Title
A Review of Burr Formation in Machining

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Abstract One of the major concerns in deburring technology is centered on how to predict the size and shape of burrs to insure uniform removal and, if this is possible, how to design the process or product in advance to minimize or control the burr size. This paper reviews some of the research done over the past several years on this important topic. The paper includes a discussion of burrs in conventional machining, process planning for burr minimization as well as micromachining applications.

Keywords Burr · Machining · Size effects

1 Introduction

1.1 Motivation

There has been a steadily increasing emphasis on enhanced quality of machined workpieces while at the same time reducing the cost per piece. Accompanying this is the decreasing size and increasing complexity of workpieces. This has put continual pressure on improvements in the machining process in terms of new processes, new tooling and tool materials, and new machine tools. Fundamental to this continual improvement is understanding edge finishing of machined components, especially burrs. Deburring, like inspection, is a non-productive operation and, as such, should be eliminated or minimized to the greatest extent possible.

An understanding of the fundamentals of burr formation leads us to procedures for preventing or, at least, minimizing, burr formation. This depends on analytical models of burr formation, studies of tool/workpiece interaction for understanding the creation of burrs and, specially, the material influence, data bases describing cutting conditions for optimal edge quality, and design rules for burr prevention as well as standard terminology for describing edge features and burrs. Ultimately, engineering software tools must be available so that design and manufacturing engineers can use this knowledge interactively in their tasks to yield a mechanical part whose design and production is optimized for burr prevention along with the other critical specifications. A review of the background to burr control is given first.

1.2 Introduction and Background

Burrs in machined workpieces are complex and troublesome problems. They require additional finishing operations (deburring) and complicate assembly as well as risk damage to the part. Handling parts with burrs is a challenge for workers. In a perfect world we'd like to avoid, or at least minimize, burrs by careful choice of tools, machining parameters and tool path or work material and part design. The fact is that most burrs can be prevented or minimized with process control. Research and interest has been focused on problems associated with generation of burrs from machining for sometime but the focus has traditionally been on deburring processes. Understanding the burr formation process is critical to burr prevention. The level of scientific knowledge on burr formation is just in the early stages of development, see Fig. 1. The critical information, associating details of the part performance and functionality with requirements for edge condition, is still not well understood. Standards and specifications are only now being developed for this led by the German automotive and mechanical parts industries, see Berger, [1].

To effectively address burr prevention, the entire "process chain" from design to manufacturing must be considered, Fig. 2. Here we see the importance of integrating all the elements affecting burrs, from the part design, including material selection, to the machining process.

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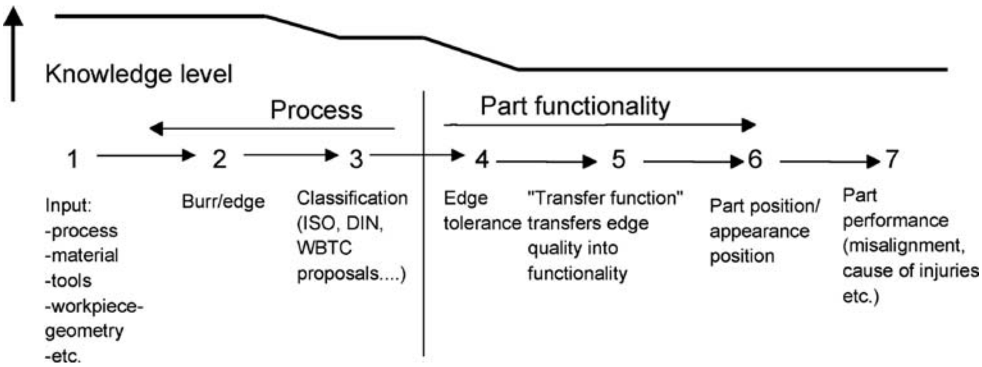


