EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF PROCESS PARAMETERS ON CHIP GEOMETRY FOR ENHANCED CLEANABILITY OF MECHANICAL COMPONENTS

Corinne L. Reich-Weiser and David Dornfeld
corinne@me.berkeley.edu
dornfeld@berkeley.edu

ABSTRACT

When a part is manufactured, different processing steps can introduce contaminants to the workpiece. One common form of contamination is the chips produced by machining, which often lodge in the crevices and pathways of the workpiece causing problems for both the accuracy of subsequent machining operations, and the usability of the part. To avoid such problems, it is important to both optimize the type of chip produced so it can be most easily removed from the workpiece, and to minimize the number of chips that remain. By varying process parameters such as feed, speed, depth of cut, and lubrication, some insight is gained as to how these parameters affect chip geometry and size. The results for drilling were mostly inconclusive, while the results for milling provided an important first step towards optimizing the chip form.

Keywords: chip formation, milling, drilling, cleanability.

INTRODUCTION

As the tolerances required for mechanical instruments become increasingly small, the requirements for contamination become more stringent. In a passageway that must be 2 microns in diameter, a stray piece of sand from a casting process, or a small chip remaining from the subsequent machining operations can be detrimental to the part's function.

Typical 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. These have an intricate maze of water and oil channels for cooling and lubrication purposes; when a machining chip travels into the maze during manufacturing, it becomes extremely challenging to remove. Current cleaning methods, including water jets and ultrasound, are ineffective for certain chip shapes that have a tendency to become firmly lodged in the passageways. However, these often release days or months into the use phase, causing premature failure. Figure 1 shows a chip found lodged in the valve that controls oil flow. Here the chip is blocking the valve's ability to close completely.

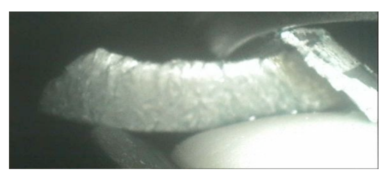

FIGURE 1. MILLING CHIP LODGED IN AN OIL VALVE.

This paper, on how chip geometry may be manipulated by varying key process parameters, is motivated by this growing problem. It is hoped that by understanding and controlling the chip form, only chips that are more easily cleaned from the part will be produced. The first step is to observe how parameters such as feed, speed, and depth of cut affect aspects of the final chip's morphology such as size, weight, and degree of straightness.

The study of chip formation is not new. Over the past century, researchers have sought to understand various material removal processes through both theoretical models and experiment. However, these researchers have mostly been interested in chip formation relative to optimizing the machining process while it is occurring. For example, many papers are interested in breaking the chip so it may be more easily moved away from the machining area to facilitate further machining.

The previous research is extremely detailed; however, the lack of focus on cleanability leaves it incomplete. In this paper chip formation and prediction is investigated with the interest of part cleanliness in mind. Thus, the measured aspects considered important about each chip were those thought to directly affect a chips likelihood of being caught in a part. It is the subject of additional research to determine exactly what the most cleanable chip is.

LITERATURE REVIEW

In 1993 a comprehensive overview of prior work on chip formation research was conducted by Jawahir and Luttervelt (Jawahir et al., 1993). Some of the relevant information from this paper includes previous work on understanding chip flow (up, side, and back), which can be used to understand the resulting chip geometry (figure 2). These researchers determined there is a good correlation between friction angle and side-curl angle, with individual variations of 0.5 to 2 degrees. The chip side-curl also appears to be influenced by the straightness of the cutting edge, the perpendicularity of the cutting edge to the direction of cutting motion (a lack of perpendicularity creates variations in the chip-compression rate along its width), and the presence of lubrication (which inhibits curl). Additionally, the chip back-flow angle can be approximately determined using slip-line theory. It is also noted that the mechanics of chip flow and curl vary with the depth of cut. In light of this previous research, this paper suggests that there is still work to be done to determine the most influential factors affecting a chip's up-curl, side-curl, and back-flow

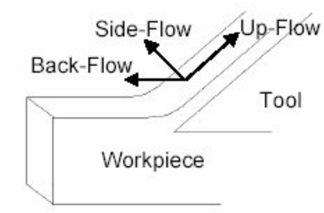

FIGURE 2. CHIP FLOW DIAGRAM.

