Title

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Strategies for Burr Minimization and Cleanability in Aerospace and Automotive Manufacturing

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ABSTRACT

The quality of machined components in the aerospace and automotive industries has become increasingly critical in the past years because of greater complexity of the workpieces, miniaturization, usage of new composite materials, and tighter tolerances. This trend has put continual pressure not only on improvements in machining operations, but also on the optimization of the cleanability of parts. The paper reviews recent work done in these areas at the University of California-Berkeley. This includes: Finite element modeling of burr formation in stacked drilling; development of drill geometries for burr minimization in curved-surface drilling; development of a enhanced drilling burr control chart; study of tool path planning in face-milling; and cleanability of components and cleanliness metrics.

INTRODUCTION

Burr formation in metal cutting is a virtually unavoidable consequence that can cause many problems from poor part assembly to accelerated wear of structures [1]. In addition, contamination of parts in the form of hard particles can produce premature wear, interference during assembly, and electrical short circuits of electro-mechanical components. To properly address these problems, steps must be taking during design, planning, and manufacturing to optimize the product development, as shown in Figure 1.

Burrs can be described as unwanted projections of plastically deformed material at workpiece edges as a result of machining operations like drilling and milling. These burrs lead to many problems, including dimensional inaccuracies, interference upon assembly, safety hazard during handling of parts, etc., if not sufficiently minimized or removed. On a large commercial aircraft, as many as 1.3 million holes are drilled and each of these is subject to a deburring operation to achieve the required edge quality [2]. Consequently, the cost of these operations can account for as much as 30% of the total cost of the structure. By minimizing or preventing the formation of burrs, significant productivity gains as well as improved part quality can be achieved.

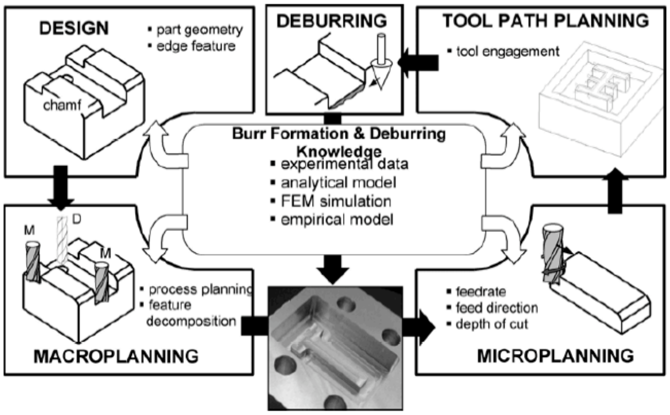


Figure 1: Five level integration required for burr minimization [1]

In order to accomplish this goal, several approaches to the modeling of burr formation have been formulated. Finite Element Modeling (FEM) has been the primary approach to gaining valuable information for drilling in flat surfaces, curved surfaces, and stacked materials. This modeling has been supplemented by experimental results and the compilation of an online burr expert database (available at http://www.burrexpert.com) to predict burr formation based on drilling parameters. Furthermore, tool path planning has been optimized with respect to burr formation in face milling by controlling the exit angle. These topics on burr formation – with a focus on the work done at the Laboratory for Manufacturing Automation (LMA) at the University of California-Berkeley – are reviewed in this paper, emphasizing their impact in the aerospace industry.

Although research on burr minimization and deburring has received strong emphasis since the 1970's in the aerospace and automotive industry, only during the past few years has the minimization of particulate contamination of parts become an important research topic. As trends in industry are directed towards the miniaturization of components, narrowing of tolerances, increase of part and assembly complexity, application of Minimum Quantity Lubrication (MQL) machining, and reduction of energy and working fluid expenditures during production, the level and nature of particulate contamination on the parts have become extremely critical. The study of cleanliness of components encompasses the following areas of study: Component properties, standardized methods for the specification and assessment of cleanliness as a new quality metric, cleaning process technologies, and expenditure of resources ("green" issues). An overview is presented on the current state of the art of the former two areas and research focus at the LMA, in collaboration with LMA partners in the automotive industry.

BURR FORMATION IN DRILLING

The analysis of burr formation in drilling operations is a complex process that has been very difficult to model. The combination of complex drill geometry, high temperature gradients, and workpiece material variations make modeling a formidable task. Modeling burr formation is especially challenging in the case of drilling stacked material, especially due to the extensive presence of FRP (Fiber-Reinforced Polymer) composites in these stackups [3]. Previous work in modeling burr formation in drilling a flat workpiece is being extended to study burr formation in drilling through curved surfaces and stackups.

CONVENTIONAL DRILLING

In conventional drilling, the morphologies and the sizes of the exit burrs are determined primarily by the feed rate and the speed of the drilling operation. Three main types of burr morphologies have been identified: uniform burrs, crown burrs, and transient burrs [4]. At low feed rates and speeds, a uniform burr is generally formed while at higher feeds and speeds, a crown burr is usually formed. A transient burr is a combination of both a uniform and crown burr. A photograph of these three types of burrs can be seen in Figure 2.

