Design and Manufacturing for Cleanability in High Performance Cutting

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Abstract: Control of surface contamination in the form of small particles is becoming a major priority in conventional manufacturing processes, due to the higher sensitivity of mechanical assemblies to contamination-related failures. At the same time, the complexity of workpieces is increasing, making the removal of contaminants more difficult. Thus there is a critical need to facilitate cleaning in order to reduce the high costs and expenditure of natural resources required for cleaning operations. The objective of this paper is to present strategies to reduce or prevent solid particle contamination by manufacturing by-products throughout the product development and manufacturing chain, via cleaning-conscious design feedback to product developers in the context of Design for Cleanability (DFC) and improved process planning for manufacturing. We also show preliminary results on the effect of cutting parameters on chip size and morphology when machining cast aluminium silicon alloy, in an attempt to control chips for easier removal.
Keywords: chip formation, cleaning, cleanliness, design-for-cleanability, particulate contamination.

1. INTRODUCTION

An emphasis on high-performance and fuel-efficient designs in the automotive and aerospace industries has led to a push for products with high performance-to-weight ratios and more features at the lowest manufacturing costs possible. Figure 1 [MTZ, 2004] shows the dramatic increase in the power density of automobile engines, doubling in the past ten years. This trend requires increased fatigue strength of engine components, higher injection pressures with smaller nozzles, and a higher number of mechatronic components, among other aspects. As the complexity and precision of parts increase to meet the new requirements, the occurrence of failures caused by hard particle contamination has grown considerably [Berger, 2006]. At the same time, it has become more difficult to access all the surfaces of parts to remove contaminants, due to miniaturization and increased geometric complexity. Consequently, in the past few years the degree of cleanliness of mechanical components has become an important quality metric in itself. This has always been the case in electronics and

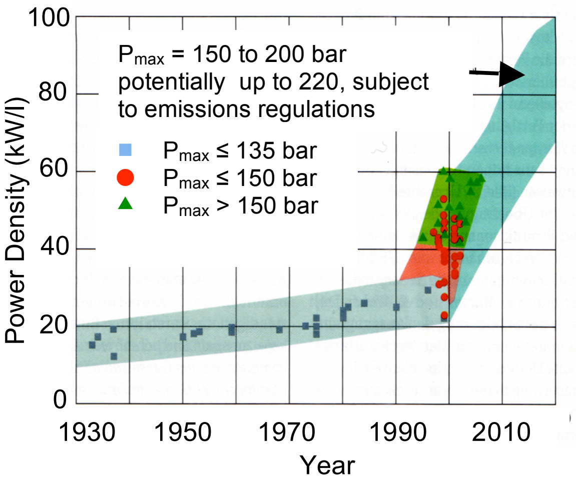

Figure 1: Trends in power density and max. pressure of automotive combustion engines [MTZ, 2004].

semiconductors, but the trend shown in Figure 1 now forces this challenge on more conventional manufacturing, where cleaning costs have increased significantly, currently comprising 8 to 10% of the manufacturing costs in some industries [Berger, 2006].

Examples of components that are difficult or even impossible to clean in existing facilities, and susceptible to contamination-related failures, are cylinder heads of internal combustion engines. During manufacturing, when machining chips travel into the intricate network of coolant and lubricant channels of the workpieces, they become extremely challenging to remove. Various cleaning methods, including high pressure jets (HPJs), flow cleaning, and brushing, can be rendered ineffective for removing chips that become firmly lodged in hard-to-access areas, or that due to flow incompatibility of the channels, cannot be transported out of the part. However, these chips often come loose during the use phase, and may cause scoring of precision surfaces, premature wear, and bearing seizure, leading to catastrophic engine failure. For example, figure 2 shows chips that were found trapped in a water channel and lodged in the valve of an engine's oil channel during use, causing premature engine failure.

The understanding needed to create the desired production environments and the type of software and tools required to meet current and future cleanliness requirements of mechanical components does not exist today. The objective of this paper is to present research at Berkeley on cleanability in mass-production environments to develop such an understanding and prototype such tools. First, we introduce the integration of cleanability as a new engineering constraint into the product development and manufacturing chain, including main influences on cleanability and cleaning technologies. Second, we present cleanability strategies that can be incorporated at the design stage in the context of Design-for-Cleanability (DFC). Next, in the area of Manufacturing-for-Cleanability (MFC), we show preliminary results of the effect of cutting parameters on chip morphology in high-speed machining of aluminum alloy engine components as a first step in correlating cutting parameters to the cleanability of the chips generated.

