lower now than in 1976.[10]

Small part manufacturing is estimated at $32.5 billion globally in a 2006 study (Richter 2006). To function properly these parts also require high quality edges. For this small sector alone a 3% deburring cost would constitute almost a $1billion global market today.

INTERNATIONAL RECOGNITION FOR BURR TECHNOLOGY CONTRIBUTIONS

[9] Table A2 reflects an estimated 300,000 workers perform hand deburring as part of their job. Machinists and machine opertors frequently have to do some deburring as part of their job, but it is not a full time task. The numbers shown in Table A3 reflect essentially full time workers in this field. As shown in Table A3 almost 900,000 workers could perform some deburring as part of their tasks.

[10] Individuals interested in performing further comparisons of deburring economics will benefit from the National Machine Tool Builders' Association (Now Association for Manufacturing Technology) 1976-1977 Economic Handbook of the Machine Tool Industry for the years 1976-1977 and 2005-2006.

Many leaders of burr technology have received national and international acclaim for their work. Takazawa and Babichev have each received SME's Gold Medal for their work on burr technology. Dornfeld received SME's Frederick W. Taylor Research Medal. Gillespie received SME's Albert M. Sargent Progress Award as has Hans Warnecke, a leader of the University of Stuttgart's IPA activities in burr technology and other fields. Khalil S. Taraman, a leader in drilling burr early research, received SME's Joseph A. Siegel Service Award. William Brandt, the leader in publishing significant vibratory finishing work in the 1960s and 1970s received the SME Progress Award as well. Hitomi Yamaguchi received SME's Outstanding Young Manufacturing Engineer Award for her work on magnetic abrasive finishing. Richard Furness, a leader in burr technology at Ford also received the SME Outstanding Young Manufacturing Engineer Award. Mark Lambeth, a robotic deburring leader in Fort Worth received the same award, as did Gloria Weins for robotic deburring at Florida, and Ranga Narayanaswami (one of the CODEF researchers). Lori Russin of Westinghouse pursued burrs and also received the young engineer award. Anthony Sofranas, worked on drilling burrs at Bendix and the University of Detroit before he received the same award. Dornfeld, and Gillespie received Fellow Member status within SME and in 2006 Koya Takazawa will receive Fellow Member status for their contributions. Hisamine Kobayashi, President of Shiskashima Tipton, produced over 500 Japanese and U.S. patents in mass finishing technology. He received the third order of merit from Emperor Hirohito for distinguished services for barrel finishing.

Clearly there are many other contributors to burr technology who also have received high acclaim. The author just does not know the recognition details. Fifty-five of the key leaders have been cited and their works identified elsewhere (Gillespie 2004).

The success of burr technology advances has come in part because of the international network of burr technology researchers and promoters. It began in 1974 with the tie between SME's BEST Committee and the formation of Japan's BEST-J organization. Since that time Takazawa has been the world's key promoter organizing and supporting international conferences around the world to share our corporate knowledge of burr technology through the World Wide Burr Technology Committee and the Asia Pacific Forum on Precision Surface Finishing and Deburring Technology Conferences. That brought an unprecedented international communication that continues today. The CODEF team provides another communication aspect. The individuals at CODEF who have performed the myriad studies in burr technology have come from around the world. When they finish they have similarly gone back around the world to lead other studies and further advance the technology. As part of the communications the leaders of these efforts have not only communicated what is known, but have brought awareness to their countries of progress in the technology and have brought additional researchers into the fold of individuals working on the technology.

PROJECTIONS FOR THE NEXT 10 YEARS

The next ten years will bring progress in several areas including:

- Software
- Prevention
- Minimization
- Edge standards

SOFTWARE

Burr technology software has only come into prominence in the past ten years. It is an overlooked aspect of burr technology. While logic and understanding allow us to make good choices, the multitude of choices needed in manufacturing and the rapidity they are needed to meet needs demands software. The only recorded burr technology software includes Kittredge's MF-CALC program for selecting mass finishing capacity needs (Kittredge 1985) and that used by the 1985 Shiskashima Tipton's Mechatro Barrel (Flexible Finishing) Pavillion (Ioi 1985). The later requires a complete logic for part needs and process capability and the associated database. It is not software that is available to others in general, although some aspects may be built into individual systems. The Kittredge program requires the computer to have an empirical understanding of part motion through vibratory media.