In the fifteen or so years since Jawahir's review paper, many new strides in chip formation research have been achieved. This includes work on chip classification (Astakhov et al., 1997), who points out that the chip flow direction and causes of curl are unclear; but these must be understood so chips can be classified by their method of formation. Astakhov discusses previous efforts by Timme on chip fracture, Ernst and Merchant on the shear plane, Lee and Shafer on slip line theories for perfectly plastic material, Shaw, Cooke and Finnie on shear and friction inter-relations, Hill on the lack of a unique state of stress and strain in chip, and Okushima and Hitomi on discontinuous chip formation. Astakhov finishes by asserting how a radiused groove on the tool rake surface would initiate chip curl.

Ning et al. (2001) observed 4 chip types while ball nose end milling hardened steel: completely rolled chips, unstable chips, critical chips generated by chatter, and severe chips produced by too large a depth of cut. Interestingly, no adiabatic shear type chips were observed, which may be explained by the tool geometry or work material. In 2001, Fang et al. confirmed and explained previous assertions that chip formation problems have a non-unique solution, by discussing and refining Dewhurst's universal slip-line theory involving a plane-strain rigid-perfectly-plastic material. The non-uniqueness of this problem comes from the 4 equations (balance of forces in two directions; moment balance; tool-chip contact length), and 5 unknowns (4 slip-line field angles and the hydrostatic pressure where the workpiece outer surface meets the chip).

Recently, work on chip formation has turned towards micro machining (Jackson, 2005). Jackson observed tight curled chips in the short regime of machining before the secondary shear zone develops. Because it is micro machining, this model includes the effect of tool bending; a new development in chip formation modeling.

Additionally, Jackson's theory states that the primary chip curl is greatly affected by the presence of BUE, which agrees with earlier assertions that the tool tip shape/radius greatly affects chip flow.

It is important to note that in addition to theory and experiment on chip formation, researchers have begun to use finite element analysis as a prediction tool, where the material is modeled as elastic-plastic (Mamalis et al., 2001). In the work of Mamalis, there was no comparison of chip shape with experiment, however a final comparison of cutting forces proved the model successful. It can be argued that cutting forces affect the final chip shape; thus, this FEM is only a few steps away from predicting chip form.

Chip formation is closely related to burr formation; in many cases a burr is a chip that has not left the workpiece. Although the mechanics of formation of chips and burrs can be very different, it is important to combine knowledge of both to optimize the cutting conditions. Important work on burr formation and minimization (size, location, shape, etc.) has been done by Dornfeld and co-workers (Ávila et al., 2005) and others. Loose burrs are treated here as chips due to many similarities in size and shape.

EFFECT OF MACHINING PARAMETERS ON CHIP MORPHOLOGY AND CLEANABILITY

The previous efforts on controlling, classifying, and predicting chips are the first steps toward understanding chips to reduce their impact as a contaminant; however, previous research doesn't consider how the remaining chips will affect the function of the final part, assuming that once the machining operation is complete, any remaining chips can be easily removed.

As a first step to address this issue, it was desired to discover which of the following have the greatest impact on chip formation: feed, speed, lubrication, or DOC. From this information, simpler models of chip formation may be developed for use in industry to control chip geometries and sizes.

Experimental Procedure

Both milling and drilling were performed to mimic conditions within the DaimlerChrysler powertrain factory in Stuttgart, Germany. All chip types produced by each experiment were investigated, because they are all present under true machining conditions. Machining was done on sand-cast aluminum alloy AlSi7Mg used for DaimlerChrysler's cylinder heads using both a worn tool and a new tool from the production line. The machining operations were conducted and planned by technicians and researchers from DaimlerChrysler.