Fig. 1 State of knowledge in burr formation

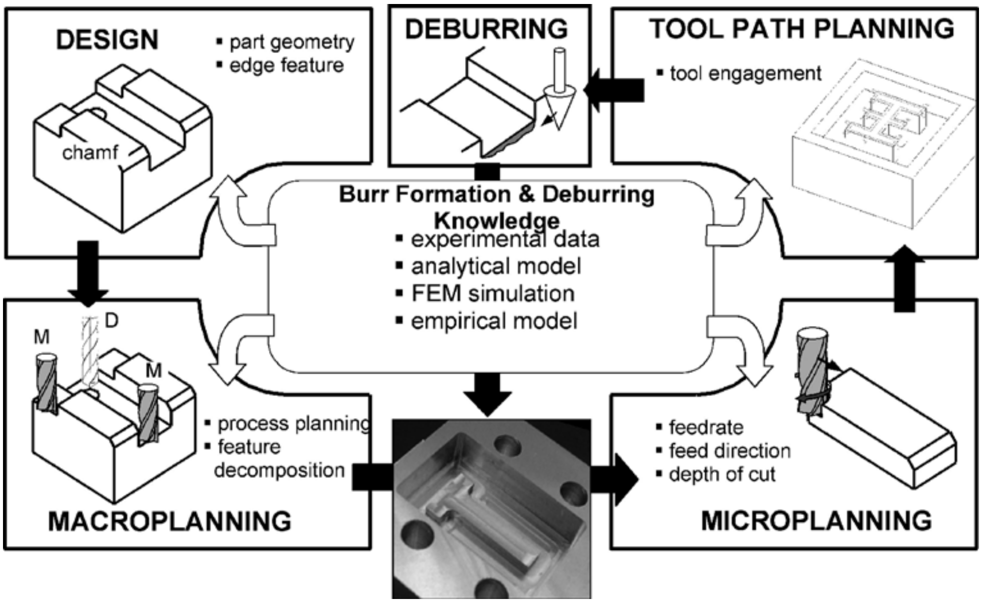
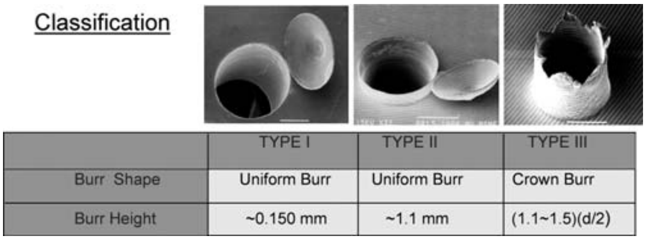


Fig. 2 Five level integration required for burr minimization, Dornfeld and Lee [2]

Burr formation affects workpiece accuracy and quality in several ways; dimensional distortion on part edge, challenges to assembly and handling caused by burrs in sensitive locations on the workpiece and damage done to the work subsurface from the deformation associated with burr formation. A typical burr formed on a metal component due to the exit of a cutting edge can range in shape and size from small and uniform (as in a "knife burr") to rather large, nonuniform in shape and many millimeters in length. A number of things are clear from close inspection of burr images. There is substantial subsurface damage and deformation associated with a burr, the shape is quite complex and, hence, the description of a burr can be quite complex, and the presence of a burr can cause problems in manufacturing. More recently the problem of burrs and other machining and manufacturing related debris causing problems in the smooth functioning of precision mechanical devices has been addressed by a number of researchers. This just adds additional importance to the understanding of burr formations.

In fact, the range of burrs found in machining practice is quite wide, specially when the full range of processes from drilling to grinding is considered. To emphasize the point, Fig. 3 shows typical drilling burrs and their classification in stainless steel as an indication of the potential variation. Burrs in milling and turning exhibit wide variation as well.

The costs associated with removing these burrs is substantial. The typical cost as a percentage of manufacturing cost varies up to 30% for high precision components such as aircraft engines, etc. In automotive components, the total amount of deburring cost for a part of medium complexity is in the range of 15–20% of manufacturing expenses. Industrial practice has shown that the actual investment in deburring systems increases with part complexity and precision.



	TYPE I	TYPE II	TYPE III
Burr Shape	Uniform Burr	Uniform Burr	Crown Burr
Burr Height	~0.150 mm	~1.1 mm	(1.1~1.5)(d/2)

Fig. 3 Three typical burrs in drilling stainless steel, Dornfeld and Lee [2]

A better strategy is to attempt to prevent of minimize, or prevent, burrs from occurring in the first place. This has two immediate benefits in that, first, it eliminates the additional cost of deburring the component and the likelihood of damage during the deburring process and, second, in the case burrs cannot be eliminated it improves the effectiveness of any deburring strategy due to reduced and more standard burr size and shape. This requires a comprehensive approach to burr prevention and minimization consisting of a number of components.

To minimize or prevent burr formation requires that all stages of manufacturing from the design of the component through process planning and production be integrated so that the potential part features and material constraints, tooling and process sequences and process variables be considered from a perspective of the potential for creation of burrs on the workpiece, as seen in Fig. 2. That is, the inputs (process, material, tools, workpiece geometry, fixturing, etc.) must be considered along with the part functionality (part performance, fit and assembly requirements) as well as any expected or required deburring processes. This is most successful when clear standards and classifications are available, edge tolerances can be specified and the relationship between the edge quality and part functionality is clearly understood as shown in Fig. 1. This is not generally the case.

