Modeling of Chip Dynamics in Drilling

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Abstract
Drilling is a major operation for many companies; in fact, one engineer in an automotive company recently said, "We are not a manufacturing company, we are a hole making company!" Approximately 60% of their manufacturing processes is drilling. Despite the importance of drilling to manufacturing, the formation of the chip and the dynamics of the chip is still least understood of all cutting processes. In this paper, a discussion of drilling chip formation is supported with physical experimentation. While drilling is not an orthogonal machining operation, this discussion builds on a foundation of chip formation from orthogonal machining. Furthermore, these observations are extended to understanding flute transport.

Introduction:
Chips, machining swarf and cutting fluids are the major waste by products of machining operations. Chips are unavoidable since a certain amount of material must be removed during the machining process. Researchers in environmentally conscientious manufacturing initially focus on cutting fluid reduction; however, they soon learn that chips and machining swarf become problematic in the absence of cutting fluids. In high volume production, cutting fluids are often used for a secondary role of removing the machining offal away from the cutting zone and the machine tool. In the absence of cutting fluids, this secondary function is lost and alternative means are necessary for chip removal and transport. Therefore, it is essential to understand the formation of the chip and the dynamics that are imparted to the chip to develop effective chip collection and transport systems. In this paper, the major concern is continuous chips in drilling operations since these pose the greatest problems for manufacturers.

The development of mechanisms for chip removal begins with an understanding of the chip morphology and the dynamics of the chip following creation until the time the chip comes to rest. The study of chip creation and morphology has been an active research topic. Fisphanen (1948) commented on chip formation in the late 1940's. Both Stabler (1951) and Cowell (1959) in the 1950's presented geometric models of chip formation. Oxford (1955) discussed drilling mechanics. Pekelharing (1964) attempted to explain why chips break in the CIRP Annals in 1964 by showing how small forces influence chip curvature. Spans (1971), Pekelharing's student, studied the fundamentals of chip control. Kahng and Koegler (1976) examined chip breakage in drilling operations. Significant study of the chip formation process was performed by Nakayama (1962,1963, 1972, 1978) in the 1960's and 1970's with efforts looking at restricted contact lengths and material properties. The theory of plasticity as a means for modeling chip formation was used by Zorc (1963, 1966), Kudo (1965), Childs (1972), Dewhurst (1978), Oxley (1988) and Liu (1995).
Zarev's book, *Metal Cutting Mechanics*, remains a classic in the study of chip formation today. Strenkowski (1990) used finite element modeling to understand chip formation. Modern research includes analytical models presented by Fang and Jawahir (1996). Jawahir and van Luttervelt (1993) also looked at modern methods for chip control. As can be concluded from this brief review of the literature, the problem of chip morphology and chip dynamics is a continuing subject for serious research.

**Orthogonal Model Considerations**

Our basic understanding of chip dynamics in drilling begins with the chip dynamics of the orthogonal model. There are three major observations which affect the dynamics of metal cutting chips. The first is the velocity of the chip due to chip growth. Because the metal cutting process is considered isochoric (volume preserving), the tangential velocity of the chip is proportional to the cutting velocity. If one assumes no widening of the chip from its undeformed width, then the tangential velocity can be expressed as

\[
    v_c = \frac{v_{cut} t_c}{r} = \frac{v_{cut}}{r}
\]

where \( v_{cut} \) is the cutting velocity,

\( t_0 \) is the undeformed chip thickness,

\( t_c \) is the chip thickness,

and \( r \) is the cutting ratio.
The second observation is that chips curl away from the tool rake face under most cutting conditions. The traditional orthogonal cutting model is used an initial approximation of the formation of the chip. In this model, it is assumed that one can ignore the motions of material parallel to the cutter edge. The traditional model assumes that shear takes place along a flat plane extending from the tool nose to the outer apex of the chip and workpiece. This assumption requires that for material continuity that the chip does not curl. In order to understand chip morphology, one must abandon the concept of the shear plane used in elementary force analysis for a model in with the shear zone has definitive thickness and consists of a primary region and a secondary region. The primary shear zone approximately includes that region about the traditional shear plane. The secondary shear zone is a near triangular zone that extends from the tool nose into the workpiece and up the workpiece along the tool rake face. While the shear zone edges in Figure 1 have been approximated by lines, one should not assume that these edges are linear.

