Strategies for Preventing and Minimizing Burr formation

David Dornfeld
University of California at Berkeley
Berkeley, California USA

1 – Executive Summary

The past years have seen emphasis on increasing the 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. This often falls under the terminology of High Performance Cutting (HPC) — the theme of this conference. A recent CIRP keynote /1/ outlined and explained some of these drivers for enhancement in machining technology. Fundamental to this continual improvement is understanding edge finishing of machined components, specially 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. This paper reviews recent work done in all these areas with an emphasis on research at the University of California at Berkeley.

2 – Introduction and Background

Burrs in machined workpieces are real “productivity killers.” Not only do they require additional finishing operations (deburring) and complicate assembly, but these operations can damage the part. Handling parts with burrs is a challenge for workers. Ideally, 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. In fact, most burrs can be prevented or minimized with process control. Recently, more research and interest has been focused on problems associated with burrs from machining. The focus has traditionally been on deburring processes but understanding the burr formation process is critical to burr prevention. However, the level of scientific knowledge in this is just developing, (see figure 1). It is vital to be able to associate details of the part performance and functionality with requirements for edge condition. Standards and specifications are only now being developed for this /2/.

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

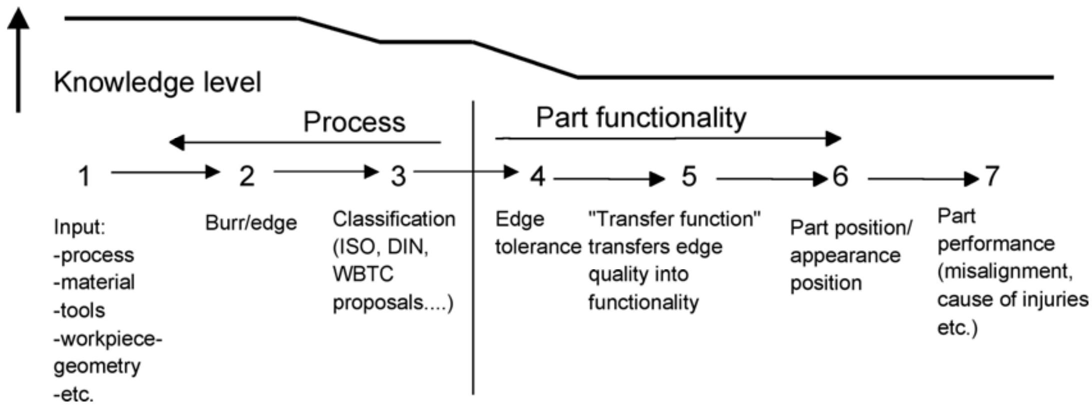


Figure 1 State of knowledge in burr formation

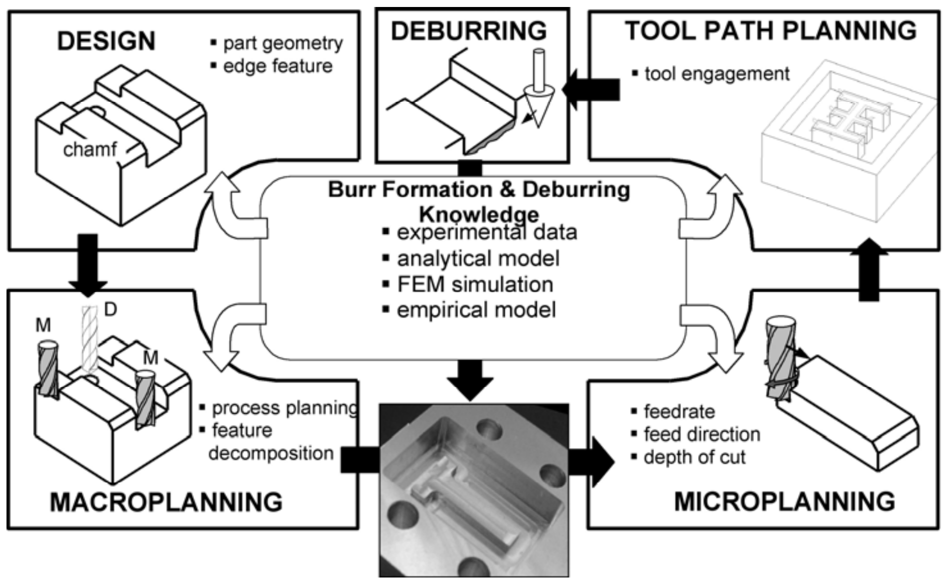
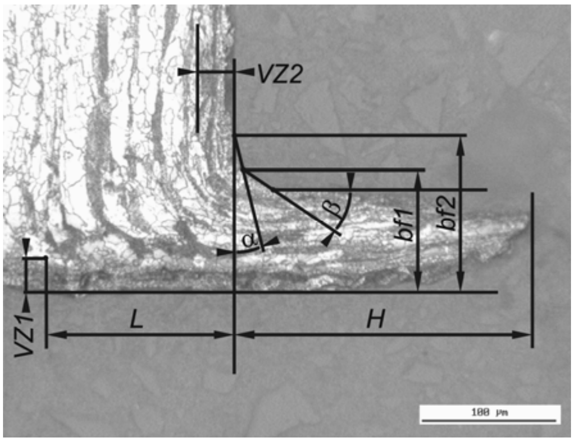