The successful implementation of integrated burr control methodologies is necessary to overcome the limitations of burr issues in machining. The future development of comprehensive integrated strategies for burr minimization and prevention will depend on:

- the continued development of predictive models with competent databases, including "expert data bases" for process specification
- simulation models of burr formation capable of indicating the interaction and dependencies of key process parameters for burrs at all scales
- strategies for burr reduction linked to computer aided design (CAD) systems for product design and process planning (and close coordination with CAD/CAM resource suppliers)
- inspection strategies for burr detection and characterization including specialized burr sensors
- development of specifications and standards for burr description and measurement

Specialized tooling for deburring is not discussed in this paper although that is an important area and is covered to some extent by commercial organizations today.

2 Process-Based Solutions

2.1 Introduction

The models, databases and strategies mentioned above must be linked to the process of interest to be most effective. There are substantial differences between burr formation in drilling, milling and grinding, for example. In drilling, feed rate usually plays an important role in the development of drilling burrs. In addition, the drill geometry can affect the size and shape of the burr formed as well as prevent burr formation in some cases. Analytical models are increasingly supplemented with finite element method (FEM) models of the drilling process to predict effects of drill geometry, process parameters and workpiece characteristics on size and shape of the burr. Applications to aerospace component manufacturing, specially multi-layer structures and composite materials, is a primary area of focus for FEM drilling process modeling. In addition, the problem of burr formation in intersecting holes in precision components is well suited to analytical approaches for parameter selection and tool design. These approaches are also applicable to milling but less so due to the complexity of the milling process. Grinding geometry is typically more straight forward but the multiple abrasive "tools" with complex shapes complicates the analysis.

2.2 Milling

Since milling (specially face milling) figures so prominently in the manufacture of so many parts, for example, automotive engines and transmission components, it has been a major focus for burr reduction and prevention for many years. In milling, the kinematics of tool exits from the workpiece are a dominant factor in burr formation and, as a result, substantial success has been realized by adjusting the tool path over the workpiece, Fig. 4. The principal criteria in tool path determination have been:

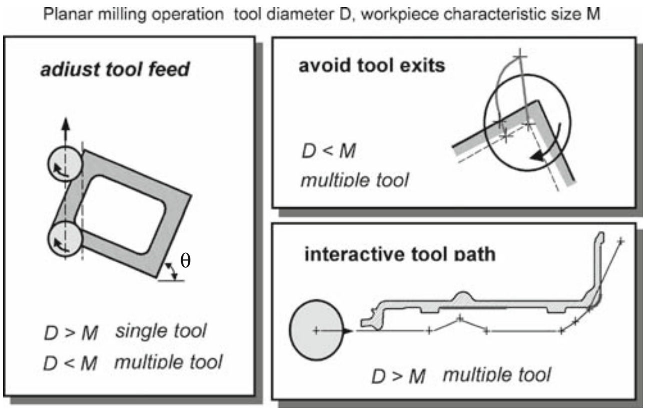


Fig. 4 Tool path strategies for minimizing and preventing burrs in face milling

- avoiding exits of inserts (or always machining on to the part edge)
- sequencing of process steps to create any burrs on a last, less significant edge
- control of exit order sequence (EOS) by tool geometry and path variation
- maintaining uniform tool chip loads over critical features
- lift and re-contact of milling cutter for some features where maneuverability is limited
- avoiding "push exits" (those with long cutter path/edge contact length)

While these criteria are often difficult to apply in all situations they have shown dramatic reductions in burr formation with the corresponding increases in tool life (tools are often changed when burr size reaches a specification limit) and reductions in deburring costs. In all circumstances cycle time constraints must be met with any redesigned tool paths as do surface finish and form criteria.

With burr expert data bases for different materials and process parameters and the software for tool path planning, the possibility of designers being able to simulate the likely scenario of machining a component and any resulting problems with burrs as part of a conventional CAM software program is becoming a reality. These software systems must also be comprehensive enough to include other process steps and constraints so that other critical specifications are not compromised.

2.3 Drilling

Burr formation in drilling is primarily dependent upon the tool geometry and tool/work orientation (that is, whether the hole axis is orthogonal or not to the plane of the exit surface of the hole). The burr types illustrated in Fig. 3 are created by a sequence of events starting when the drill action first deforms the material on the exit surface of the workpiece through creation of the hole, Fig. 5. When intersecting holes are drilled, the specific orientation of the axis of the intersecting holes will have a tremendous effect on the location and creation of burrs around the perimeter of the holes. Figure 6 shows a schematic of burr formation in intersecting holes. Since the "exit angle" of the drill varies around the circumference of the hole intersection, the potential for burr formation will vary. This means that intersection geometry as well as tool geometries optimized to minimize adverse burr formation conditions can be effective in minimizing burr formation. Burr formation in intersecting holes shows high dependence on angular position under the same cutting conditions. Large exit angles, as seen in Fig. 6, yield small burrs. There is also a strong dependence on inclination angle (that is the degree of inclination of the intersecting hole from perpendicular.) Research shows that an inclination angle of 45° reduces burr formation. Further, research on drilling and intersecting hole challenges, Min [3], shows that the kinematics of edge exit sequence relative to the instantaneous geometry relationship between drill cutting edge and hole edge geometry can