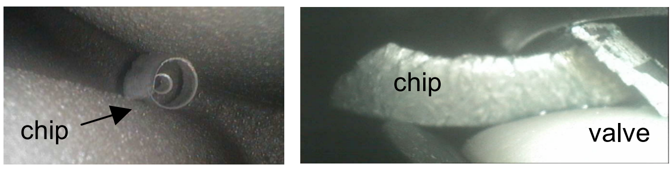

Figure 2: Chips lodged in cylinder block water jacket [Friedrich, 2004] and cylinder head oil valve [Reich-Weiser, 2006].

2. CLEANABILITY AS A PROCESS METRIC IN THE DESIGN-TO-MANUFACTURING CYCLE

Ideally, a systematic approach to *cleanability*, defined as the ratio between the degree of cleanliness obtained and the amount of cleaning effort or resources invested, would involve the totality of stages that comprise the design-to-manufacturing cycle, since cleanliness depends on decisions made from early product conceptualization through finishing operations. The traditional approach, which addresses the problem at the cleaning stage exclusively, offers limited flexibility and fewer opportunities to obtain optimal solutions in high-volume production systems.

The integration of design, manufacturing, and finishing tasks can be divided into four levels of flexibility of engineering decisions that are aimed at predicting, influencing, and optimizing a particular quality metric [Stein and Dornfeld, 1997]. Such a classification is used to describe the architecture of the *desired production environments and the type of software and tools required within each level to attain a set of goals*. Table 1 presents the four levels of integration, using cleanability as the process metric.

Table 1: Four levels of integration in the design to manufacturing cycle.

Integration Level	Cleanability-Enhancing Expert Tasks	Flexibility for optimization
Level I **Design**	Design for cleanability: prediction, control, & optimization of cleanability in an iterative design environment.	Design: High Manufacturing: High Cleaning: High
Level II **Macroplanning**	Prediction, control, & optimization of cleanability through manufacturing systems design in a macro-planning environment.	Design: Low Manufacturing: High Cleaning: High
Level III **Microplanning**	Prediction, control, & optimization of cleanability through limited adjustments to existing manufacturing processes in a micro-planning environment.	Design: Low Manufacturing: Limited Cleaning: High to Low
Level IV **Finishing**	Prediction, control and optimization of cleanability through modeling and adjustments of cleaning operations.	Design: Low Manufacturing: Low Cleaning: High

At the highest level of integration, Level I, product developers have the maximum flexibility in the selection of designs topologies, geometric parameters, and surface structures that facilitate cleaning and reduce the parts' susceptibility to contamination during production. Feedback about the impact a given set of design alternatives is predicted to have on the cleanability of a part is evaluated during this decision-making stage in order to conceive the most *cleanable* design. Moreover, any tradeoffs between cleanability and the functional performance of the design must be analyzed in order to set bounds on feasible design parameters in the context of Design for Cleanability (DFC). At Level II, although design specifications are set, it is possible to affect cleanliness and cleanability via the selection of the type of manufacturing and cleaning processes, as well as the layout and process plan. Manufacturing methodology determines the type of manufacturing byproducts in the form of debris, e.g. embedded sand from casting or chips from machining. The associated contaminant types present determine the cleanability constraints set at Level I, in addition to the selection of cleaning processes and parameters in Level IV. Once the process, layout, and macroplans are set, it is still possible to fine-tune the manufacturing process parameters to improve the process metrics (Level III). For example, as discussed in section 4, the type of machining chips generated can be modified via cutting parameter adjustments to facilitate cleaning and to control the location and strength of burrs. Levels II and III constitute the Manufacturing for Cleanability (MFC) framework. At the lowest level, Level IV, adjustability is limited to the cleaning processes; process parameters are tuned to assure efficient and controllable cleaning.

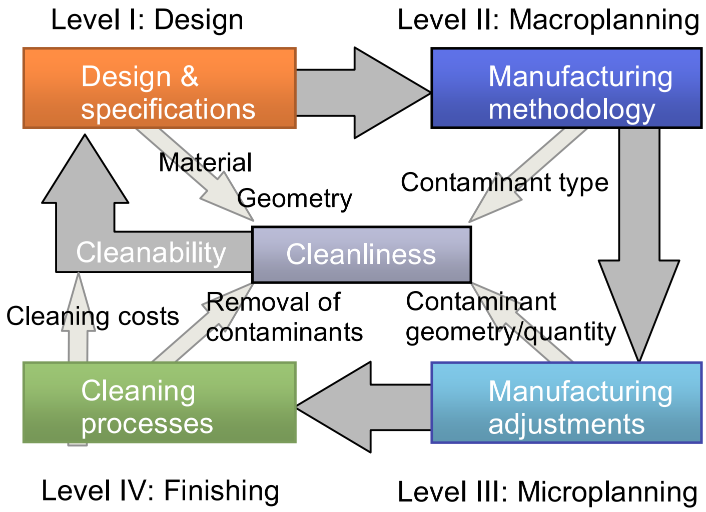

Figure 3: Cleanability in the design-to-manufacturing cycle and main influences.