Figure 2 Five level integration required for burr minimization

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 is seen in Figure 3, after /3/. A number of things are clear from this image– 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.

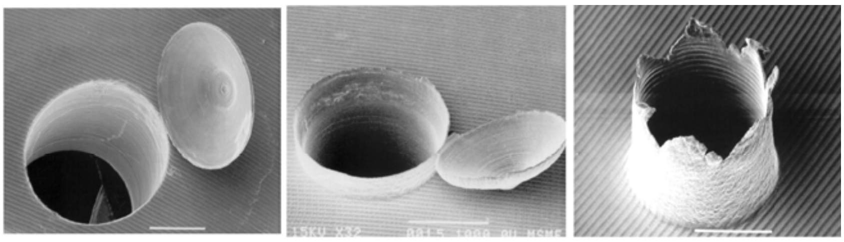


α,β tilting angle
VZ1 deformation zone lateral bore
VZ2 deformation zone main bore
b_{f1},b_{f2} dimensions of burr root

Figure 3 Typical burr and proposed measuring nomenclature, from /3/

In fact, this burr shown in cross-section in Figure 3 gives the appearance of a rather simple phenomena. 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, Figure 4 shows typical drilling burrs and their classification in stainless steel as an indication of the potential variation /4/. Burrs in milling and turning exhibit wide variation as well.

Classification



	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)

Figure 4 Three typical burrs in drilling stainless steel, from /4/

The costs associated with removing these burrs is substantial. The typical costs 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 approximately 14% of manufacturing expenses /5/. The actual investment in deburring systems increases with part complexity and precision as seen in Figure 5 from /5/.

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.