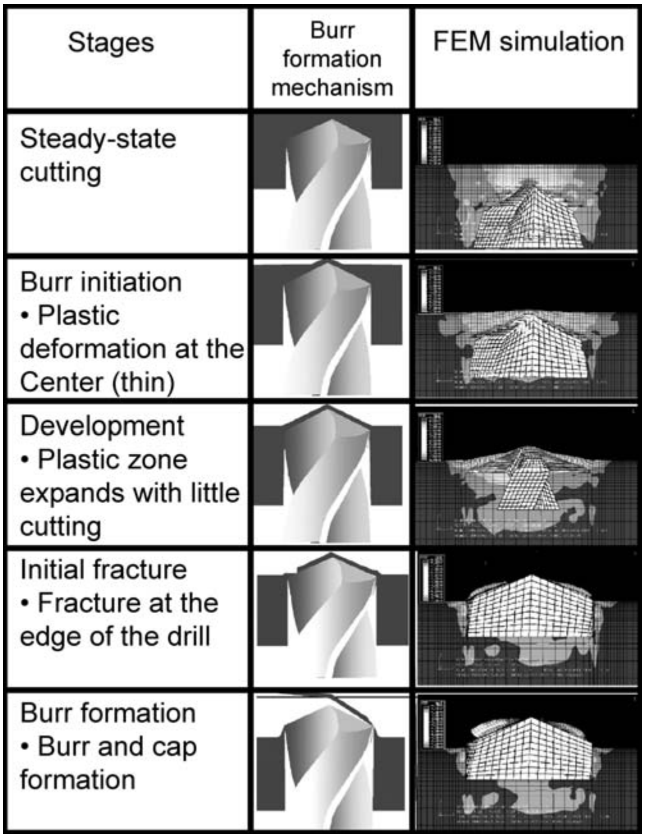


Fig. 5 Sequence of burr formation in hole drilling for uniform burr with cap

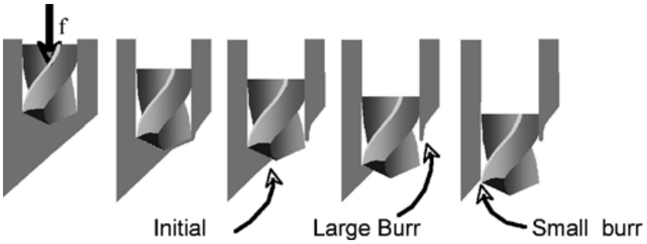


Fig. 6 Schematic of burr formation in intersecting holes

predict the burr formation potential (basically when the vector sum of tool rotation and feed are in a "forward" direction relative to the feed motion). Hence, drill designs that minimize this forward vector for as much of the hole circumference as possible could be effective in burr minimization.

Further, holes in multilayer materials offer additional challenges. This is specially true in aerospace applications where structures are often composed of "sandwich" configurations of metal, composite and sealant as found in advanced aerospace structures. Burr formation here is challenging as interlayer burrs often need to be removed before final assembly. Finite element analysis of these types of specific situations often offers increased understanding of the problems. When drilling multilayer material structures, the fixturing often plays an important role in determining the size and location of burrs. The gap that occurs between sheets during drilling provides space for burr formation at the interface of the two material sheets, see, for example, Newton et al. [4] and Choi et al. [5].

2.4 Grinding

Research on burr formation in grinding is less well developed in terms of literature. Grinding burrs are complicated by the specialized removal mechanisms seen in grinding. Figure 7 shows the basic configuration of burrs in surface grinding, from [6], and a closeup of a an exit burr in grinding, sometimes referred to as a "Karpu" burr after the distinctive moustache of Professor B. Karpuschewski in Germany.