Cleaning processes can be divided into three broad categories according to the principal driving force of the cleaning action: i) mechanical, ii) chemical, and iii) thermal. Mechanical cleaning processes are the most effective at removing hard particles of a few microns in length and larger, which are associated with decreased performance and service life of mechanical components, and also use less energy than thermal methods and avoid safety and environmental hazards involved in chemical cleaning. The most important mechanical methods used today are high-pressure Jets (HPJs), where the cleaning action is obtained from the impact of a high-speed jet of cleaning media (e.g. water, dry abrasive particles, etc.) with the substrate and contaminants; flow-cleaning methods, whereby contaminants are transported out of the workpiece by cleaning media flow at relatively low pressures; and solid contact cleaning methods, where direct contact of cleaning tools, such as brushes, scrapers, wipers, vibratory shakers, etc., generates the cleaning action.

3. DESIGN FOR CLEANABILITY

Since the majority of manufacturing cost become fixed in the design stage, it is vital that designers be able to accurately assess manufacturing costs, including cleaning costs, at every stage of the design process. Experience in the automotive industry has

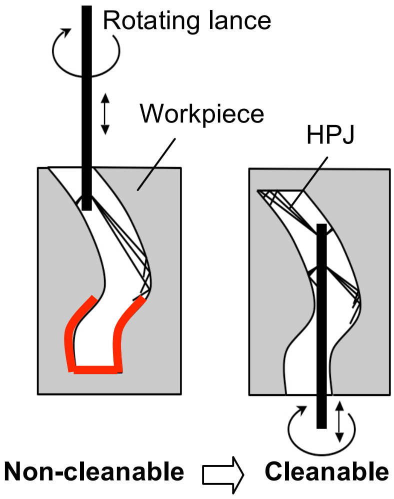

Figure 4: Enabling access of vertical HPJs by design modification.

shown that workpiece geometry is one of the most important influences on cleanability. For example, for cleaning of sand castings, it has been found that direct impact of HPJs is a necessary condition for the removal of embedded sand which, in turn, is conditional upon the accessibility of the nozzles into the internal surfaces of the parts. For the removal of loose particles, whether sand or chips, the geometry must allow out-flushing of the cleaning media and contaminants. Unfortunately, most workpiece geometries are currently not fully accessible to cleaning tools and are susceptible to remnant loose particles and cleaning media after cleaning takes place.

DFC has previously been applied in the design of conduits and valves for the biomedical and food processing industry. Prior studies [Hose, 1992; Millar and Moody, 1992; Jensen et al., 2005] have found that stagnant areas, in which the local velocities are substantially lower than the transport velocity of the fluid, are undesirable, insofar as there is a potential to accumulate particulate matter in such areas. However, no prior work has addressed the accessibility and geometry aspects of HPJ and flow cleaning. In fact, there has been virtually no literature addressing cleanability as applied to mechanical components since the seminal work of Sipitkowski [1993], which focused on rinsing and drying aspects of water-based cleaning.

Case studies on the cleaning of components in a production line environment and cleaning experiments provide grounds for the development of a DFC knowledge-base of favorable and unfavorable geometries and the influence of dimensional parameters on cleanability. As a first step in the creation of the DFC knowledge-base, we are surveying parts and features from automotive production lines to identify advantageous and disadvantageous geometric parameters from a cleanability standpoint when using HPJs and flow cleaning.

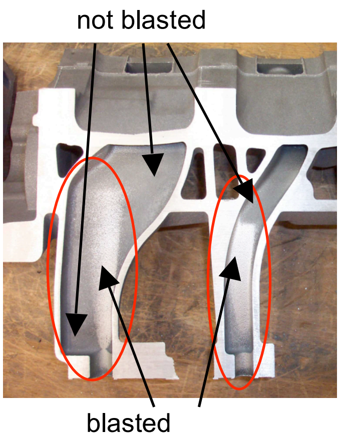

Figure 5: Inaccessible areas in a casting.

Another important tool we are investigating for analyzing geometry and providing cleanability feedback *interactively* is the programmable capability of Graphical Processing Units (GPUs) –modern graphics cards. GPUs can be used to speed up not only geometric but also numerical calculations [Owens et al., 2005]. For example, solving dense linear systems (via LU-decomposition and pivoting) using optimized CPU solutions (LAPACK) is 50-400% slower than on the latest GPUs [Galoppo et al., 2005], with the performance gap widening.