The experiments conducted were milling with a 125mm diameter tool, 6 PCD inserts, wet and dry cutting, 1500 and 3000 m/min speed, 0.1 and 0.2 mm/tooth feed, and 0.5 and 2mm depths of cut; and drilling with a 12mm diameter carbide tool (with lubrication holes in the tip), new and used, MQL and wet, feeds of 0.15 and 0.3 mm/rev, and speeds of 188 and 377 m/min.

These chips were collected in a bin placed below the machined surface, and carefully poured into plastic bags for later analysis.

Because the main goal of this research is to better understand how variations of cutting parameters affect the chip form so it can be controlled for optimum cleanability, it was imperative to measure aspects of the chips that might affect their cleanability. To this end, the following aspects of the chips were measured: wavelength, width, length, maximum and minimum diameter, and the height of the "teeth" (i.e. ridges produced by localized shear); see Figure 3.

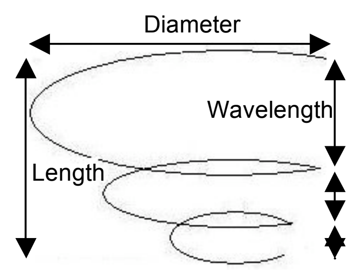

FIGURE 3. SOME CHIP GEOMETRY MEASUREMENTS.

It was first noticed that given a single set of cutting parameters (feed, speed, depth of cut), approximately five different chip sizes/geometries were produced. This is understandable given the sensitive nature of the process. For example, slight variations in the machine vibrations or the material properties could produce variations in the chip. Additionally, newer models of chip formation, which use slip-line theory, propose that the final chip shape is nondeterministic (Jawahir et al., 1993).

To accurately represent the output of each machining operation, the chips were divided into categories by size and shape (Figure 4). These were then weighed and counted so it could be said that for one machining operation, x-percent of the output corresponded to a y-type of chip.

FIGURE 4. DRILLING AND MILLING CHIPS SORTED BY SIZE AND SHAPE.

Experimental Results & Analysis

As seen in Figure 4, for each individual experiment, there were multiple outputs. To rectify these into a single measured output for each input, the results were averaged based on the number of each type of chip. For example, if there were 8 chips of length A and 2 chips of length B, then the result of that experiment would be chips of length [0.8(A) + 0.2(B)].

There was also the option to average the results based on the weight of each chip type. For example, if all the chips of length A were a combined weight of 3 grams, and all the chips of length B were a combined weight of 7 grams, then the final length would be [0.3(A) + 0.7(B)]. However, the data presented in this report was not averaged by weight, but by number as discussed above. This prevents one large chip from greatly skewing the data of many small chips.

Milling. By varying the speed, feed, lubrication (dry or wet), and depth of cut (DOC), a wide variety of chip sizes and shapes were created. To describe these chips, the weight, rotations (for example figure 1 has 3 complete rotations), maximum diameter, minimum diameter, length (maximum distance across the chip), width, wavelength and average shear "tooth" height were measured.

From this data, the correlation between varying the input parameters and the outputs were found mathematically. The results of this are seen in Table 1. Here, the values that show a significant correlation are highlighted. Due to the inaccuracies of data measurement, and the problems inherent to averaging many data points, a statistical correlation of greater than 80% (greater than 0.8 or less than -0.8) was considered noteworthy.

TABLE 1. MILLING CORRELATIONS.

	Weight	Rotations	Max Diam	Min Diam	Length	Tooth Height
Speed	-0.33	-0.41		-0.35	-0.55	-0.34
Feed	0.67	-0.80		0.83	-0.50	0.85
Lubrication	-0.61	-0.90	-0.86	-0.18	-0.70	
DOC	0.89	-0.41	0.48	0.39	0.92	

The first thing to notice from this data is the lack of correlation between speed and each of the measured parameters. This is not an obvious result, because the speed should affect the temperatures and thus the material properties. Perhaps, because the cutting process is so fast, the chip does not have time to absorb the process heat, and so it is not affected by the increased speed.