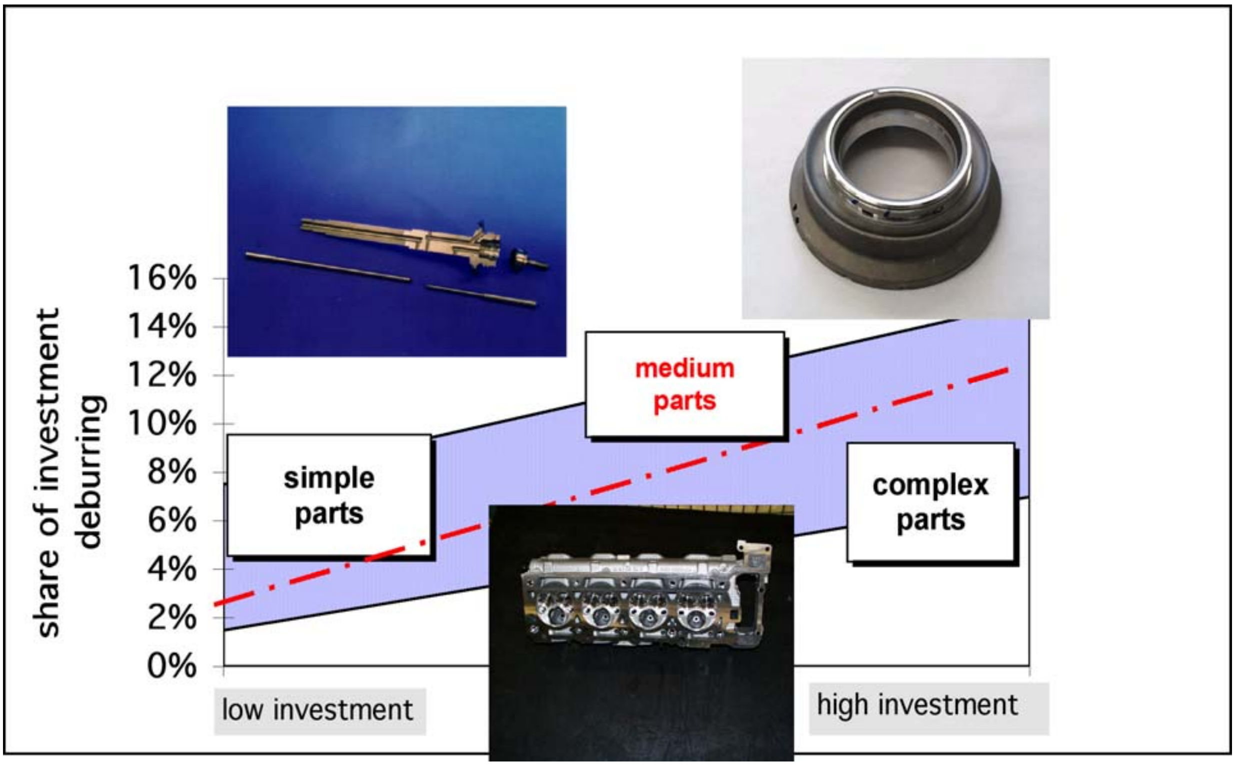


Figure 5 Investment in deburring systems as a function of part complexity and total investment in manufacturing system /5/

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 Figure 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. This is not generally the case.

The future development in this regard is seen to depend on the following:

- the 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 (finite element models, for example)

- strategies for burr reduction linked to computer aided design (CAD) systems for product design and process planning

- inspection strategies for burr detection and characterization including specialized burr sensors.

One could also add here the development of specialized tooling for deburring and inspection to insure burrs are removed, although that is an area well covered commercially today.

3 – Process-based solutions

The models, databases and strategies mentioned in the previous section must be linked to the process of interest to be most effective. There are substantial differences between burr formation in drilling and milling for example. In drilling, infeed can play an important role in the development of drilling burrs /6,7/. In addition, the drill geometry can affect the size and shape of the burr formed as well as prevent burr formation in some cases /8, 9/. 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 /10, 11/. Applications to aerospace component manufacturing, specially multi-layer structures, is a primary area of focus for FEM drilling process modeling. This is also applicable to milling but less so to date due to the complexity of the milling process.

- 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. The principal criteria in tool path determination have been /12/:

- 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

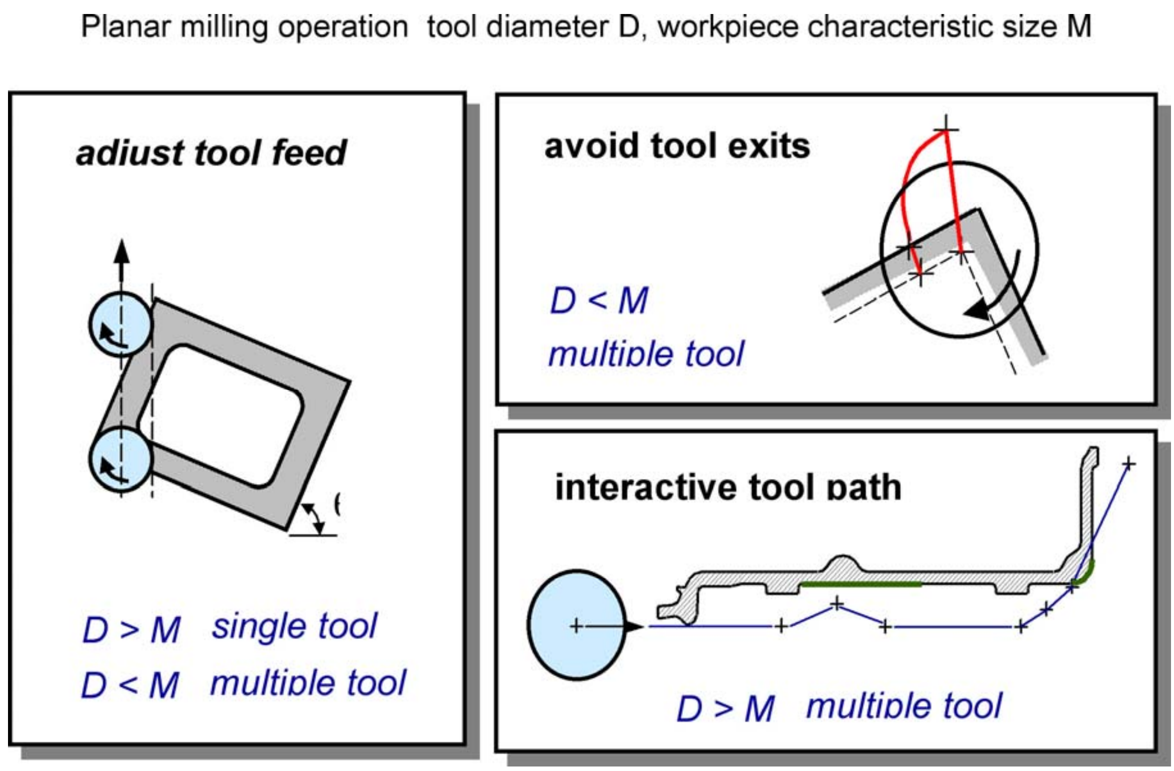


Figure 6 Tool path strategies for minimizing and preventing burrs in face milling, /11/

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.