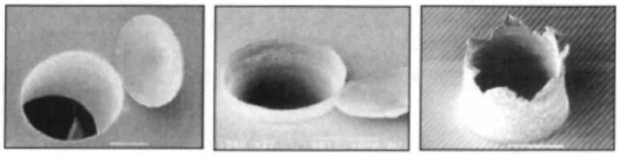


Figure 2: (From left to right) Uniform burr, transient burr, and crown burr in AISI 304L [4]

To model this burr formation, a lagrangian finite element model was constructed using Abaqus [5]. The simulation used an effective-plastic-strain-at-failure criterion to model material separation and a software tool for twist drill design to model the drill [6]. The simulation produced results that were very similar to actual drilling tests. Results from the model showing both uniform burr formation and crown burr formation can be seen in figures 3 and 4, respectively.

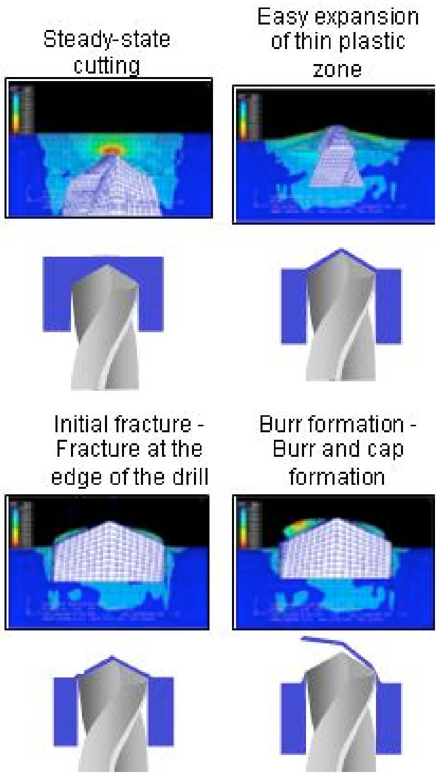


Figure 3: Formation of a uniform burr using a finite element simulation with a relatively low feed rate [5]

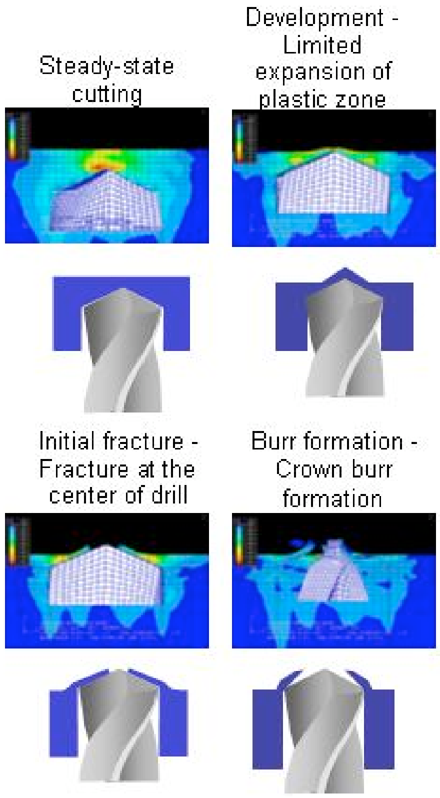


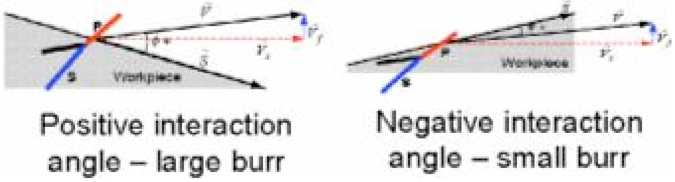
Figure 4: Formation of a crown burr using a finite element simulation with a relatively high feed rate [5]

With this agreement between experiment and simulation, the modeling of burr formation in drilling of flat surfaces is very useful in determining key process parameters for manufacturing operations. In addition, the simulations give valuable information concerning the residual stresses in the workpiece, heat transfer and temperature effects, and strain hardening characteristics of the workpiece. This is valuable information in metal processing especially in aerospace manufacturing, where residual stresses could lead to decreased fatigue life and premature failure.

CURVED SURFACE DRILLING

Following the results in modeling burr formation in conventional drilling of flat surfaces, an exploration into the burr formation in curved exit surfaces has been initiated. The study of this burr formation is of particular importance in intersecting holes or wherever drills exit on complex geometries. These complex geometries make deburring operations difficult and time consuming which damages productivity.