The mechanisms for chip curl are not fully understood and therefore frequently debated. Whatever the mechanism, however, the cause for chip curl must occur either in the shear zones or very near to the shear zones. Hahn [1953] showed that residual stress is not a cause of chip curl. He is quoted at the source for the statement “chips are born curled.”

The force free body diagrams can be drawn as shown in Figure 2. Continuing the analysis in this manner soon leads to problems which, at this time, are insurmountable. The system as presented is indeterminate. Thus a knowledge of the material mechanics is necessary to solve this problem. A constitutive equation for a metal under the strain rates and energy conditions of machining is still unknown. However, it is clear from the free body diagrams that the forces on the chip and particularly those that cause the chip to curl are dependent upon the material behavior in the secondary shear zone.

It is clear that both normal and shear stresses exist on the tool face. The normal stress was modeled by Childs and Madhi [1989] as

$$\sigma_n = \sigma_{max} \left(1 - \mu e^{k x / t_c}\right)$$

where $\sigma_n$ is the normal stress,

$k$ is a "saturated friction condition" shear stress,

and $\mu$ is the friction coefficient.

Finnie and Shaw [1956] and Usui and Shiraskashi [1982] suggested that the shear stress had an exponential character:

$$\tau = k \left(1 - e^{-\mu \sigma_n / k}\right)$$

which appears to model the split tooling results of Kato [Kato, et. al, 1972], Figure 3, reasonably well. The normal stress is measured along the tool face. The flat region particularly evident on the aluminum curve agrees with the stick region of a stick-slip friction model for tool face friction.

Where built up edge (BUE) conditions exist, the BUE further complicates the geometry of the shear zones, the computations of stresses and the resulting computation of forces. BUE is clearly a factor in chip dynamics. Nakayama [1963] showed that BUE takes a triangular shape which is consistent with the path of chip curvature.

The third observation is that continuous and semi-continuous chips appear to break where the bending moment is maximum on the thinnest part of the chip. Using the orthogonal model, a bending moment may be placed on the chip through several mechanisms. In an unobstructed state, the curl of the chip may cause the chip to rotate until it strikes the work after a rotation of nearly 180 degrees. Depending on the angle of contact, the forces imposed at this point and the material conditions of the chip, the instantaneous chip velocity with respect to the cutting edge may either increase or decrease (motion away from the tool edge or towards the tool edge.)
Figure 2: Force Free Body Diagrams

To better understand these processes, a set of orthogonal machining experiments were designed and filmed using high speed photography. Using a Cincinnati Milacron 8C Series 1208 CNC lathe, large diameter disks of tool steels L6 and O1 were fixtured to a mandrel and machined radially with a tool wider than the disk. Machining conditions are given.
in Table 1. A total of 45 experiments were conducted for each material. The cutting and thrust forces of the experiments were recorded using a AMTI model MCL6-6-2000 dynamometer.

<table>
<thead>
<tr>
<th>Condition</th>
<th>L6</th>
<th>O1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (sfm)</td>
<td>300/550/800</td>
<td>300/550/800</td>
</tr>
<tr>
<td>Rake (deg)</td>
<td>-10°/5°/5°/10</td>
<td>-10°/5°/5°/10</td>
</tr>
</tbody>
</table>

The shear stresses for these experiments were analyzed and can be found in Batzer (1998); however, these results are not particularly germane to drilling conditions and are therefore not replicated here.