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 is becoming a reality, These software systems must also be comprehensive enough to include other process steps and constraints so that other critical specifications (surface roughness, for example) are not compromised.

- **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 Figure 4 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, Figure 7, /8, 9/. 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 8 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 minimizng burr formation. Burr formation in intersecting holes shows high dependence on angular position under the same cutting conditions. Large exit angles, as seen in Figure 8, 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.

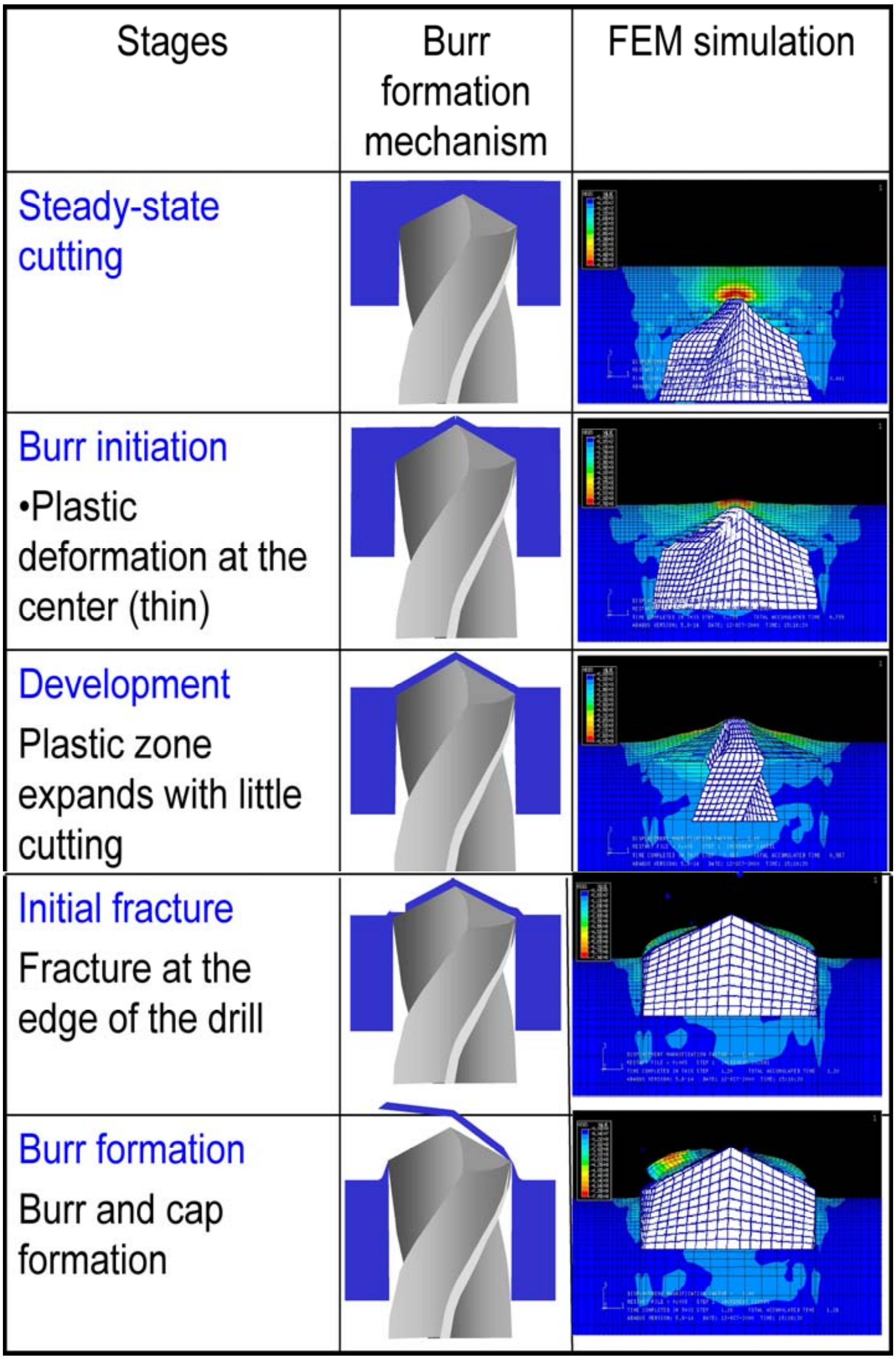


Figure 7 Sequence of burr formation in hole drilling for uniform burr with cap

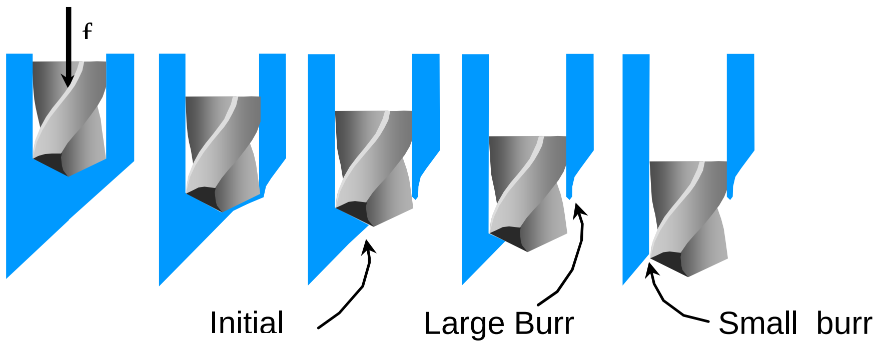


Figure 8 Schematic of burr formation in intersecting holes