Burrs in curved surfaces are rather unpredictable and tend to occur only on certain parts of the exit hole rather than uniformly around the exit. This is a function of the geometry of the exit surface as well as the geometry of the drill. On certain parts of the exit surface, the drill is pushing into the workpiece whereas on other parts it is pushing out of the workpiece. This can be modeled though the definition of an “interaction angle”, φ [7]. A positive interaction angle will produce a burr by pushing out the workpiece while a negative interaction angle will not produce a burr by pushing into the workpiece. This is modeled in Figure 5.

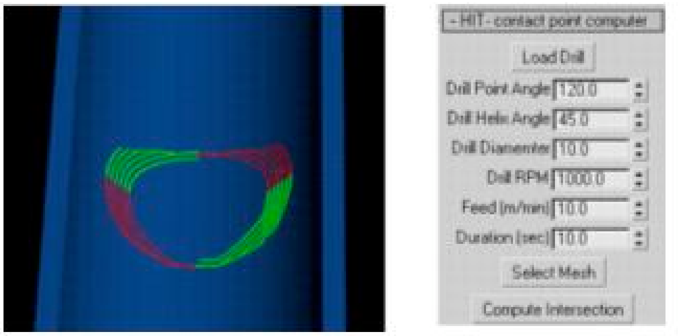

Positive interaction angle – large burr

Negative interaction angle – small burr

Figure 5: Definition of interaction angle [7]

These interaction angles have been studied based on their relation to drill geometries and process parameters. Simulations have been run to calculate the interaction angle to predict where the burrs will form. A sample of the simulation output and the user interface is shown in Figure 6.

To supplement the analytical modeling, FEM simulations have been performed using DEFORM. Since the drilling module for this program is still in its beta version, full results have not been achieved. However, Figure 7 shows the formation of a burr in a flat surface. This simulation can be extended to drill through a curved surface to analyze the burr formation. The ultimate goal of these simulations is to model different drill geometries to identify the best drill for a given surface. One of the key problems in achieving this is obtaining a good model for the drill. The complex geometries of the web, point angle, chisel edge angle, lip relief, etc., make this a formidable task.



Drill Point Angle 120.0

Drill Helix Angle 45.0

Drill Diameter 10.0

Drill RPM 1000.0

Feed [m/min] 10.0

Duration [sec] 10.0

Figure 6: Simulation used to model the interaction angle and burr formation in the exit of a curved surface. Green and red lines indicate negative interaction angle (no burr) and positive interaction angle (burr), respectively [7]

Progress has been made to achieve more reliable models and simulations that show accurate burr formation in drilling. In addition to DEFORM, Third Wave AdvantEdge is also another FEM package that may be employed to study burr formation in drilling.

Figure 7: DEFORM simulation showing the formation of a burr in a flat exit surface

STACKED DRILLING

Multilayer materials (or stackups) are used extensively in the construction of aerospace structural members. They provide increased strength-to-weight ratios compared to traditional structural materials. Also, the different layers provide a wide range of functionality that increases the utility of the structural member. Composite materials are increasingly being used as constituents of these stackups in the aerospace industry, as seen in Figure 8.

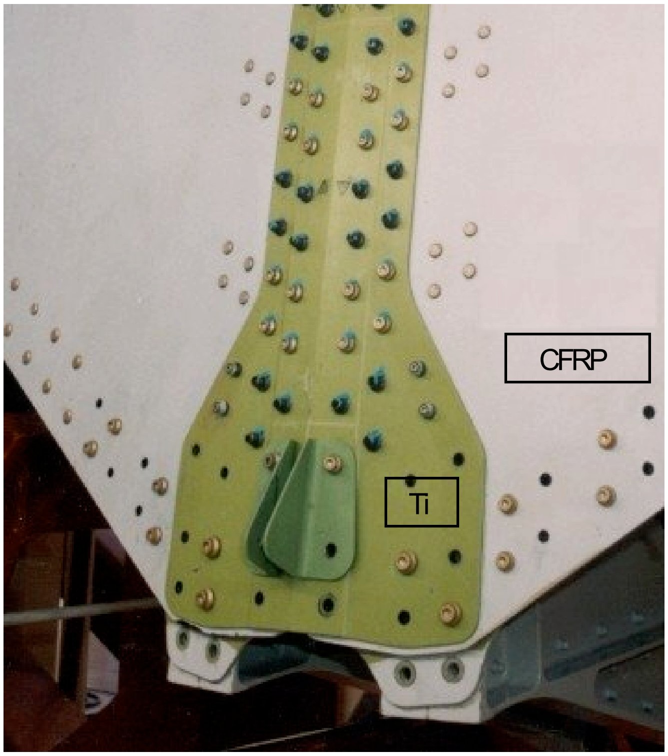


Figure 8: Section of a horizontal stabilizer of a commercial aircraft made of a metal (Ti) – composite (CFRP – Carbon Fiber Reinforced Polymer) – metal (Ti – unseen) stackup [2]

The principal machining operation performed on these stacked structures is drilling. These structures are usually assembled and then drilled. As a consequence of the assembly before drilling, burrs are formed at the interfaces of the materials. The aim is to control these interface burrs from occurring. The need in industry is to be able to drill through these materials in one operation without any reworking (i.e. the parts do not need to be disassembled, deburred, and refastened). Currently, deburring operations can account for as much as 30% of the total manufacturing costs for some aerospace structures [2]. Examples of aerospace panel stackups are CFRP/CFRP (Carbon Fiber Reinforced Polymers), CFRP/Titanium, CFRP/ Titanium/CFRP, and CFRP/Aluminum.