The CODEF software for minimizing burrs is the type of most needed software. Automated deburring process selection software is another need for today's users. When it appears it will help guide users to some of the least cost processes before they buy equipment.

Users do not believe they can afford process experts like they did in the 1970's. Experts are disappearing from U.S. shores and popping up in other parts of the world. Users want immediate answers and answers that they do not have to have the intensive background to understand. They do not in general want to invest in the Ph.D. learning process to answer deburring questions. They want a program, and a program that is easy to use. It is an issue that is important to our educational system as well as to the potential graduates, particularly those who want to begin new businesses.

On-line decision making software is another aspect that will appear in the coming decade. The platforms for providing it exist and require nothing more. Several models for paying for the opportunity to use such programming also exist. The logic and ruggedized code does not, in general, exist, nor is it clear who will offer these services. In fact, deburring software is just one of many opportunities for software programming that exists as a result of many manufacturing advances published in learned journals. It is a field of manufacturing that seems to have been overlooked.

BURR PREVENTION AND MINIMIZATION

Burr prevention and minimization will still be a target of study, a target garnering more attention and financing. It is the right answer for all manufacturing. It is the right answer for lean principles, the elimination of waste. It may not be the most cost effective approach for all plants and products, but it should be the goal against which to measure performance.

EDGE FINISHING STANDARDS

Despite the progress made in providing useful plant and international edge standards many companies still do not have written standards or written practices that would benefit them. As noted in the published sources that promote the standards, there is nothing negative about stating clearly what a company expects and inspects for. Standards do not have to be restrictive – they need to (and do) state what the company needs.

DATA NEEDS FOR ADVANCEMENT

While the past fifty years have brought major advancements to burr technology there are still mountains of unanswered questions. Deburring and edge finishing still have pockets of missing data. Centrifugal disk finishing lacks the data on edge radiusing, surface finishing and stock loss that exist for vibratory and centrifugal barrel tumbling. Little data has been published on the burr removal capability of the new stiff brushes used for on-machine finishing. Laser deburring and deflashing has no published data. Cryogenic deflashing has the same lack of numerical capability data and it could be a field unto itself. Chemical aided mass finishing lacks capability data. There is no data on finishing ceramic parts.

Despite all the handbooks and articles on burrs, there is still not one guide that takes a user through each step in the edge finishing decision process that looks at all the needs of a part and allows easy decision points. The Mass Finishing Handbook comes closest to meeting that need for several processes, but not for all covered by that book.

Burr technology for composites is becoming a more pronounced field, yet no one article describes or addresses all the needs of this material group. Prevention of burrs in composites, minimization, and burr removal as a family of issues have not been addressed with data. The field of composites is growing as a challenge with metal/ceramic/plastic combinations and critical interface junctions.

Burr technology includes many tricks of the trade or shop shortcuts that have never been publicized. 50,000 machining shops each have one or two ways they minimize the problems of burrs. There is room for a book just on this subject, to join the existing book on hand deburring. Edge finishing economics is covered in at least two books, yet few studies delve into the real economic decisions that are made. It is a natural adjunct to the work on decision making guides and software.

Flash prevention is at the point that burr technology was 30 years ago. The basic concepts are understood, but the predictive mechanics are not yet developed.

Magnetic finishing is one of the processes which has made a niche market for itself. When parts require high luster, fine surfaces and burr free edges it stands alone as a simple process to accommodate these outcomes. Despite its technology it is not used in the U.S. Only Japan and Russia seem to have incorporated this technology (Babichev and Morozov 1970; Baron 1975, 1979, 1986; Shinmura 1986). The breadth of the development is impressive with dozens of research reports describing new findings.

MISCELLANEOUS EMERGING TOPICS

A field is beginning in the topic of microburrs. That requires sophisticated Scanning Electron Microscopes, enhanced definitions, and new studies of removal and prevention.