Although it is not shown in Table 1, the data also showed a direct 100% correlation between the chip's thickness and the depth of cut. In theory, the chip width should be the DOC divided by the cosine of the axial rake angle; so this direct correlation was expected.

To control weight, it makes sense that the depth of cut is the factor of primary importance. A deeper cut will produce thicker and longer chips (as evidenced by the data), which are inherently heavier.

The number of rotations seen on each chip is influenced by how long a chip has to form before breaking and how much it curls (i.e. diameter). Previous research at UMIST has shown chip flow angle to increase almost linearly with feed (Jawahir, 1993), where this affects the initial or minimum radius of curvature (in agreement with above results). The data indicates that if the feed decreases, the minimum diameter decreases, and the number of rotations increases. Here, lubrication also plays an important role in the rotations by minimizing the appearance of built up edge on the tool tip, which would alter the tool shape. Wang and Mathew showed a strong relationship between chip flow angle, tool nose radius, and edge inclination (Jawahir, 1993).

The maximum diameter also appears to be most controlled by lubrication. The maximum diameter is considered by researchers to occur at the end of the chip formation process when the chip contacts the workpiece surface. The chip is described as a rigid beam that curls away from the tool and contacts the workpiece surface creating a bending moment with a non-rigid base (the shear zone). This bending moment serves to widen the chip's diameter. It is unclear at this time why lubrication decreases the maximum diameter.

Chip length correlates well with the depth of cut. This can be explained by a reduced curvature as the chip leaves the tool; thus, there is a longer time until the chip contacts the workpiece and fractures. Additionally, a thicker chip is stronger against fracture (however, a very thin chip will be very ductile because the dislocations within the material can easily travel to the surface, implying there is an optimal chip thickness to be found where it will be most easily broken).

The shear zone height (i.e. teeth height), appears to be correlated with the feed; teeth are shown in Figure 5. Based on the geometry of milling, the feed rate should be directly related to the chip's width perpendicular to the face of the cutting tool. Therefore, if the tooth height can be considered some fraction of the total thickness, then increasing the thickness should increase the height.

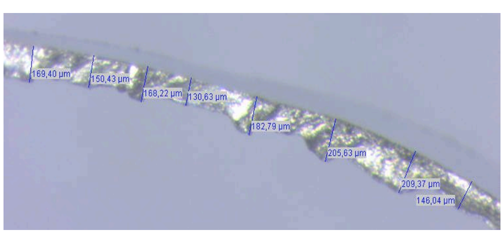

FIGURE 5. "TEETH" ON A MILLING CHIP.

Drilling. For the drilling experiments, the speed, feed, lubrication (minimum quantity lubrication (MQL) or wet), and tool wear were varied to see the affect on the chip's weight, rotations, maximum diameter, and overall length.

TABLE 2. DRILLING.

	Weight	Rotations	MaxDiam	Length
Speed	0.16	0.28	-0.09	0.19
Feed	0.81	0.57	0.61	0.55
Lub.	0.71	0.51	0.67	0.39
Wear	0.44	0.28	-0.20	0.55

The correlations seen here are inconclusive, except for that between the feed and the weight. In the case of drilling, the feed is similar to the depth of cut in milling; thus, it makes sense that here feed would affect weight just as DOC affected weight for milling.

CONCLUSION

This research was proposed with the goal of determining how to create a chip that is most easily cleaned from a part after all the machining is complete. Based on the assumptions of this researcher, a smaller and less curled chip has a reduced likelihood of becoming lodged or wedged somewhere in the part. Based on the data presented in this paper, the best way to create this type of chip is with a reduced depth of cut, increased lubrication, and increased feed for milling, assuming rotations are likely to cause entanglement, and the minimum diameter is overshadowed by the maximum diameter in a crevice.

This research is just the start to understanding how process parameters affect the complete final chip geometry. With these in place it is possible to conduct further experiments, which may focus on the process parameters deemed most influential. Additionally, much research is required to establish what aspects of the chip determine if it will be a problem for the component cleanliness or not. This may include research on drag, adhesion, and various methods of cleaning (including the current method of water jet blasting)

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