Modeling of stacked drilling is a challenging task because results from previous work on FE modeling of drilling cannot be applied directly to the stacked drilling problem [5, 8]. This problem should be considered as a fundamentally different problem; some of the differences in the model setup between conventional and stacked drilling are discussed in Table 1.

The multilayer drilling problem also opens up more interesting machining parameters to study which are not pertinent to the single layer problem. These parameters include the effect of clamping position on gap separation [8], burr formation/debris accumulation, and the effect of stacking order on burr formation and morphology.

Table 1: Contrasts between multilayer drilling and conventional single layer drilling

Aspect	**Single Layer Workpiece**	**Multilayer Workpiece**
Steady State Assumptions	Taken as a spatial criterion. Usually, process is considered as steady state when the drill tip is fully embedded in the material.	For similar length scales, several “steady states” may be present in one drilling operation. Depending on the relative material thicknesses, there may not be a “steady state.”
Burr Morphology	Existing FE simulations have demonstrated the formation of crown and uniform burrs as a function of the drill feed [5].	It is unknown if the standard morphologies are also applicable when multiple materials are present in the workpiece.
Temperature Effects	Temperature properties are constant across the workpiece. Only one set of thermo-mechanical relationships have to be considered.	Temperature properties are dependent on the material in each layer of the workpiece. Temperature properties will vary by direction in the case of composite materials.

Fiber Reinforced Polymer (FRP) composite materials are of increasing importance in multilayer stackups, especially in the aerospace industry. The primary challenge in FRP modeling is that FRP materials are heterogeneous and exhibit strong anisotropy. Clear distinctions have to be made between the strong, reinforcing fiber and the soft polymer matrix. Hence, for accurate modeling, information on the constitution of the composite has to be explicitly known, which may either be deterministic or stochastic.

The chip formation mechanism in FRP machining involves brittle fracture, unlike metal cutting, where chip formation occurs from plastic strain. The chip formation mechanism depends on the relative orientation of the fiber in the matrix to the moving tool edge [9]. The chips are generally small, dust-like particles. Due to their anisotropic nature, FRP materials display several failure modes that are dependent on the local orientation of the fibers and loading conditions [10]. Therefore, FE models for FRP behavior need to account for these multiple local failure modes.

Delamination failure is the main failure mode during drilling and is caused by out-of-plane stresses. The path of failure crack propagation in the FRP is also dependant on the local conditions at the crack tip. Crack propagation depends not only on the properties of the fiber and the matrix, but on the bonding strength of the matrix to the fiber [10]. Cracks in FRPs are not necessarily catastrophic and failure can occur locally. This local failure may occur due to stress concentrations and the presence of defects, which may weaken the material. Hence, to fully capture the failure behavior of FRP materials, the FE model needs to be able to capture local properties dynamically and watch for failure to occur arbitrarily.

In addition to the challenge of modeling the anisotropy of the workpiece, the effect of the tool on the machining quality cannot be ignored in these models. Tool wear during stacked machining accelerates the formation of burrs and other defects. Tools should be modeled as dynamic objects with both stress and thermal effects. Special tool wear models also have to be incorporated to capture tool wear and its effect on the defects.

Modeling drilling is complex as it is a 3D, dynamic cutting problem with multiple cutting edges. The drilling process can be dissected as a composition of several orthogonal cutting operations. As a precursor for modeling the drilling of stacked materials, it is instructive to first study the orthogonal cutting of the individual members. Orthogonal cutting of metals has been studied extensively, but orthogonal models of FRP machining are needed. These simulations will shed more light on the behavior of FRPs during machining and can produce results that can be used to make more efficient drilling simulations. Subsequently, stacked drilling simulations can be studied. The complexity of the material models used to describe the FRPs can also be increased gradually. As a first step, FRPs can be idealized as orthotropic and then can be modeled as anisotropic. Once these basic steps are completed, the effect of different materials and drill geometries on burr formation can be studied and optimal drill geometries can be achieved specific to the configuration of the stacks.

Choi et al. [8] applied Min et al.'s FE model [5] to simulate gap formation during the drilling of multilayered materials. Using a similar software-based approach to model the drill, the gap formed between two sheets of AISI304L being drilled was simulated as shown in Figure 9.