Aurich et al. [6] summarized the results of early grinding burr research as follows:

- superabrasive grinding leads to a significantly higher degree of burr formation
- burr length and burr height are more influenced by the workpiece material than by the cutting parameters (for superabrasive grinding)
- hybrid wheels (that is, combination of superabrasive and conventional features) seems to produce similar or slightly less burr as the conventional grinding wheel; the abrasive has the dominant influence on burr formation

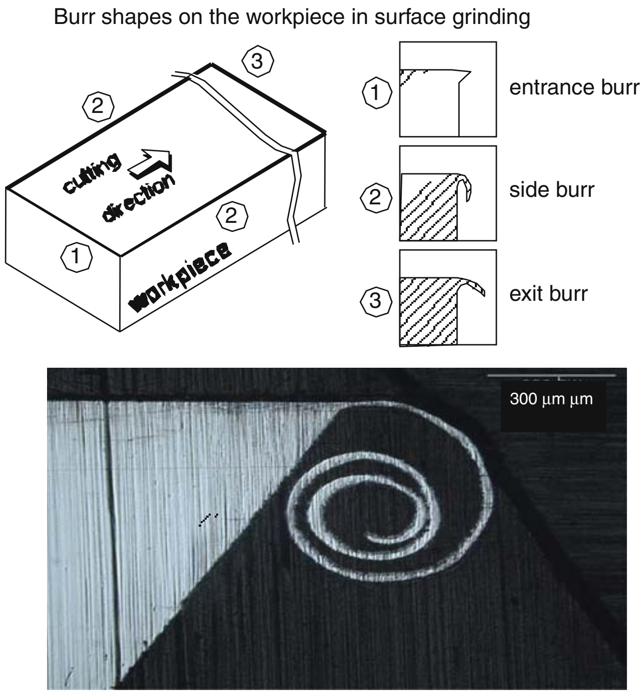


Fig. 7 Typical burr shapes in surface grinding and closeup of "Karpu" burr, [6]

3 Examples of Application of Burr Minimization Strategies

3.1 Tool Path Planning in Milling

One of the most successful areas of application of burr minimization strategies is in tool path planning for face milling. To a great extent, burr formation in milling can be prevented by adjusting the path of the milling cutter over the workpiece face. Specific cases have been evaluated in automotive engine manufacturing with major automobile companies. This can be extended to optimization of the process to insure that surface quality, including flatness, specifications are met or exceeded. Usually, burr size is used to indicate state of tool wear and when burr size increases beyond a predefined level the tool/insert is changed. Reduction in burr size (or increased number of parts produced before the burr size exceeds limits) directly relates to increased tool life and the accompanying reduction in tooling costs and tool change costs.

Figure 8 shows a conventional tool path for face milling a surface on a cast AlSi alloy automotive engine block. The presence of substantial burrs at critical locations required frequent tool changes as well as additional deburring operations. The optimized tool path using the criteria described above is shown in Fig. 9 and, in Fig. 10, shows the resulting burr free workpiece. Although the tool path is substantially longer in this example, it was possible to increase the feedrate without loss of surface finish to maintain the required 5 s cycle time for the process. The tool life (as a result of dramatically reduced burr formation) was increased by a factor of 3 with substantial resulting savings per machine/year.

Other examples of these kinds of tool path planning improvements are available, [7–11]. All rely on a geometric definition of part geometry, quantitative description of tool path, or tool exit/edge geometry or sequential geometrical relationship between tool cutting edges and part geometry on tool exit from the work linked to data on burr formation potential as a function of material properties (ductility and composition, for example).

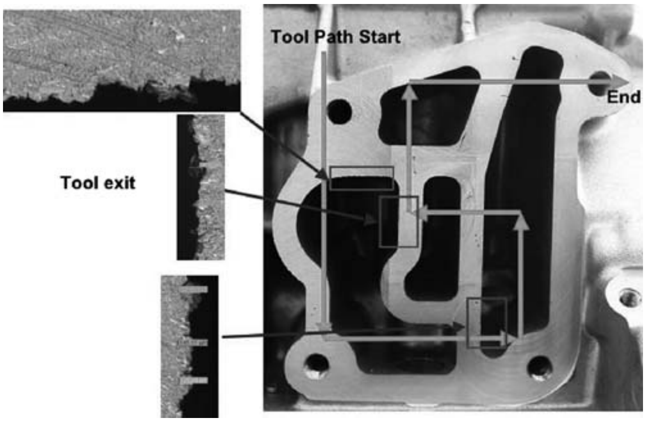


Fig. 8 Conventional tool path for face milling engine block face and resulting burrs at key locations