The photographs in Figure 4 are representative of the macro-chip breakage processes. If the motion of the chip is away from the tool, the chip will take increasingly larger radius as the chip grows. This results in the formation of the “ear” shaped chip. If the motion is toward the tool edge, the chip will attempt to form a helical spiral with the free edge to the center of the chip. In doing so, the free edge is forced initially to shorten its natural radius of curvature. However the continuing growth of the chip, the forces at the point of contact and the forces resisting bending of the coiled chip will cause the new material to take a larger radius. The larger radius artificially increases the contact length at the tool chip interface which leads to increased heating of the chip due to friction with the tool. This is evident experimentally by the residual tempering color of the chip. The location of the point along the chip of greatest bending moment depends on the forces present at the point of contact of the chip. If the frictional forces at this location are small, the greatest bending moment will occur near the root of the chip resulting in chip breakage. If however the frictional forces at the point of contact are great, the point of maximum bending moment will occur midway along the outside loop of the chip causing failure along the exterior loop. This is useful in understanding the failure mechanisms of both fan shape and conical shape drilling chips despite the added complexities of the drilling configuration.

Figure 3: Compressive Stress Distribution (After Kato, et al.)
Drilling Chips
The drilling operation is different than that of orthogonal machining for the following reasons:

a) Most orthogonal cutting analyses consider the cutting velocity across the cutting edge as constant. In drilling the chip formation process is complicated by the radial changes in velocity. At the very center of the drill, theoretically, the cutting velocity is zero. The velocity then increases linearly to the outside edge of the drill. The parameters in modeling the cutting velocity include the rotational speed of the drill and the point angle.
b) Orthogonal models of cutting assume only one mechanism in the chip formation: that of shearing in near planar shear zone. Drilling has two distinct chip formation processes: the first is an extrusion process caused by the wedge point of the drill and a shearing operation caused by the cutting edge of the drill. See Figure 5.

c) Orthogonal models of obstructed chip formation limit chip formation using a planar obstruction but allow the radius of the chip to grow freely except as constrained by the planar obstruction. A major factor in chip formation and breakage in drilling is the added obstruction caused by the limitations of flute space. Unlike other machining operations, the chips in drilling are contained within the flutes for a significant period of time before ejection. Free radial growth is not permitted.

Drilling Experimentation, Analysis and Discussion

These differences were reflected in a set of experiments designed to characterize the factors which affect drilling operations. The drilling experiments were performed with 5.5 mm diameter drills on a Fadal CNC 88HS vertical mill which was instrumented for recording forces and fluid flows. The test plans are represented in Tables 2 and 3. The work material were aluminum alloys 308 and 390. The chips were collected from each test for analysis. The drills were new drills and wear was not a factor. Cutting fluid where indicated was a water soluble oil of the indicated concentration. Flow rate was approximately 330 cm³/sec at a pressure of 44 kPa.

Since the formation and the breakage of the drilling chip is hidden from view, high speed photography of the processes are not available. However, post testing qualitative analysis of the chips was conducted and is herein reported. The analysis of the chips revealed the following: the significant factors in chip formation are the drill type, the feed and the work material. Feed was the single most significant factor affecting chip size and its mass. An increase in feed resulted in larger chips. These chips also had greater strength which delayed chip breakage. While not tested in these experiments, excessive feed results in reduced flute transport of the chips and is an imminent factor in drill breakage.