Surface integrity will re-emerge as a topic of interest and concern as manufacturers must understand the potential of new processes and the positive or negative impact on subsurface properties that affect fatigue and endurance.

The shortage of skilled help in the US will drive more companies to outsource and require additional automation of deburring.

We are still assessing the impact of the Internet on manufacturing. It does not seem to have had a direct impact on deburring, other than allowing international researchers to more quickly find the information they need. The Internet will have more impact, we just do not understand in what form this will happen.

SUMMARY

Deburring and edge finishing quietly evolved to a very robust technology that has reduced costs and made the lives of all citizens more economical. Progress was the result of hundreds, perhaps thousands of incremental improvements as well as some major steps. These improvements have come in our lifetime, and many of the speakers at this conference have driven the significant changes and communication of technology. The changes have resulted in billions of dollars of savings each year and over a 40 year period might amount to as much as $100 billion. It is an amazing story saving billions of dollars for something no one wanted in the first place. The minute burr was winning the battle, but your burr technology effort changed the world.

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APPENDIX

Table A1. History of Modern Deburring Developments
Table A2. History of Deburring Processes
Table A3. US Department of Labor Production Classifications

Table A1. History of Modern Deburring Developments

1857	Barrel tumbling widely used in industrial revolution	
1891	Scissors handles are dragged through barrel of abrasive to deburr and polish them. (Flow finishing process)	Patterson 1891
1898	Abrasive Blasting introduced	
1899	First patent for Fixtured parts in barrel tumbling	Kellard 1955
1916	Flexible shaft electric motors introduced for hand finishing	
1916	Power buffing widely used for deburring and polishing	Anonymous 1916c
1920		
1933	Blasting used specifically to remove burrs and flash	
1943	Power brushing becomes widely used to deburr as part of World War II effort and availability of bench and pedestal grinders and portable hand tools	Scheider 1990
1945	Electropolishing used for deburring	1945
1947	Liquid honing used for deburring	1947
1950	Westinghouse completes major study looking at how tool properties affect burr height in blanking laminates	Hamill 1950
1952	First learned journal published paper on deburring	Hisao, Suda, Kadowaki, and Tanaka 1952
1952	Flame deburring in use for smoothing glass edges, but never became a significant process for metal	Lemay 1952
1953	Electropolishing use for deburring documented in trade magazines.	Anonymous 1953
1955	First English language book on barrel finishing	Enyedy 1955
1955	Vibratory deburring begins	
1956	Impact of tumbling process on residual stresses documented	Letner 1956
1956	Spindle finishing introduced in U.S.	Squibb and Hall 1956
1956	First research report on chemical barrel tumbling	Sachs and Odgers 1956
1956	Chemical vibratory finishing introduced	Sachs and Odgers 1956
1956	First research report of embedment of loose abrasives in finishing	Williams 1956
1957	Ultrasonic deburring introduced	Wright 1957
1958	Burr effects of punching operations explained	Wukusik 1958
1958	PERA (England) produces 5 reports on deburring technology	Anonymous 1958b,c,d
1958	PERA publishes first report on prevention of burrs	Anonymous 1958d
1958	Vibrating barrel introduced in trade magazines.	Anonymous 1958e
1958	Vibratory Deburring used commercially	Anonymous 1958