Additional study of burr formation in stack drilling will allow for improved manufacturing processes and optimal hole quality. The elaboration of these FEM simulations will assist in the achievement of these goals and help improve aerospace manufacturing techniques for drilling.

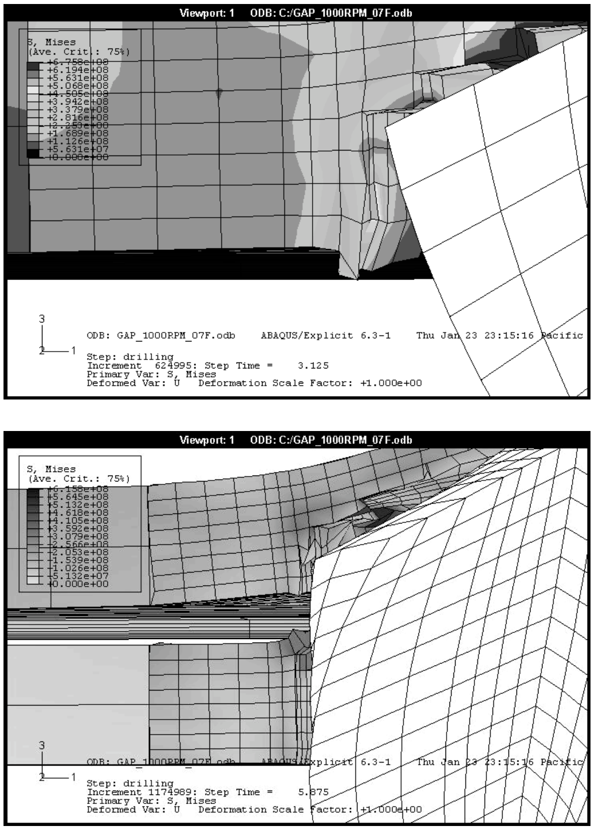


Figure 9: Entrance burr and gap formation in stacked SS304L drilling [8]

DRILLING BURR DATABASE

In addition to having a background in modeling of burr formation, it is also important to have experimental results to quickly predict burr formation in drilling based on machining parameters. To accomplish this objective, a database of burr size measurements has been compiled to predict burr formation based on parameters of feed, speed, and hole size. These measurements provide the basis for a burr control chart. These charts are useful for all materials of the same type (carbon steel, for example), and are normalized to cover a range of drill diameters. They also provide information on what range of process parameters should be used to optimally minimize burr formation.

As an example, Figure 10 shows typical burr control charts for stainless and low alloy steels; the burrs were formed by drilling with a split point twist drill. This chart predicts the approximate boundary between three burr types: uniform burrs (Type I), transient burrs (Type II), and crown burrs (Type III). The burr height scales with distance from the origin, and the grey box indicates common recommended process parameters for this material.

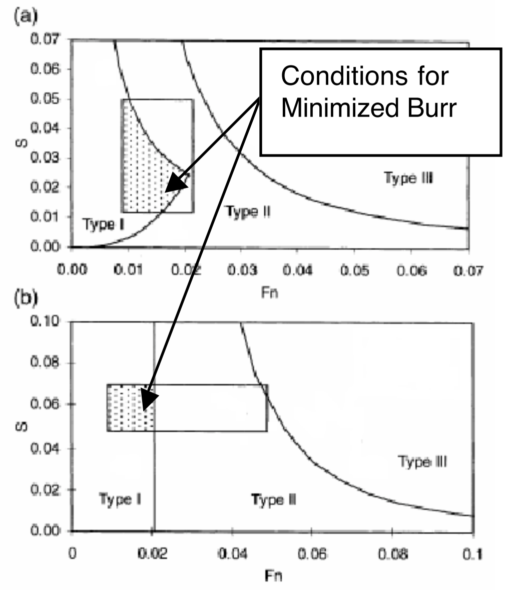


Figure 10: Drilling Burr Control Chart for (a) Stainless Steel (AISI 304L) and (b) Low Alloy Steel (AISI 4118), where $S=10^{-5}$ dN; d is the drill diameter (mm), N is the spindle speed (rpm), F_n is the normalized speed (feed rate (mm/rev) divided by d) [11] [12]

Currently, the burr control charts are material specific. Although a chart for every individual material is unreasonable, this problem can be solved by adding a third dimension to the chart that accounts for material properties. The influence of material properties has been acknowledged by a great many researchers, but Link was the first to quantify this effect with a parameter called the "burr tendency", G [13]. This burr tendency value is higher when burrs are more likely to form in a material. To understand how a three dimensional control chart might appear, Link's G-value is used as the third axis in Figure 11. The more ductile stainless steel forms burrs more easily than low allow steel (Type II burrs appear closer to the origin) according to the burr tendency G-value.