Drill type resulted in the formation of different shapes of chips. In particular, the straight fluted drill resulted in an undesirable long chip with inconsistent curl and breakage. The helix fluted drills all produced conical chips, and fan chips described below. Drill type 4, a carbide drill with a medium helix had a longer cutting edge and resulted in wider and thinner chips which appear to be readily broken. The parabolic flute drill had greater flute volume and permitted larger chips to pass unbroken to the hole surface.
Table 2: Test Variables for Each Experiment Design

<table>
<thead>
<tr>
<th>Design</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
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<tbody>
<tr>
<td>Type</td>
<td>$2^4$</td>
<td>$2^7$</td>
<td>$2^5$</td>
<td>$2^6$</td>
<td>$2^4$</td>
<td>$2^4$</td>
<td>$2^4$</td>
<td>$2^4$</td>
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<tr>
<td>Cutting Fluid</td>
<td>Off / 8%</td>
<td>Off / 8%</td>
<td>Off / 8%</td>
<td>Off</td>
<td>Off / 2%</td>
<td>Off / 8%</td>
<td>2% / 8%</td>
<td></td>
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<tr>
<td>Drill Type</td>
<td>1</td>
<td>1 / 2</td>
<td>3</td>
<td>4 / 5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Work Material</td>
<td>308</td>
<td>308 / 390</td>
<td>308 / 390</td>
<td>308 / 390</td>
<td>308 / 390</td>
<td>308 / 390</td>
<td>308 / 390</td>
<td>308 / 390</td>
</tr>
<tr>
<td>Feed (x.001&quot;/tooth)</td>
<td>1.5 / 3</td>
<td>1.5 / 3</td>
<td>1.5 / 3</td>
<td>1.5 / 3</td>
<td>1.5 / 3</td>
<td>1.5 / 3</td>
<td>1.5 / 3</td>
<td>1.5 / 3</td>
</tr>
<tr>
<td>Depth (diameters)</td>
<td>2 / 4</td>
<td>2.5 / 4.5</td>
<td>2.5 / 4.5</td>
<td>4.5</td>
<td>4.5</td>
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<tr>
<td>Overhang (mm)</td>
<td>50</td>
<td>45 / 50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>-70 / 100</td>
<td>25</td>
<td>25</td>
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</tr>
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</table>

Table 3: Drill Geometries and Materials

<table>
<thead>
<tr>
<th>Drill Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
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<tr>
<td>Diameter (mm)</td>
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<td>5.7</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Material</td>
<td>Carbide</td>
<td>Carbide</td>
<td>HSS</td>
<td>Carbide</td>
<td>HSS</td>
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<tr>
<td>Helix</td>
<td>High</td>
<td>Straight</td>
<td>Parabolic High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Flutes</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Point Angle</td>
<td>140°</td>
<td>135°</td>
<td>135°</td>
<td>118°</td>
<td>135°</td>
</tr>
<tr>
<td>Point Style</td>
<td>S</td>
<td>Straight</td>
<td>Split</td>
<td>Straight</td>
<td>Straight</td>
</tr>
<tr>
<td>Drill Profile</td>
<td><img src="image1" alt="Drill Profile 1" /></td>
<td><img src="image2" alt="Drill Profile 2" /></td>
<td><img src="image3" alt="Drill Profile 3" /></td>
<td><img src="image4" alt="Drill Profile 4" /></td>
<td><img src="image5" alt="Drill Profile 5" /></td>
</tr>
</tbody>
</table>

The higher silicon aluminum alloy (SAE 390) had lower ductility and consistently resulted in smaller and better broken chips than did the SAE 308 alloy. This was particularly evident where the medium helix carbide bit was used.

There are essentially eight types with six of the types represented in Figure 6. The seventh type is a dust-like chip most likely formed during chip breakage processes and later damage as the chips move up the flute. The eighth type (long pitch helix) was not observed in our experiments although these have been experienced in other testing. The long pitch helix is a generally flat continuous chip that follows the helix pitch of the flute. This chip is probably caused under conditions where the natural chip curl radius is larger than that forced on the chip by the flute helix.