1958	Reciprocating blanking introduced to reduce burr formation	Maeda 1958
1958	Landmark fundamentals of barrel finishing research published	Matsunaga 1958
1958	The first learned journal report on formation of burrs is published	Okushima and Hitomi 1958
1958	Chemical deburring used	Anonymous 1958c
1959	First data driven book on barrel finishing published	Matsunaga 1959
1959	Harper introduces centrifugal barrel finishing in trade journals. It actually was in use in 1958.	Harper 1959
1960	Flow finishing introduced	Kobayashi 1960
1960	The first of many English language suggestions for minimizing blanking burrs	Straser 1960
1961	American Society of Tool and Manufacturing Engineers use burr measurements to complete major study of stamping burrs	Biegel and Holmes 1961
1963	Electrochemical deburring used commercially	Anonymous 1963a
1963	Chlorine deburring announced, but never used commercially. It was developed in 1962.	Anonymous 1963b
1963	One of the first studies on drill burrs is reported	Bell and Kearsley 1963
1963	Electrochemical deburring developed	
1964	Landmark paper describing burr measurements for punched parts	Wentzel and Mehlhorn 1964
1964	Microblasting machines introduced	Anonymous 1964
1964	Water Jet deburring introduced	Arnold & Evans 1964
1965	German researchers complete major study of burrs from stamping	Seidenberg 1965
1965	One of the first guides to designing for burrs	Anonymous 1965
1965	First scholarly work on vibratory finishing	Matsunaga and Haguida 1965
1966	First known research on vibratory deburring effects on edge breaks based on machine conditions	Robbins 1966
1966	Electrochemical vibratory deburring developed.	1966
1966	Abrasive Flow Deburring used commercially	Hoffman 1966
1967	Landmark scholarly report on barrel finishing	Matsunaga and Hagiuda 1967
1967	First scholarly report on drilling burrs begins long series of work on this topic	Zaima and Yuki 1967
1967	Cryogenic Deflashing commercialized	Domielly and Adams 1967
1969	Landmark paper on lack of repeatability of burr height in punching and use of design of experiments	Wang, Taraman and Wu 1969
1969	First paper on EDM edge quality	McBride 1969
1969	First scholarly work on burr prevention in grinding	Sato 1969
1969	First scholarly work on burr minimization in turning	Takeyama 1969
1970	Magnetic vibratory finishing appears	Babichev and Morozov 1970
1970	Electrolytic vibratory finishing patented	Anonymous 1970a
1970	Thermal Energy Method (explosive) deburring introduced commercially. (It was actually developed in 1969 as a result of work on plastic membrane deflashing).	Anonymous 1970b

1973	The first U.S. mathematical treatment of burr formation	Gillespie 1973a
1973	Recipro-Finishing patent awarded in U.S.	Kobayashi 1973
1974	First comparative summary of all known deburring processes published	Gillespie 1974c
1974	First cumulative bibliography of deburring literature published by SME (earlier version published by Bendix in 1971)	Gillespie 1974d
1974	Burrs produced by reaming are reported	Gillespie 1974a
1974	Burrs produced by ball broaching are reported	Gillespie 1974b
1974	Effect of laser cutting on edge quality is reported	Heglin 1974
1974	Opposed die approach to preventing burrs commercialized	Kondo 1974
1974	Magnetic abrasive polishing begins	Makedonski 1974
1974	Sharp edge tester introduced	Sorrels and Berger 1974
1975	First data driven report on hand deburring capabilities	Gillespie 1975b
1975	Effect of part edge angles on resulting radius in vibratory finishing	Gillespie 1975d
1975	First report of burrs produced by side milling	Gillespie 1975c
1975	First research report of impact of tumbling processes on plating adhesion	Gillespie and Clay 1975
1975	Landmark paper on impact of part design on burrs and deburring	Schäfer 1975a
1975	Landmark German book on burr formation and deburring	Schäfer 1975b
1976	Orboresonant energy deburring introduced	Anonymous 1976a
1976	Ultrasonic assisted chemical deburring is introduced	Bullen 1976
1976	Empirical study of burrs produced by end mills	Gillespie 1978
1976	First robotic deburring report	Kaufmann 1976
1976	Immersion lapping appears as deburring process	Wolfhard 1976
1977	One of the first efforts to define burr related terms	Gillespie 1977a
1977	First comprehensive look at side effects of deburring processes	Gillespie 1977b
1977	First article on turbo-abrasive finishing	Kremen and Massarsky 1977
1977	First standard for defining edge conditions	Schafer 1977
1977	Burr free slitting processes developed in Japan	Maeda and Murakawa 1977
1977	First extensive review of deburring processes in trade magazine provides widespread overview of the major processes and issues.	Drozda 1977
1978	Burr formation during face milling	Schäfer 1978
1978	Roll Flow finishing is first described in print	Anonymous 1978
1979	Suggests use of pseudo burrs in deburring	Gillespie 1979
1980	First Japanese book on all deburring processes	Takazawa 1980
1980	First database established for automatic selection of deburring processes	Ioi 1980
1981	World's first computer controlled flexible finishing factory appears	Anonymous 1981
1981	Face Milling burr formation described	Kishimoto 1981
1981	The day to day mathematics of mass finishing are described	Kittredge 1981