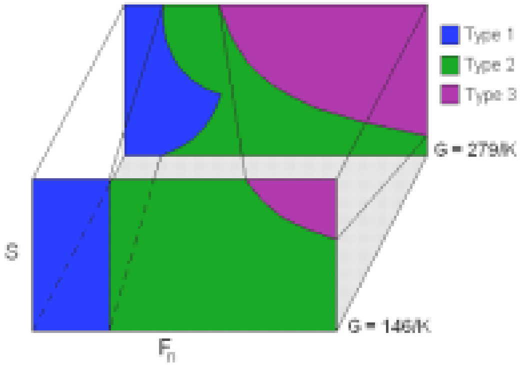


Figure 11: Three dimensional burr control chart example. Stainless steel (AISI 304L) has a burr tendency value of 146/K and low alloy steel has a burr tendency of 279/K.

Burr databases such as the burr control chart can be integrated with an internet-based expert system (www.burrexpert.com) to provide quick results for solving industry problems. An example of this scheme can be seen in Figure 12, where the process parameters are supplied as input, and the predicted burr is represented as a red dot on the control chart.

The first stage of the Burr Expert website will include modules and case studies from UC Berkeley's short course on burr minimization. It will also provide a forum for members to exchange ideas and technology, thus providing users a fast and effective source of data and insights from researchers in the area.

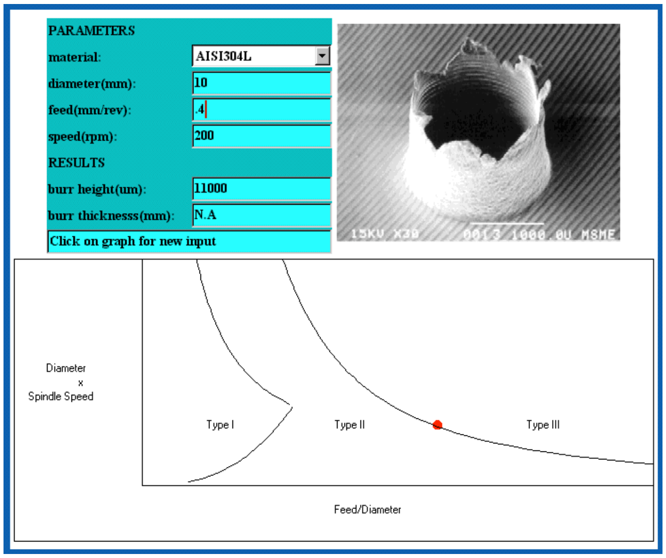

PARAMETERS
material: AISI304L
diameter(mm): 10
feed(mm/rev): .4
speed(rpm): 200
RESULTS
burr height(um): 11000
burr thicknesss(mm): N.A
Click on graph for new input

Figure 12: Web-based drilling burr control chart for predicting likely burr formation. [1]

BURR FORMATION IN FACE MILLING

Although burr formation in drilling operations are a primary concern in the aerospace industry, burrs formed during face milling are also a significant concern. As a consequence, various strategies to predict and minimize burrs in face milling have been developed. For a given workpiece material, tool-engagement conditions will determine burr formation. Chern [14] and Rangarajan [15] found that the burr size increases significantly with increasing exit angles (defined in Figure 15) and very large entrance angles.

Tool path planning based on limiting the entrance and exit angle below a threshold, was developed by Rangarajan [15] and implemented by Ramachandran [16]. The approach, called the "Feasible Region", involves the calculation of an area where both entrance and exit angle thresholds are not violated and the the shortest tool path is drawn. A sample part showing this approach can be seen in Figure 14.

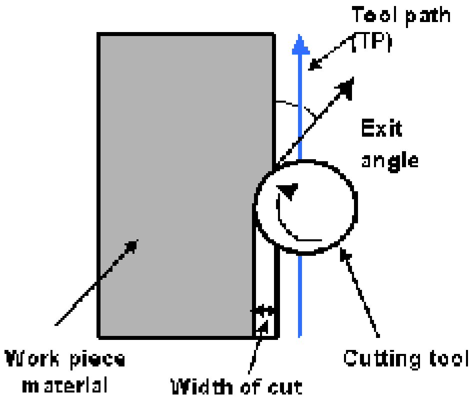


Figure 13: Definition of exit angle in face milling

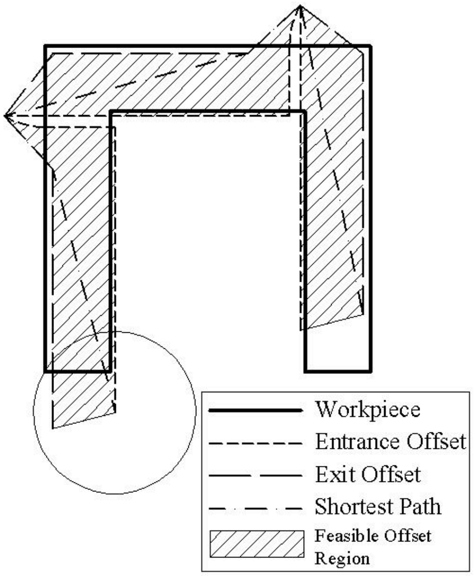


Figure 14: Burr formation minimization using the feasible region approach on a sample part [16]

Recent research has focused on comprehensive tool path planning for burr and cycle time minimization. An algorithm has been developed to generate tool paths for geometrically complex parts while at the same time meeting the cycle time requirements [17].