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, Figure 9. 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. Figure 10 illustrates the “gap formation” occurring during drilling of sandwich materials in the absence of proper fixturing. The gap provides space for burr formation at the interface of the two material sheets /13/.

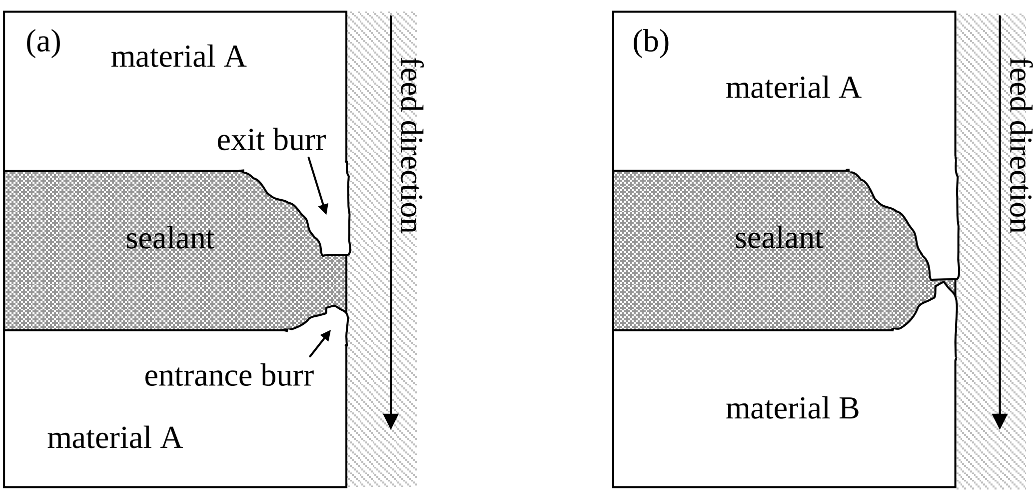


Figure 9 Examples of interlayer burrs in sandwich materials (multi-layer)

Gap formation at interface due to drilling forces

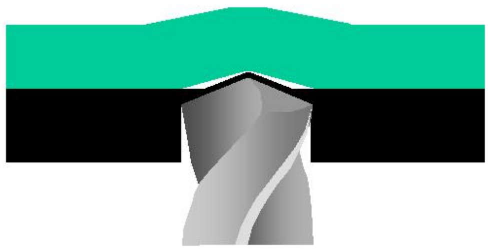


Figure 10 Schematic of interlayer burr formation due to gap during drilling

4 – Examples of application of burr minimization strategies

- 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. Figure 10 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 Figure 11 and, in Figure 12, 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 second cycle time for the process. The tool life (as a result of dramatically reduced burr formation) was increased by a factor of 3 and the resulting savings per machine/year were estimated at approximately $50,000 /12, 14/.