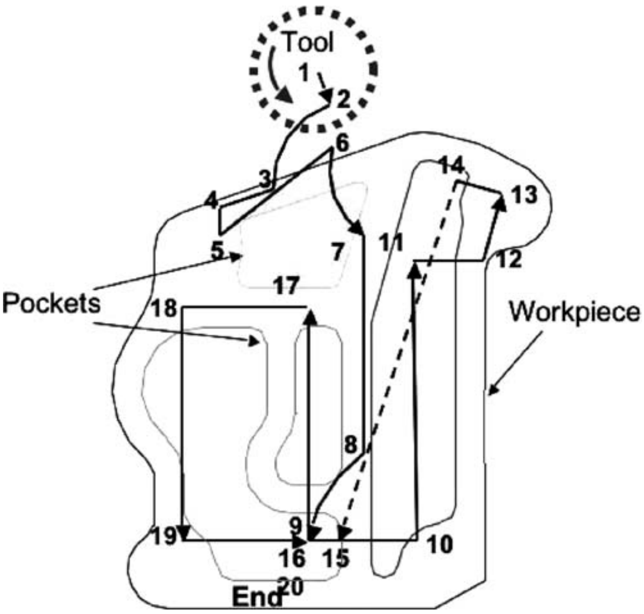


Fig. 9 Modified tool path for part in Fig. 8

Fig. 10 Workpiece resulting from optimized tool path; Tool path length: old path – 209 mm, new path – 524 mm, cycle time (with increased feedrate) remains at 5 s

3.2 *Drilling – Burr Control Chart*

Burr minimization and prevention in drilling is strongly related to process conditions (feedrate and speed, for example) and drill geometry. It is possible to represent the reasonable ranges of operating conditions for drilling by use of a "burr control chart" derived from experimental data on burr formation for varying speeds and feeds. This can be normalized to cover a range of drill diameters and, importantly, can be used across similar materials (carbon steels, for example). Data shows the likelihood of creating one of three standard burrs, as shown in Fig. 3, namely, small uniform (Type I), large uniform (Type II) and crown burr (Type III). Figure 11 below shows a typical burr control chart for 304L stainless steel. Continuous lines delineate different burr types. Type I is preferred. Burr height scales with distance from the origin. This burr control chart can be integrated with an expert system allowing queries of likelihood of burr formation to be shown on the control chart when information on drill diameter, speed, feed, etc. are input. Typical burr sizes expected are shown.

An interesting example applying this burr control approach was described by Min and Dornfeld [12] for an

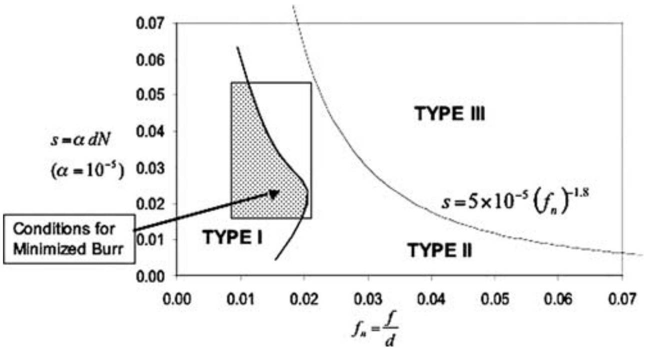
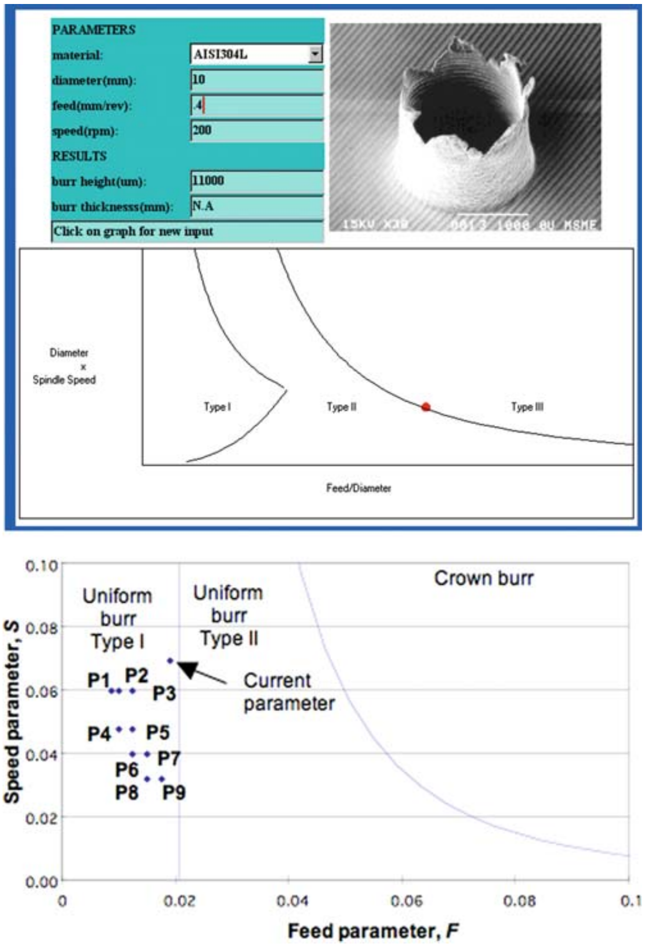