1982	Vibratory conveyor deburring process developed	Aoki Iida and Jimbo 1982
1983	Cascade finishing commercialized	Meehan 1983
1983	Chemical vibratory finishing is explained	Dargis 1983
1985	Deburring plant operation is simulated	Ioi 1985
1985	Vision system uses color to assist deburring operation	Takeuchi 1985
1988	Ballizing is used as deburring process	Grodsky 1988
1991	Capacitance sensor used for detecting burrs	Anonymous 1991
1993	Computer modeling of burr formation	Park 1993
1998	Micro burr technology begins	Ko, Lee and Jun 1998
1999	Most comprehensive English language book on burrs and deburring published	Gillespie 1999
1999	Classification system established for burr formation	Hashimoto 1999
2000	Compilation of references on measuring sharpness	Gillespie 2000b
2000	A 350 page guide to deburring products is published	Gillespie 2000a
2000	Burr formation in planing is described	Baron 2000
2004	History of burr technology contributors published	Gillespie 2004

Table A2 Deburring Processes Known in 2006 [11][12]

Process (code)		**Source**	**Year**	**Qty in US**	**Qty in World**
Abrasive Finishing (A)					
	Barrel Tumbling (Al)	Beaver 1948	1885	8,000	16,000
	Vibrating Barrel Tumbling (A1v)	Anonymous 1958e	1958	200	400
	Vibratory Finishing (A2)	Kittredge 1980	1955	12,000	30,000
	Vibratory Shaker Mixer Finishing (A2s)[13]	Gillespie 1999	1954	15	30
	Vibratory Spindle Finishing (A2SP)	Babichev 1993	1993	0	4
	Tube Flow Through Vibratory (A2t)	Thompson 1983	1983	4	5
	Roll-flow (Centrifugal Disc) Finishing (A3)	Anonymous 1978; Okumura and Cantwell 1991	1978	300	500
	Centrifugal Barrel Finishing (A4)	Harper 1959	1958	1,000	2,000
	Spindle Finishing (A5)	Squibb and Hall 1956	1956	500	1,200
	Fluidized Bed Spindle Finishing (A5a)	Kremen and Massarsky 1977	1977	20	40
	Recipro Finishing (A6)	Kobayashi 1973	1973	0	5
	Orboresonant Finishing (A7)	Anonymous 1976a	1976	5	10
	Flow Finishing (A8)	Kobayashi 1960	1960	5	10
	Cascading Media (A9)	Meehan 1983	1983	35	50
	Immersion Lapping (A10)	Wolfhard 1976	1976	10	50
Chemical Loose Abrasive Finishing (AC)					
	Chemical Barrel Tumbling (AC l)	Sachs and Odgers 1956	1956	100	200
	Chemical Vibratory Finishing (AC2)	Shainskii 1965	1956	200	400
	Chemical Roll-flow (Centrifugal Disc) Finishing (AC3)	Gillespie 1999	1999	5	10
	Chemical Centrifugal Barrel Finishing (AC4)	Hignett 1978	1978	10	20
	Chemical Spindle Finishing (AC5)	Gillespie 1999	1999	0	0
	Chemical Fluidized Bed Spindle Finishing (AC5a)	Gillespie 1999	1999	0	0
	Chemical Reciprofinishing (AC6)	Gillespie 1976a	1976	0	0
	Chemical Orboresonant	Gillespie 1999	1999	0	0

[11] These estimates are based on the intentional use of the process identified for deburring. Several of these processes also perform other finishing functions. Several processes have been studied in the laboratory, but not used industrially. Manual deburring refers to the number of persons estimated to perform deburring using some form of hand held tool.
One source notes that over 400 applications exist in Russia for magnetic abrasive finishing.
Another source notes that 1500 robots reportedly are used for deburring in Germany. No separate verification exists for that number.