- 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

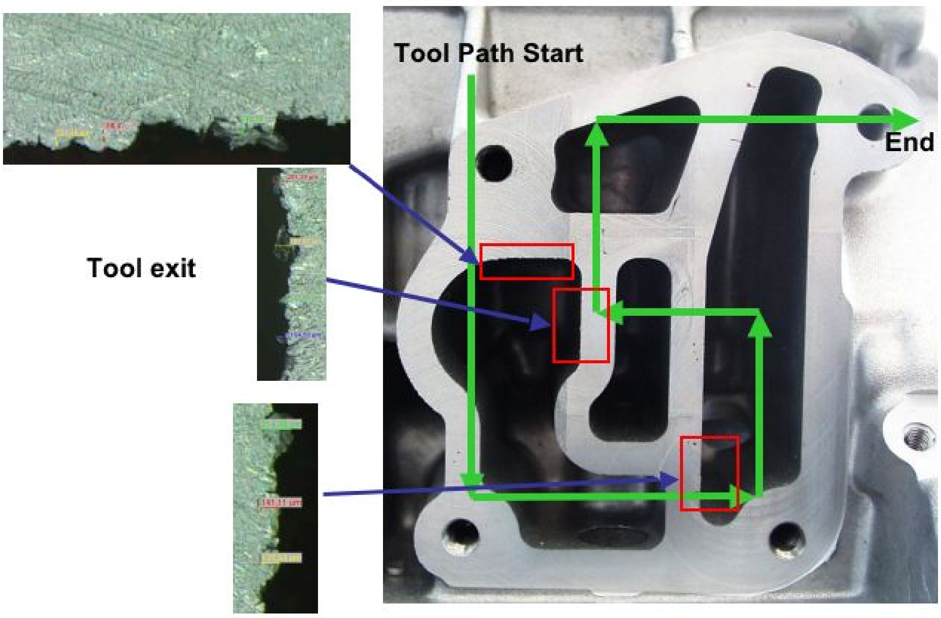


Figure 10 Conventional tool path for face milling engine block face and resulting burrs at key locations

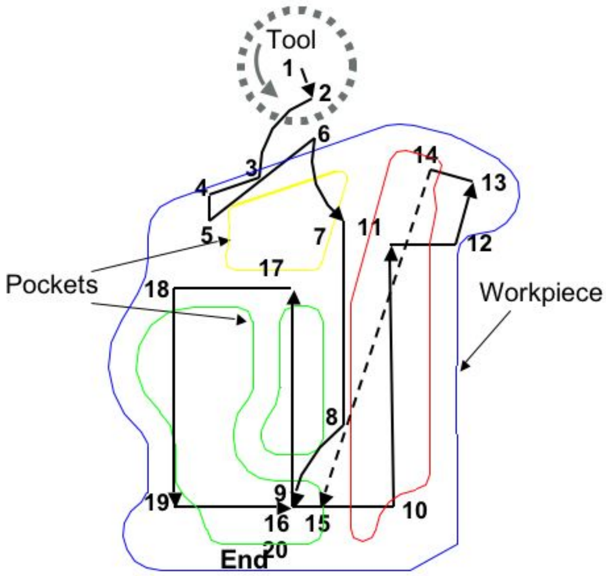
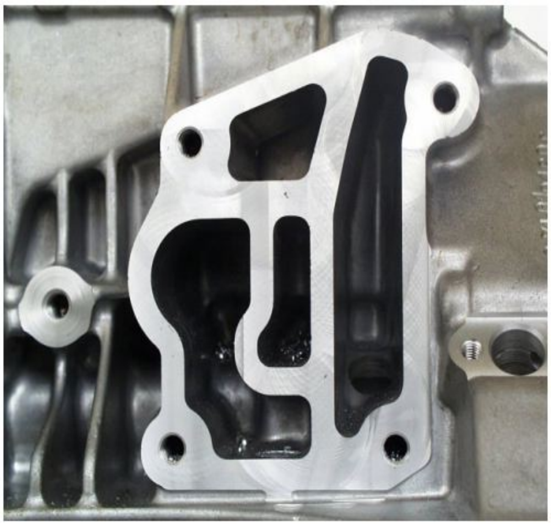


Figure 11 Modified tool path for part in Figure 10



Tool Path Length:

Old path – 209 mm
New path – 524 mm

Cycle time (with increased feedrate) stays at 5 seconds

Figure 11 Workpiece resulting from optimized tool path and tool path specifics example). Data shows the likelihood of creating one of three standard burrs, as shown in Figure 4, namely, small uniform (Type I), large uniform (Type II) and crown burr (Type III) /15, 16/. Figure 12 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.