Fig. 11 Drilling burr control chart for 304L stainless steel material showing normalized speed, s (vertical axis) vs. normalized feed, f (horizontal axis), d is drill diameter. Minimized burr conditions are indicated in crosshatched region



PARAMETERS
material: AISI304L
diameter(mm): 10
feed(mm/rev): .4
speed(rpm): 200
RESULTS
burr height(um): 11000
burr thicknesss(mm): N.A
Click on graph for new input

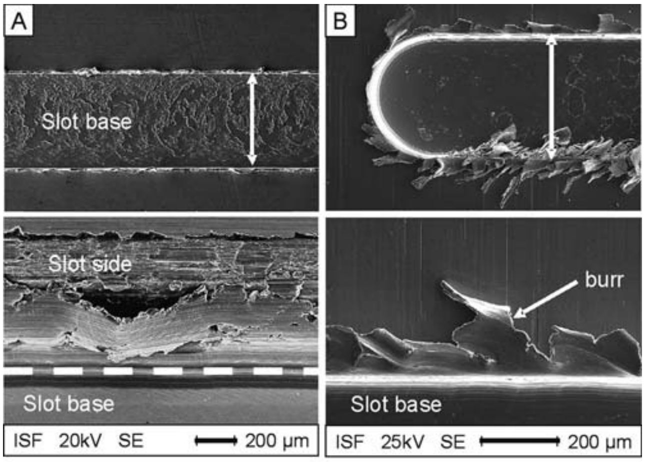
Fig. 12 Application of burr control chart in automotive application, [12]; *top* – DBES output for original machining conditions; *bottom* – suggested conditions with parameters adjusted for cycle time constraints

automotive application. Using the Drilling Burr Expert System© (DBES) [3], cutting conditions were tested in order to obtain small burrs in a situation previously creating unacceptably large burrs leading to shorter tool life. By moving the process operation location on the Drilling Burr Control Chart (DBCC) (that is, in the "speed vs feed" domain), the DBES suggested new process parameters and burr size prediction, Fig. 12, top. In order to minimize burr formation, new cutting conditions that meet cycle time constraint were chosen and its location on the DBCC is shown in Fig. 12, bottom.

The DBES did not have data for the workpiece material for the part (AISI 5046). But from the perspective of burr formation, the behavior of AISI 5046 is similar to low alloy steel, AISI 4118, which is available in the DBES. In general, alloy steels behave in a similar fashion in terms of burr formation. Hence, burr sizes were estimated from the DBCC for AISI 4118 and then, scaled linearly using a scale factor for AISI 5046. The scale factor, S_f, was obtained using measurements of the burrs on holes machined with new drills using current cutting conditions as the ratio of estimated burr sizes for 4118 to measured burrs size for 5046.

3.3 *Burrs in Precision Machining*

As described above, various problems such as surface defects, poor edge finish, and burrs in conventional machining have plagued conventional manufacturing for some time. These problems are also significant in micromachining and require much more attention because, in many cases, inherent material characteristics or limitations in part geometry do not allow some of the solutions used in macromachining. Figure 13 shows some typical defects in micromilling including burrs on the edges of the slots.



Adhesion

Burr formation

Fig. 13 Typical surface defects in micromilling (work material: NiTi shape memory alloy), from Weinert et al. [13]

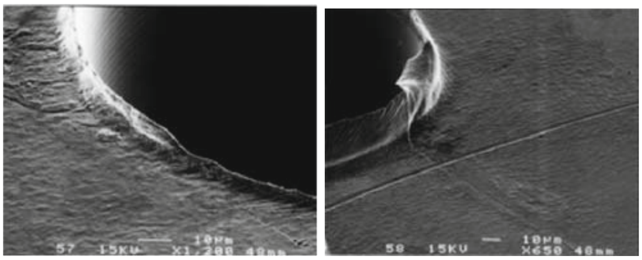
NiTi work material is used for many medical applications, such as surgical implants, and micromilling is commonly used to fabricate these products. This material is very ductile and easily work hardens during machining causing adhesion and high burr formation. Additionally, high ductility causes adverse chip formation, long and continuously snarled chips. At the micro level, these chips interfere with tool engagement and burrs and contribute to poor surface quality of finished parts.

As part of a study on the burr formation in micromachining Lee and Dornfeld [14] conducted micro-slot milling experiments on aluminum and copper and found various standard burr types depending on location and work geometry. Interestingly, these burr shapes were similar to those found in macromachining in terms of formation mechanisms and influence of cutting parameters. One major difference found was that the influence of tool run-out on burr formation was significant in micro-slot milling.