[13] There are many more machines than this in use in the US and the world, but these numbers represent an estimate of those dedicated to deburring.

	Finishing (AC7)				
	Chemical Flow Finishing (AC8)	Gillespie 1999	1999	0	0
Cryogenic Loose Abrasive Finishing (ACRY)					
	Cryogenic Barrel Tumbling (ACRYL)	Domielly, T.R. Jr. and Adams, R.S. 1967	1967	50	90
	Cryogenic Vibratory Finishmg (ACRY2)	Hishaw 1973;Meyers, Robert J. 1985	1973	50	90
	Cryogenic Vibratory Shaker Mixer Finishing (ACRY2s)	Gillespie 1999	1999	0	0
	Cryogenic Roll-flow (Centrifugal Disc) Finishing (ACRY3)	Gillespie 1999	1999	0	0
	Cryogenic Centrifugal Barrel Finishing (ACRY4)	Gillespie 1999	1999	0	0
	Cryogenic Spindle Finishing (ACRY5)	Gillespie 1999	1999	0	0
	Cryogenic Fluidized Bed Spindle Finishing (ACRY5a)	Gillespie 1999	1999	0	0
	Cryogenic Recipro Finishing (ACRY6)	Gillespie 1999	1999	0	0
	Cryogenic Orboresonant Finishing (ACRY7)	Gillespie 1999	1999	0	0
	Cryogenic Flow Finishing (ACRY8)	Gillespie 1999	1999	0	0
Magnetic Loose Abrasive finishing (AM)					
	Magnetic Abrasive Barrel Finishing (Aml)	Gillespie 1978	1973	5	50
	Magnetic Abrasive Vibratory Finishing (AM2)	Babichev and Morozov 1970	1970	0	0
	Magnetic Abrasive Spindle Finishing (AM5)	Shinmura, Hatano and Takazawa 1986	1986	0	5
	Magnetic Abrasive Cylindrical Finishing (AM5a)	Makedonski and Kotshemidov 1974	1974	0	5
	Magnetic Abrasive Tube-ID Finishing (AM5b)	Shinmura and Yamaguchi 1993	1993	0	5
	Magnetic Abrasive Ball Finishing (AM5c)	Shinmura, Takazawa and Harano 1985	1985	0	5
	Magnetic Abrasive Special Shape Finishing (AM5d)	Shinmura, Takazawa and Harano 1985	1985	0	5
	Magnetic Abrasive Prismatic Finishing (AM7)	Shinmura and Aizawa 1989	1989	0	5
	Mixed Metal Fibers Magnetic Media (AM8)	Suzuki and Uetnatsu 1994	1994	0	1
Chemical Magnetic Loose Abrasive Finishing (AMC)		Gillespie 1976a	1976		
	Chemical Magnetic Abrasive Barrel Finishing (AMCL)	Gillespie 1976a	1976	0	0
	Chemical Magnetic Abrasive Vibratory Finishing (AMC2)	Gillespie 1976a	1976	0	0