The conical chip type was present in all experiments with the exception of those conducted with bits with no helix in the flute (straight fluted drills). When conical chip breaks at the cutting edge, subsequent chips have the fan-shaped characteristic. In addition, fan chips are also created when the radius of the cone exceeds the flute cross sectional di-
Figure 6: Drilling chip shapes:
A: Conical, B: Fan Shaped, C: Chisel Edge, D: Amorphous, E: Needle, F: Impacted

tance. The amorphous chip was formed with drills with no helix. The chips did not have a consistent chip curl radius and were guided unbroken up the drill flute. Needle chips resemble fan like chips but smaller. It is postulated that these chips are formed by a built up edge on the drill. The impacted chips are the result of fan chips and conical chips being damaged as they are force up the drill flute. Damage mechanisms include the production forces of the new created chips below, the forces caused by the delay, and jamming of the chips above the reference chip, frictional forces of rubbing against the flute and hole sidewalls and the welding to both the drill and the hole sidewalls. Generally, impacted chips indicate that the flute transport of chips is degrading and that the surface roughness of the sidewalls is also deteriorating.

Several types of chips were generated under each testing condition. This is consistent with the creation mechanisms of drilling chips. Because of the extrusion zone at the point of the drill, we expect to see the chisel edged chips regardless of cutting conditions. However, these chips may be transformed or otherwise absorbed into other types of chips.

At the present time, no quantitative model, known to the authors, represents the formation, breakage and subsequent motion of drilling. However the following comments are offered on the dynamics of chips in drilling operations.

Critical importance must be given to flute transport. Unlike open machining operations which allow the chip to escape the cutting region, the drilling chip loads the drill flute and must be pushed to the hole surface by subsequently cuttings. The major factor in flute transport is the available area and volume of the flutes. The area of the flutes can be estimated by partition the flute area into four distinct regions. See Figure 7. The greater this area is filled by cut chips, the more likely the flute will jam with incipient drill breakage. The conical chip and the amorphous chip type results in a more volumetric chip and is therefore more likely to cause jamming of the flute. This was evident where drill breakages did occur.

A second factor in flute transport is centripetal force put on the chips caused by the drill rotational speed. This has the tendency for forcing the chips to the sidewalls of the drilled hole. Where the chips are strain hardened, this will cause the sidewalls to marred. In addition, if a cutting fluid is not used or is ineffective, the heat of the chip and the increased frictional energy of the chip dragged along the sidewalls may result in the chips welding to the sidewall causing high torsional stresses on the drill. This was observed in scanning electron micrographs of sidewalls in the
experiments. This is amplified if the chips are more massive such as in the case of amorphous chips and aggregated impacted ship as greater forces are created by the centripetal force.

The velocity of the flute transport depends upon the rate at which chips are produced and the volume filling of the chip produced. In general, one can expect some packing of chips in the flutes. As a result the relative motion of the chips in the flutes is less than the production rate of chips. The mean flute velocity of the chips is the chip velocity at the cutting edge multiplied by the packing ratio. Because of the force effects including welding mentioned above, the flute velocity will vary.

Based on the observation of the chip damage, it is likely that the smaller chips tumble in the flutes; however conical chips and the slow pitch helical chip tend to ride the flute without tumbling. Where, these chips do tumble in the flutes, they are likely to be converted into impact type chips.

Conclusions

Drilling is a major operation for many companies; in fact, one engineer in an automotive company recently said, "We are not a manufacturing company, we are a hole making company!" Approximately 60% of their manufacturing processes is drilling. Despite the importance of drilling to manufacturing, the formation of the chip and the dynamics of the chip is still least understood of all cutting processes.

This paper discusses the formation of drilling chips and supports the discussions with observations from physical experimentation. We conclude that a description of the dynamics of drilling chip formation is still qualitative although what is known can be applied to modeling flute transport. Quantitative dynamics of drilling chips is still an area of further research. At least part of the problem is the inaccessibility of direct observation. Because of the varying velocity along the cutting edge, drilling chips have a side curl that can not be understood from the orthogonal model. Research of side curl models from oblique cutting has yet to be fully developed and has yet to be applied to the conditions of drilling.