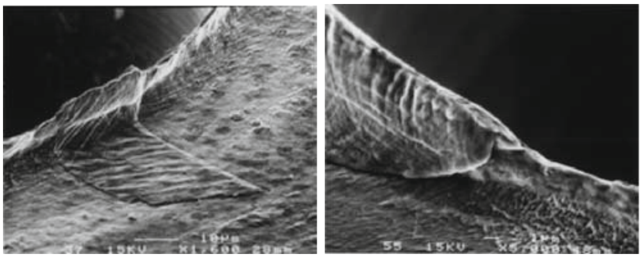
Min et al. [15] conducted micro-fly cutting and micro-drilling experiments on single crystal and polycrystalline OFHC copper in order to understand the effects of crystal orientation, cutting speed, and grain boundaries on surface roughness, chip formation, and burr formation. Certain crystallographic orientations were found to yield rougher surface finish, as well as significant burrs and breakout at the tool exit edge. The <100> and <110> direction of machining on the workpieces exhibited the greatest amount of variation in formation of burrs and breakout at the exit edge and in chip topology as a function of the angular orientation of the workpiece. This corresponded to a variation in the interaction between the tool and the active slip systems. They also conducted slot milling experiments on the same material and found a strong dependency of top burr formation on slip systems of each crystal orientation except (100) workpiece.

Bissacco et al. [16] found that top burrs are relatively large in micromilling due to the size effect. When the ratio of the depth of cut to the cutting edge radius is small, high biaxial compressive stress pushes material toward the free surface and generates large top burrs. Ahn and Lim [17], Ahn et al. [8] proposed a burr formation model in a microgrooving operation based on a side shear plane and an extended deformation area which is caused by the tool edge radius effect. The material near the cutting edge experiences the side shear deformation due to hydrostatic pressure. Aluminum and OFHC generated larger burrs than brass, and thus it was concluded that the thickness of the burr is proportional to the ductility of the material.

Further work by Schaller et al. [19] showed that when fabricating microgrooves in brass, burr formation can be drastically reduced by coating the surface with cyanacrylate. Sugawara and Inagaki [20] investigated the effect of drill diameter and crystal structure on burr formation in microdrilling. They utilized both single crystal and polycrystalline iron with a thickness between 0.06 and 2.5 mm and high speed twist drills with diameters from 0.06 to 2.5 mm. In general they confirmed that burr size is reduced and cutting ability increased as drill size decreases.



(a) 10 mm/min, 7000 rpm (b) 5 mm/min, 6000 rpm



(c) 5 mm/min, 7000 rpm (d) 10 mm/min, 8000 rpm

Fig. 14 Microdrilling burr formation (250 μm diameter); (**a**) burr within grain boundary, (**b**) burr across grain boundary, (**c**) burr over small grain, **(d)** grain boundary follows burr topology, from Min et al. [15]

Min et al. [15] found that grain orientation affected burr formation in drilling of polycrystalline copper, Fig. 14. A single material may produce a ductile-like cutting mode in one grain and brittle-like cutting in another, indicating that favorable and non-favorable cutting orientations for good surface and edge condition exist as a function of crystallographic orientation.

Additional micro-drilling research indicated that the effects seen at a larger, macro, scale (transition from uniform to crown burr with feed increase and basic similarity in burr shapes) also holds for microdrilling [21]. This means the drilling burr control chart concept could be applied at this scale also.

4 Summary and Conclusions

Although edge finishing in machined components is a constant challenge in precision manufacturing of mechanical components, there are a number of strategies, built on competent process models and extensive data bases, that can substantially minimize or eliminate burrs. These strategies, some illustrated above, can be incorporated in the software relied upon by design and manufacturing engineers in their normal activities to insure that the conditions which can lead to burr formation can be avoided while insuring that production efficiency is maintained. This is part of the development of the "digital factory." Recent experience indicates that the basis for this process optimization may also yield increases in throughput due to decreases in cycle time thanks to optimum part orientation on the machine during machining. In situations where burrs cannot definitely be eliminated there is the possibility, using these tools, to at least control their size over a range of conditions so that commercial deburring techniques are more reliably implemented – techniques such as abrasive filament brushes, for example. Finally, the inclusion of design rules for burr minimization will allow the design engineers to reduce the likelihood of edge defects at the most effective stage – during product design. Future work on burr prevention must focus more on tool design. The potential for substantial improvement, especially in drilling, will depend on analysis of drilling burr formation with the objective of optimization of tool drill design.

It may be some time before it is possible to prevent all burr formation during the machining of mechanical components. But, in the meantime, there is much that can be accomplished towards that goal using the techniques and systems discussed in this paper to produce parts with higher edge precision.

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