	Chemical Magnetic Abrasive Spindle Finishing (AMC5)	Gillespie 1976a	1976	0	0
	Chemical Magnetic Abrasive Cylindrical Finishing (AMC5a)	Gillespie 1999	1999	0	0
	Chemical Magnetic Abrasive Tube-ID Finishing (AMC5b)	Gillespie 1999	1999	0	0
	Chemical Magnetic Abrasive Ball Finishing (AMC5c)	Gillespie 1999	1999	0	0
	Chemical Magnetic Abrasive Special Shape Finishing (AMC5d	Gillespie 1999	1999	0	0
	Chemical Magnetic Abrasive Prismatic Finishing (AMC7)	Gillespie 1999	1999	0	0
Electrochemical Loose Abrasive Finishing (EAC)					
	Electrochemical Barrel Tumbling (EACL)	Shimizu 1975	1975	0	0
	Electrochemical Vibratory Finishing (EAC2)	DeGroat 1969	1966	1	0
	Electrochemical Roll-flow (Centrifugal Disc) Finishing (EAC7)	Gillespie 1999	1999	0	0
	Electrochemical Centrifugal Barrel Finishing (EAC3)	Shimizu 1975	1975	0	0
	Electrochemical Spindle Finishing (EAC4)	Shimizu 1975	1975	0	0
	Electrochemical Fluidized Bed Spindle Finishing (EAC4a)	Gillespie 1999	1999	0	0
	Electrochemical Recipro Finishing (EAC6)	Gillespie 1999	1999	0	0
	Electrochemical Orboresonant Finishing (EAC7)	Gillespie 1999	1999	0	0
	Electrochemical Flow Finishing (EAC8)	Gillespie 1999	1999	0	0
Lapping (A9)		Indge 1991	1991	10	20
Abrasive Jet Deburring (AB1)		Plaster 1972	1935	20,000	40,000
	Ice Blasting (AB1I)	Settles 1998	1998		
Cryogenic Abrasive Jet (ABC1)		Anonymous 1961	1961	5	0
Liquid Hone Abrasive Flow Deburring (AB2)		Gillespie 1976	1947	1	5
Abrasive Flow Finishing (AB3)		Hoffman 1966	1966	2500	3000
Abrasive Flow Orbital Finishing (AB3o)		Gillespie 1999	1999	2	4
Abrasive Flow Stream		Gillespie 1999	1999	1	2

Finishing (AB3s)					
Ultrasonic Abrasive Flow Finishing (AB3u)		Gillespie 1999	1999	1	2
Ultrasonic Liquid Deburring (AU1)		Wright 1957	1957	20	30
Ultrasonic Slurry Finishing (AU2)		Blundell 1965	1965	10	15
Chemical Deburring (C1)		Anonymous 1958c	1958	20	40
EDM Deburring (EI)		Anonymous 1976b	1976	1	2
Electrochemical Deburring Processes (EC)					
	Electrochemical Deburring (Salt) (EC1)	Fishlock 1960	1960	600	1,200
	Electrochemical Rotary Electrode (EC1R)	Risko 1997	1997	1	2
	Electrochemical Deburring (glycol) (EC2)	Koroskenyi 1995	1995	50	90
	Electrochemical Mesh Deburring (EC5)	Fromson 1976	1976	0	0
	Electrochemical Moving Electrode Deburring (EC4)	Shimizu 1975	1975	0	0
	Electrochemical Brush Deburring (ECM3)	Wicht and Kurze 1973.	1973	0	0
	Electrochemical Orbital Abrading (ECM5)	Vishnitsky 1989	1989	1	1
	Electrochemical Nonwoven Abrasive Magnetic Finishing (ECM6)	Yuquan 1994	1994	0	6
	Electrochemical Ultrasonic Deburring	Blundell 1965	1965		
Electropolish (EL3)		Anonymous 1953	1945	50	100
Manual Deburring (MI)			3000 B.C.	300,000	800,000
Mechanized Cutting (M2)		Hubbard 1923; Anonymous 1880b	1880	10,000	20,000
Lapping (M11)		Indge 1991	1991		
Orbital vibration Lapping (M11o)		Anonymous 1977b	1977		
Ballizing (M11)		Gazan 1977	1977	4	10
Tearing (M12)		Stoeckhert 1998	1998	10	50
Edge Skiving (M2s)		Barnes 1996	1996	50	100
Edge Shavine (M2Sa)		Kelley 1983	1983		
Robotic Deburring (M2R)		Kaufman 1976	1975	300	500