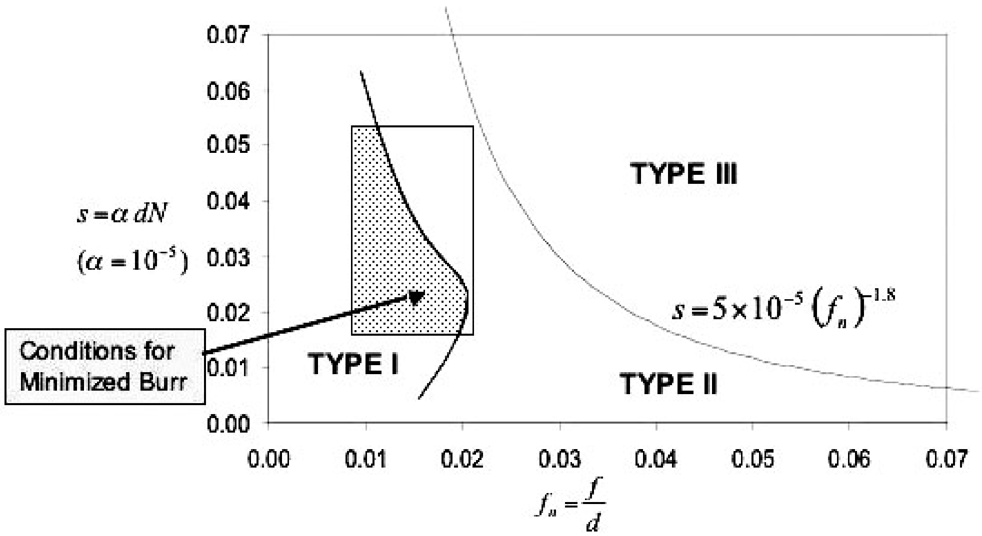


Figure 12 Drilling burr control charf for 304L stainless steel material showing normalized speed,s (vertical axis) vs. normalized feed, f (horizontal axis), d is drill diameter. Minimized burr conditions indicated.

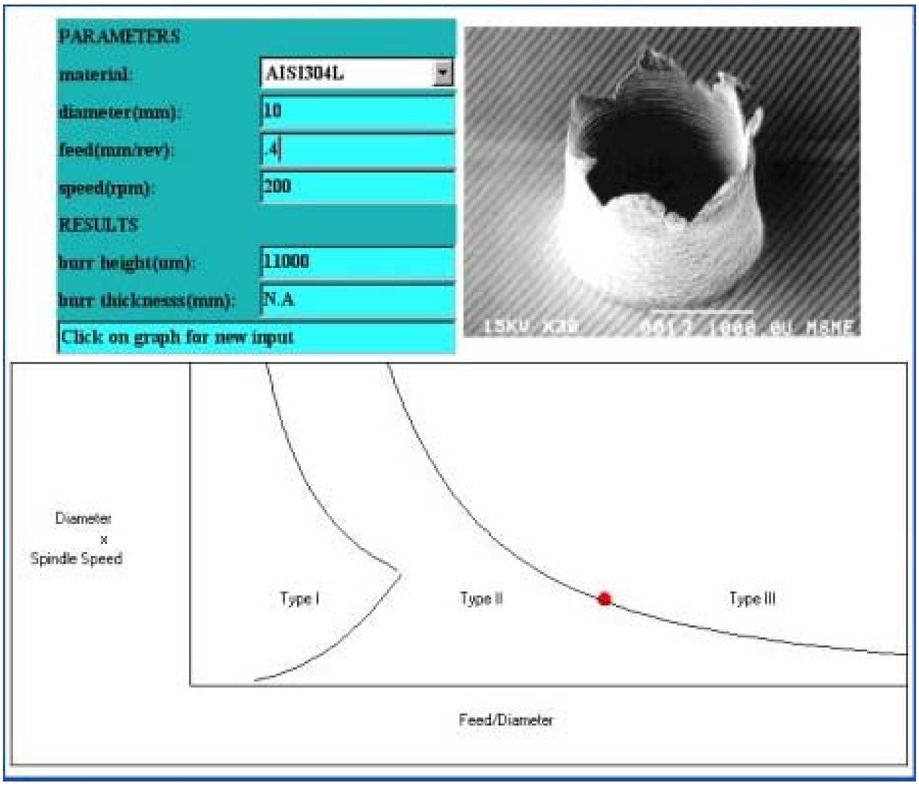


Figure 13 Web-based drilling burr control chart/burr expert for predicting likely burr formation

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, red dot in Figure 13. Typical burr sizes expected are shown.

- Integrated process planning and burr minimization

It is not sufficient to simply try to adjust process parameters for burr minimization or prevention alone. One should also consider other important constraints in machining, e.g. surface finish and dimensional tolerances. Figure 14 shows the process considerations for insuring optimum performance in face milling from the so-called macro planning at a higher level to detailed micro planning selecting machining conditions. The constraints include cycle time, flatness and surface roughness, burr height, surface integrity, etc /17/.