A preliminary survey of production parts has identified features such as undercuts, sharp corners, and sharp changes in cross-sectional areas as flow-incompatible. We have developed GPU-based techniques to dramatically speed up identification of and geometric feedback about the exact locations of undercut locations [Khardekar et al., 2006]. We are able to test a direction for undercuts in less than a millisecond for parts defined by tens of thousands of facets, and highlight the undercuts at interactive frame rates during display. Identifying globally-flow-incompatible features and developing GPU-compatible algorithms for recognizing such global features, as well as the other relevant local features, are left to future work.

4. MANUFACTURING FOR CLEANABILITY

Machining byproducts in the form of chips quite often contaminate parts in automotive production. In the context of MFC, at Level III (see section 2), it is possible to enhance the cleanability of machined components by controlling machining chip properties, via the adjustment of cutting parameters. Chip geometry influences a chip's tendency to enter the workpiece and become trapped by internal features. Here we present our preliminary study on the effect of machining parameters on chip geometry. These results can be used to generate chips that improve the cleanability of the parts. The aspects of the chip that make it more or less cleanable must be the topic of future research.

4.1. Experimental setup

Planar milling and drilling experiments were conducted on cast AlSi7Mg blocks. For the milling experiments, a 125 mm ∅ indexed mill with six PCD inserts was used. Axial rake and radial rake angles were kept constant at 90^0 and $+4^0$, respectively. Lead angles of 0^0 and 15^0 were tested. Two levels of cutting speed (1500 and 3000 m/min), feed (0.1 and 0.2 mm/tooth), depth of cut (0.5 and 2 mm), and lubrication (dry and wet using Ecocut HFN 10 LE) were investigated. Drilling was performed using a 12 mm ∅ single-point carbide twist drill with point, chisel, and helix angles of 120^0, 55^0, and 30^0, respectively. The drill had lubrication outlets in the tip. Two levels of speed (188 and 377 m/min), feed (0.15 and 0.3 mm/rev), lubrication (MQL using Multicut Micro SP 51 and wet lubrication using Ecocut HFN 10 LE), and tool wear (new and old tools) were used.

Chips were collected to measure their mass and geometry using a precision scale and optical coordinate measuring machine. The chip geometry characteristics measured were length, maximum diameter, minimum diameter, average width, number of curl rotations, and average shear zone height (from stick-slip on the tool face), as shown in Figure 7. From this data, the correlation ρ between the input parameters *X* and the measurements or outputs *Y* were calculated by:

$$\rho(X,Y) = \mathrm{Cov}(X,Y)/(\sigma_x\sigma_y) \tag{1}$$

where Cov(X,Y) is the covariance and σ is the standard deviation of the data.

At the current state of research, a series of chip geometric characteristics that are believed to be relevant to cleanability were measured. Chip diameter, length, and width are the largest dimensions, which could establish the tendency of the chip to become stuck in a passageway, for example. The chip's width can be associated with its strength, which can also be, in turn, related to how easily chips can be broken down into smaller particles by cleaning media or tools for easier extraction from the workpieces. Chip weight establishes how easily it may be swept away using cleaning methods such as a water jets. And, the number of rotations and shear zone height may affect the likelihood of the chip to snag on inner features or with other chips.

4.2. Results

The correlations are shown in Tables 2 and 3. Due to the subjectivity of chip measurement, imperfect alignment with the optical measuring machine, and the inherent variability of chip formation (due to vibrations, material effects, temperature, etc.), a statistical correlation of greater than 80% (greater than 0.8 or less than -0.8) is assumed to be noteworthy, and is highlighted in the tables below.

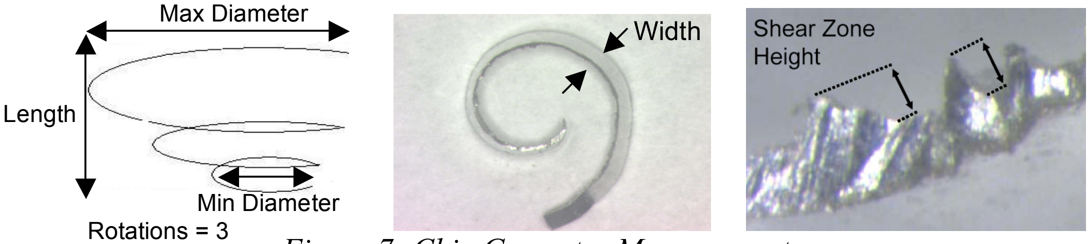

Figure 7: Chip Geometry Measurements.