References


Batzner, S. A., J. W. Sutherland and W. W. Olson, "Chip Morphology and Bending Moment Models for Orthogonal


Appendix: Computation of the drilling flute area

The following assumptions are used in computing the flute area:

a) the lip is a straight edge
b) the lip is tangent to the heel
c) the heel is a circular cross section in a plane normal to the drill axis
d) the area of the flute is measured in a plane normal to the drill axis
e) the drill margin area can be neglected in the computation of flute transport area.

The flute area is subdivided as shown in Figure A1. The lip edge must be projected to a plane normal to the drill axis for the length 1:

\[ l = l_1 \sin \left( \frac{\theta}{2} \right) \]

Referring to Figure 2. The area of region 1 is the difference between the sector of region 1 and a triangular piece formed by the point radius, \( w \), the lip edge, \( l \), and the drill radius, \( r \). Letting \( \alpha_1 \) be the angle that subtends the sector of region 1, by the law of cosines,

\[ \alpha_1 = \arccos \left[ \frac{l^2 - r^2 - w^2}{2rw} \right] \]

Then the area of region 1 is

\[ A_1 = \text{area of the sector of } \alpha_1 - \text{area of triangle } w-r-l \]

\[ = \frac{r^2\alpha_1}{2} - \frac{rw \sin(\alpha_1)}{2} \]

The areas of region 2 is computed similarly. As in region 1 is defined by the law of cosines

\[ \alpha_3 = \arccos \left[ \frac{r^2 - l^2 - w^2}{2lw} \right] \]

The interior angle of region 1 is therefore \( \pi - \alpha_3 \). The side of region 2 opposite region 1 is defined by a line from the end of the lip edge thru the center point for the heel radius to the outer drill circle edge. Because of the assumption that the heel is tangent to the lip edge, this side line must be perpendicular to the lip edge. Therefore the interior angle region 2 is \( \alpha_3 - \pi/2 \). The edge length, \( d \), for region 2 is defined by

\[ d = l \times \tan \left( \alpha_3 - \frac{\pi}{2} \right) \]

By the law of cosines the interior sector angle, \( \beta_1 \), is defined by

\[ \beta_1 = \arccos \left[ \frac{d^2 - r^2 - w^2}{2rw} \right] \]

The area of region 2 is then:

\[ A_2 = \text{area of the sector of } \beta_1 - \text{area of triangle } w-r-d \]

\[ = \frac{r^2\beta_1}{2} - \frac{rw \sin(\beta_1)}{2} \]
Figure A1: Basic definitions

Region 3 is a sector based on the heel radius, \( r_h \). The distance from the drill axis to the center point of \( r_h \), the radial, \( r_d \), can be found by

\[
r_d^2 = w^2 + r_h^2 - 2wr_h \cos(\beta_3)
\]

\[
\beta_3 = \acos \left[ \frac{r^2 - d^2 - w^2}{2dw} \right]
\]

It can be shown that the angle subtended by the sector of region 3, \( \gamma \), is

\[
\gamma = \gamma_1 + \gamma_2
\]

\[
\gamma = \acos \left[ \frac{r_d^2 - r_h^2}{2r_dr_h} \right] + \acos \left[ \frac{w^2 - r_d^2 - r_h^2}{2r_dr_h} \right]
\]

resulting in the area for region 3

\[
A_3 = \frac{r_h^2 \gamma}{2}
\]

The area for region 4 is found in a manner very similar to regions 1 and 2:

\[
\delta = \acos \left[ \frac{\Delta^2 - r_d^2}{2rr_d} \right]
\]

\[
A_4 = \text{area of the sector of } \delta - \text{area of triangle } r-r_d-r_h
\]

\[
= \frac{r^2 \delta}{2} - \frac{rr_d \sin(\delta)}{2}
\]

2C7-14
Figure A2: Delineation of Regions

The total flute area is the sum

\[ A = \sum_{i=1}^{4} A_i \]
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