This enhanced process planning can be integrated with the basic design process to insure compliance with design criteria and manufacturing process optimization, Figure 15. This is consistent with recent efforts at implementing the “digital factory” and relying in comprehensive software links between individual elements of design and process planning, with competent process models included, for allowing a view “down the manufacturing pipeline” from any position in the design to manufacturing process. The scheme illustrated in Figure 15 is called

P4 for Probabilistic Precision Process Planning, implying the capability to update the process models and databases (like the drilling burr control charts) as additional data is available.

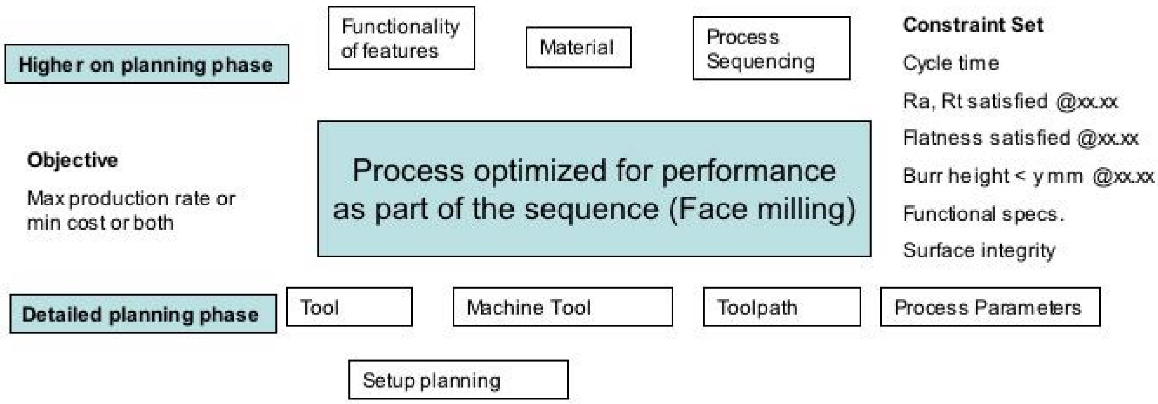


Figure 14 Considerations in optimization of face milling process including burr formation

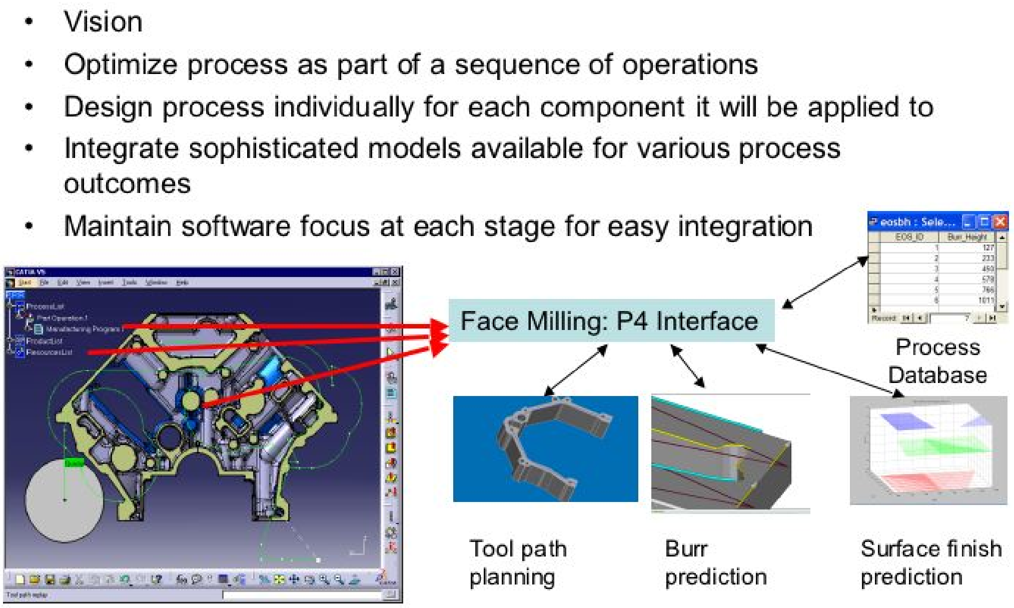


Figure 15 Schematic of integrated process planning with burr minimization, called P4

5 – 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 /18/. 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, specially in drilling, will depend on analysis of drilling burr formation with the objective of optimization of tool drill design. Many ideas on this are already under investigation at Berkeley.

It may be some time before we can declare that it is now 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.

6 – Acknowledgements

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