This approach to minimizing burr formation has achieved significant success in the automotive industry and can have applicability in the aerospace industry where burr formation in face milling operations needs to be controlled.

CLEANABILITY OF MASS-PRODUCED COMPONENTS

Current trends in automotive manufacturing focus on the cleanability of parts and assemblies, defined herein as the ability to achieve particulate contamination levels of components that meet predefined cleanliness specifications. In recent years, contamination of parts has become a cardinal cause of failures since narrow tolerances, power density requirements, miniaturization, and complexity of the components make them more sensitive to particulate contaminants. It is then desirable to optimize the manufacturing process, spanning all levels of manufacturing flexibility, from the design stage to cleaning processes to quality assessment, in order to minimize failures and cost penalties associated with residual contamination. The study of cleanability can be divided into four main areas, from highest level to lowest level of manufacturing flexibility: component properties, cleaning process technology, expenditure of resources and environmental impact, and specification and assessment of cleanliness (Figure 15). In this section, an overview of component properties relevant to cleanability and methodologies for measurement and specification of particulate contamination levels, which are currently being investigated at the LMA in collaboration with the automotive industry, is presented.

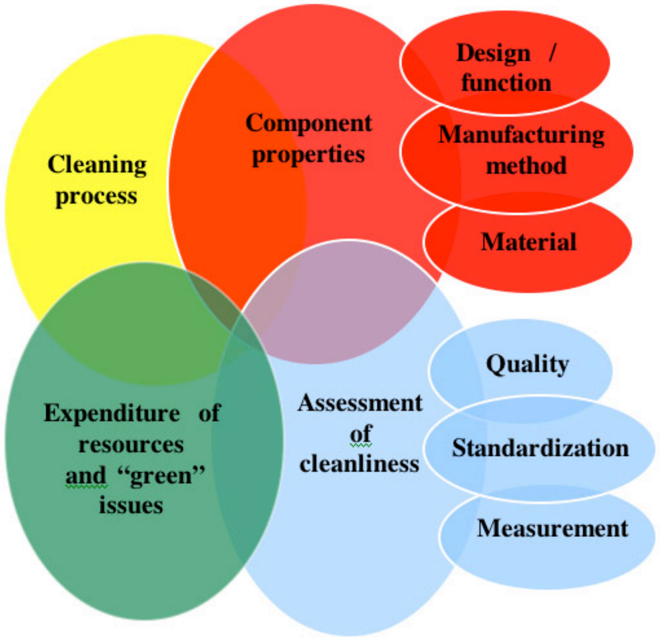


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Figure 15: Areas of study in cleanability of components in the automotive industry

COMPONENT PROPERTIES

The ability to clean a component to the required cleanliness level (cleanability), depends on the entire chain of events, from design to service, that is necessary to produce the part and assemble it into a final product that satisfies performance, service life, and cost requirements. In essence, component properties relevant to cleanability include its design and functional view, material and surface properties, and manufacturing method.

Design and functional view

The most important design parameter of a component as regards cleanability is its geometry. Geometry plays an important role in the accessibility of cleaning media with the required kinetic energy for the removal of adhered particles on external and internal surfaces, and in the "flow friendliness" necessary to flush the media and loose contaminants out of the workpiece. For example, the cleanability of the internal surface of a meandering lubrication circuit passage is lower than that of a straight passage, because a straight passage permits better accessibility to impinging jets (e.g. water jets) and is less likely to contain remnant media and contaminants after the cleaning process. The cleanability of a part must, in consequence, be taken into consideration from the design stage; otherwise, the required cleanliness may be unfeasible. Feature-oriented, geometric design rules for cleanability of powertrain components are currently under development at the LMA. The fundamental goal of these rules is to guide designers in the conception of parts that are cleanable in a mass-production scenario. So far, the design rules are based on heuristics derived from empirical experience. Future work will focus on the development of Computer-Aided Design (CAD) tools that simulate the cleanability of interior surfaces of parts, and the conceptualization of a geometric cleanability index for the classification of different features and design solutions according to their cleanability. The functional view of a part as a standalone entity, and as a component of a subassembly comprising the final product, in combination with its expected performance and service life, define how function critical the cleanliness of the part is. A qualitative scale that ranks how function critical a part is has been established, based on the system it belongs to in the final product, service conditions, working fluid involved, and targeted life expectancy. This scale is used to determine the cleanliness specifications on the CAD drawings of the parts. As an example, a pump for the cooling system of an internal combustion engine is considered to be less function critical than a similar pump for a lubrication system, due to the respective type of working fluids and circuits involved; hence, the cleanliness specification of the former is less stringent than that of the latter component.