Brushing (M3)		Scheider 1990	1943	50,000	100,000
Buffing (M3b)		Scheider 1990	1943	1,000	2,000
Wheel Blending (M4)		Lansing 1922	1922	300	600
Mechanized Sanding (M5)		Anonymous 1880a	1880	20,000	50,000
Vibratory Conveyor Deburring (M5a)		Armstrong 1974	1974	1	1
Abrasive Chemical (Mechanochemical Polishing) (MC1)		Lee, Du, Lee, Tsui, and Fan 2002	2002	5	20
Edge Rolling (M7)		Langton 1963	1963	400	600
Edge Curling		Wilson 1965	1965	50	200
Edge Folding (M7a)		Langton 1963	1963	50	200
Edge Peening (M13)		Anonymous 1977a	1977	1000	2000
Edge Burnishing (M8)		Gillespie 1999	1999	300	300
Trimming (press work) (M9)		Stabel 1915	1915	800	1,600
Edge Coining (M10)		Gillespie 1999	1999	100	150
Water Jet Deburring (M6)		Arnold, Evans, Johnson and Milhiser 1964	1964	500	800
Torch Cut /fire polish Deburring (T1)		LeMay 1952; Sonego 1983	1952	200	400
Plasma Deburring (T3)		Sonego 1983	1983	50	60
Plasma Glow Deburring (T5)		Gillespie 1999	1976	5	5
Thermal Energy Method (T2)		Anonymous 1970b	1970	500	700
Hot Wire Deburring (T4)		Kanda and Shimada 1995	1978	1	1
Hot Blade Deflashing (T4b)		Stoeckhart 1983	1983	100	200
Hot Tool Deflashing (MT4c)		Kanda and Shimada 1995	1995	1	1
Resistance Heat Deburring (T6)		Wakefield 1976	1976	1	1
Laser Deburring (T7)		LaRocca 1979	1979	1	5
Ion Beam Deburring (T8)		Richter 2002	2002	1	2
Chlorine Deburring (TC1)		Anonymous 1963b	1963	0	0

Table A3 U.S. Department of Labor Job Classifications (www.bls.gov/oes/current/oes_stru.htm#51-0000 July 2005)

Grouping	Job Code	Classification Title	No. in the Classification	Mean Hr Wage ($)	Mean Annual Wage ($)	Function
	51-9022	Grinding and Polishing Workers	44,890	$12.03	$25,010	Grind, sand, or polish, using hand tools or hand-h power tools, a variety of metal, wood, stone, clay, plastic, or glass objects. Include chippers, buffers and finishers.
	51-4033	Grinding, lapping, polishing etc.	101,530	$14.23	$29,600	Set up, operate, or tend grinding and related tools that remove excess material or burrs from surfac sharpen edges or corners, or buff, hone, or polish metal or plastic work pieces.
Sub Total Finishing			146,420			
	51-4032	Drill Operators	43,180	$14.72	$30,610	
	51-4034	Lathe Operators	71,410	$15.74	$32,750	
	51-4035	Mill Operators	29,140	$15.44	$32,120	
	51-4041	Machinists	368,380	$17.00	$35,350	
	51-4011	Computer-Controlled Machine Tool Operators	136,490	$15.41	$32,060	
	51-4061	Model Makers, Metal and Plastic	8,120	$22.26	$46,300	
	51-4081	Multiple Machine Tool Setters, Operators	98,120	$15.17	$31,550	
	51-4111	Tool and Die Makers	99,680	$21.61	$44,940	
	51-4194	Tool Grinders, Filers, Sharpeners	18,180	$15.64	$32,530	
	51-4199	Metal Workers and Plastic Workers All Other	49,650	$17.97	$37,380	
Sub Total Machining			879,170			
Total Machining + Finishing			1,025,590			
% Manual Finishers			4.38			best estimate for manual deburring < 2.2%
% Machine Finishers			9.90			best estimate for machine deburring < 4.9%
% All Finishers			14.28			best estimate for all deburring < 7.1%
Total Punching	51-4031	Cutting, Punching, and Press Machine Operators	265,480	$13.13	$27,310	
Total Machining and Punching			1,291,070			
% Manual Finishers			3.48			best estimate for manual deburring < 1.75%
% Machine Finishers			7.86			best estimate for machine deburring < 4%
% All Finishers			11.34			best estimate for all deburring < 5.5%