Table 2: Milling correlations.

	Weight (mg)	Number of Rotations	Max Diam (mm)	Min Diam (mm)	Length (mm)	Average Width (micron)	Average Shear Zone Height (micron)
Lead Angle (degrees)	0.58	0.37	0.11	-0.33	-0.24	0.95	Not studied
Speed (m/min)	-0.13	-0.39	0.54	0.08	-0.55	-0.11	-0.34
Feed (mm/tooth)	0.24	-0.80	-0.42	0.50	-0.50	0.26	0.85
DOC (mm)	0.89	-0.65	0.46	0.39	0.92	1.00	Not studied
Lubrication (Dry vs. Wet)	-0.61	-0.58	-0.86	-0.18	-0.70	-0.55	Not studied

Table 3: Drilling Correlations.

	Weight (mg)	Number of Rotations	Max Diam (mm)	Length (mm)
Speed (m/min)	0.16	0.28	-0.09	0.19
Feed (mm/rev)	-0.24	-0.51	0.02	-0.53
Lubrication (MQL vs. Wet)	-0.71	-0.51	-0.67	-0.39
Wear	-0.44	-0.28	0.20	-0.55

Within the parameters of the milling experiments, it is found that tool geometry (in this case, the lead angle), feed, lubrication, and depth of cut do influence chip geometry. However, there is a lack of correlation between speed and chip geometry. This is in accordance with observations from previous researchers. Kishawy [2005] found that in milling, cutting speed affected only the chip width for high speed machining of A356 aluminum alloy.

Shear zone height strongly correlates with the feed. Based on the geometry of milling, the feed rate should be directly proportional to the chip's thickness perpendicular to the face of the cutting tool (edge thickness). Therefore, if the shear height can be considered a fraction of the total width, then increasing the feed should increase the shear zone height. Similarly, the number of rotations of milling chips is most influenced by feed. Feed also correlates with edge thickness, as discussed above. This is probably because the increased edge thickness causes the chip to be less ductile (dislocations cannot travel to the surface as easily), thus it breaks more easily.

Milling chip weight is determined primarily by the depth of cut. In this experiment, a deeper cut produced thicker and longer chips, which are inherently heavier. This seems contrary to traditional chip breaking charts, where increasing the feed and depth of cut leads to broken chips; however, it is seen in these charts that increasing the depth of cut increases the chip length and decreases the diameter until breaking occurs. Until chip breaking occurs, it is likely that the chip mass increases. Additionally, the chip's width increases with depth of cut, because the chip width should theoretically be the DOC divided by the cosine of the axial rake angle (which approximately matches the experimental results).

The maximum diameter appears to be most influenced by lubrication. According to Jawahir [1993], this diameter of the chip likely occurs when the chip curls back and makes contact with the workpiece surface, creating a bending moment. This added force on the chip increases its diameter. The bending moment is about the point of the chip that is rigidly adhered to the workpiece, which is considered the shear zone by Jawahir. The presence of lubricant or coolant decreases the chip's ductility, which will inhibit the chip's ability to widen. Lubricant also decreases the tool chip contact length.

The minimum chip diameter has been studied by many researchers, and is often considered to be the diameter as the chip is first leaving the tool face. Although previous studies have shown the chip curl to be affected by lubrication [Kalpakjian, 1997] and DOC [Jawahir, 1993], it is unclear why these results were not seen in this study.

Drilling chips are reported to be most influenced by tool geometry [Ke, 2005], rather than spindle speed, feed, lubrication, or tool wear; this is in agreement with these studies.

5. CONCLUSION

Cleanliness of mechanical components has become a critical manufacturing objective. We have presented strategies to integrate cleanability as a new quality metric into the design to manufacturing cycle by exploiting the different levels of flexibility available throughout the cycle. At the highest level of flexibility, design heuristics in conjunction with cleanability simulation tools will allow product designers to evaluate design alternatives in the context of Design for Cleanability (DFC). A step lower in the flexibility scale, the choice of processes and setting of process parameters, among other manufacturing design decisions, need to be evaluated in terms of the cleanability process metric. In the realm of machining operations, our preliminary goal is to determine how to create a chip that is most easily cleaned from the workpieces. Based on our assumptions, a smaller and less curled chip has a reduced likelihood of becoming lodged, entangled, or wedged somewhere in the part. We show that a reduction in the depth of cut, an increase of the amount of lubrication used, and increased feed for milling, are more likely create this type of chip. However, in some applications it may be desirable to create larger chips, which are achieved through reduced lubrication, increased depth of cut, and reduced rake angle, in order to prevent chips from contaminating small, critical passageways.

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