Material and surface properties

The physicochemical, morphological, and mechanical properties of the surface of a workpiece influence the ability to remove adhered and loose contaminants and cleaning media from it. Therefore, selection of the type of cleaning method and cleaning process parameters must carefully consider these properties. The work of adhesion of adhered particles, which sets the amount of energy and chemical composition of the cleaning medium required to overcome the interfacial energy and remove the contaminants must me controlled. Furthermore, in the case of liquid cleaning media, the ability of the medium to wet the target surface is critical to the ability to flush loose particles away from the surface. Surface roughness also affects the wettability of cleaning liquids and loose particle retention on the substrate. Finally, mechanical properties of the substrate limit the allowed impinging energies for adhered particle removal before undue substrate damage is incurred. More specifically, the erosion resistance of the substrate must be considered in the selection of cleaning parameters that produce minimum degradation of surface finish.

Manufacturing method

The type and amount of contaminants present in a part are direct consequences of the manufacturing method, which, for the purpose of this discussion, is considered a component property. One of the most common and illustrative examples is the comparison between sand-casting and pressure-casting methods for the production of an internal feature. The amount and nature of adhered contaminants on the sand-cast feature are potentially more harmful, and put greater demands on the cleaning process, than those generated by the pressure-casting method. The selection is especially critical, or can even lead to catastrophic failure, if the feature belongs to a lubrication system. Thus, manufacturing method selection is cardinal, in particular with highly function-critical parts or features.

SPECIFICATION AND ASSESSMENT OF CLEANLINESS

Tools and standardized nomenclature for expressing cleanliness of a feature or component –a new quality metric, and standard methods for its evaluation, are of utmost importance in the study of technical cleaning. In automotive applications, cleanliness encompasses the level of residual contamination in particulate form that is found on a part. Depending upon how function critical a part is, cleanliness is expressed either as a contaminant mass per unit surface area, or as a particle size distribution. The latter method is generally reserved for parts that are the most function critical. Particle lengths studied usually range from a few microns to hundreds of microns. The limit values of residual dirt, indicated as either gravimetry or particle size distribution, are included in the list of specifications of a part or feature at the design stage (i.e. component drawings).

The measurement of cleanliness involving non-embedded particles relies upon what is known as a test cleaning method, whereby contaminants present in a workpiece are collected and measured. Collection of particles is performed by circulating a given volume of cleaning medium at certain pressure and mass flow rate throughout the surface or workpiece under study, inside of a test cleaning chamber. The fluid is circulated through a filter where the particles are collected. The particles are then weighed or inserted in a particle counter depending upon the cleanliness specification method as suggested by the functional view. One of the limitations of the current approaches is that statistical reliability of the test cleaning method cannot be established unequivocally, on the grounds of inability to repeat said tests on a unique workpiece and associated contaminants. On the other hand, current test cleaning methods are not appropriate for embedded particle quantification, most salient example of which is sand particles left behind by the sand cores in castings. Further developments in test cleaning methods are currently underway to enhance robustness of measurements and quality assurance in cleanliness.

CONCLUSION

Although burr formation is not completely preventable, the ability to minimize the burr or predict the size of the burr is a very important tool. The models presented here predict burr formation in conventional drilling, curved surface drilling, and stack drilling. In addition, experimental data have been organized into a useable database to predict burr formation based on drilling parameters. This database and other useful strategies are available online to provide others enhanced burr resources. The combination of all these resources provides a solid background to address issues in manufacturing of precision aerospace components.

The reduction of burr formation in face milling has also contributed to the understanding of burr formation in metal cutting. Through the use of reliable geometric and software tools, the burr formation can be controlled and tool life extended.

Cleanliness of components is rapidly becoming an important quality metric in industry. The achievement of cleanliness requirements of parts demands optimization of several aspects of the product development and manufacturing processes, from part design to quality assurance. The cleanability area is currently in its early stages of development in the automotive and aerospace industries. Current work is focused on the development of design rules for cleanability, assessment of cleanliness levels, and optimization of cleaning processes and upstream manufacturing steps that influence workpiece contamination, most notably sand casting, machining, and edge finishing operations.

ACKNOWLEDGMENTS

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Additional Sources

For more information on modeling of burr formation please visit the LMA website http://lma.berkeley.edu and the LMA repository at the California Digital Library http://repositories.cdlib.org/lma.