AN EXPERIMENTAL INVESTIGATION OF CHIP MORPHOLOGY IN DRILLING

Stephen A. Batzer, Praveen D. Rao, Deborah M. Haan, Walter W. Olson
John W. Sutherland
Department of Mechanical Engineering-Engineering Mechanics
Michigan Technological University
Houghton, Michigan

ABSTRACT
U.S. manufacturers are finding themselves under increasing pressure to limit their environmental impact. One of the waste streams produced by industry is used cutting fluids which require treatment. The effects of cutting fluid and other process variables on chip morphology when drilling cast aluminum alloys are investigated. The effects of material, speed, feed, depth of cut, cutting fluid presence and oil concentration, temperature, drill type and overhang were studied using statistically designed experiments. The measured responses of the drilling process were the size and shape of the generated chips and the surface finish of the hole produced. The results show that the significant variables include the feed, material, drill type and the cutting fluid.

INTRODUCTION
Current government and consumer attention to the environmental friendliness of products and processes has forced manufacturers to reduce the volume and toxicity of their waste streams. Virtually every manufacturing step undertaken to transform a raw material into a finished good has an associated waste stream. These waste streams are significant in quantity, inconvenient and expensive to dispose of, and harmful to the competitiveness of any domestic manufacturer.

Neglecting heat and vibration, the drilling process has three associated wastes streams. They are chips, worn tooling and cutting fluids. The first two, chips and tooling, are routinely recycled. Chips can be melted down, refined, and returned to the same manufacturer or other industrial consumer for re-use. Drill bits, being made of high speed steel (HSS) or carbide, also retain value for recycling. Cutting fluids, however, do not retain value to the manufacturer. In fact, the cost of their disposal often exceeds the cost of purchase. A recent study of German industry found that cutting fluid systems cost the typical high production manufacturer four times as much as cutting tools [Cselle, 1995].

Dry machining is one option to reduce cutting fluid use. An important function of the fluid, however, is to help flush the chips out of the flutes. With increased understanding of the mechanics of chip generation and transport mechanisms, cutting conditions can be specified which produce chips of the proper size, reducing the need for a flushing medium.

CHIP MORPHOLOGY
Currently, chip shapes are determined experimentally rather than predicted analytically. There have been numerous studies in determining the influence of process variables on the geometry of the chip [Shi and Ramalingam, 1993; Worthington & Redford, 1973]. Work has been done on developing finite element models for the cutting process [Usui and Shirakashi, 1982; Strenkowski and Carroll, 1985; Shih, 1998], but more work needs to be done in developing models which show the metal removed going through secondary deformation on the tool rake face, side and upward curl, obstruction and finally fracture. This process cannot be completed for drilling until all process variables affecting chip size and shape have been identified.

For drilling, small, well broken chips are desirable for
their ability to efficiently move along the flute and get out of the hole. The chips rotate with the drill and impact the walls of the hole or the interior of the flute. This impact produces a bending moment in the chip. Once the bending moment causes the chip’s maximum tensile strength to be exceeded, it will fracture.

For this analysis, chip size was chosen as the response variable since it is one of the primary determinants of maximum material removal rate. This is because as the material removal rate increases and the chips become too large, they cannot efficiently move through the flutes, increasing torque requirements, and perhaps causing drill breakage. Thus chip size/shape is being studied in order to identify conditions that promote chip evacuation.

CHIP TRANSPORT / FLUTE GEOMETRY

Often in drilling a conical chip is developed at the initial contact of the drill and the workpiece. The hole walls are not yet of sufficient height relative to the point of the drill to adequately constrain the chip. This conical chip rotates with the drill and eventually is constrained by the flute/hole volume. If the chip is not sufficiently small or flexible enough to follow the flute cavity, it will fracture. Chips created after this fracture will also not be able to follow the flute, or may be only able to stay unbroken for a small number of revolutions. Thus, the process creates two chip types. The first, the transient chip, is the conical chip created prior to the first fracture. The second, the steady state chip, is the subsequently created fan type chip [Kueter, 1995].

The flute is described by the intersection of the outer surface of the drill (the margin) and the heel and face radii, as shown in Figure 1. The geometry of the flute affects the chip curl and shape. It is necessary to balance the chip formation and transport characteristics of a drill with the strength of the drill in torsion. The cross sectional area \( A_0 \) of a drill, with outer radius \( R_m \), is equal to the nominal area, \( \pi R_m^2 \), less the volume of the two (or more) flutes. In general, the torsional strength of the drill increases as \( A_0 \) increases.

The following equations assume that the heel and face radii come together at a common tangent point at the thinnest diameter of the drill, the web. Neglecting the diameter reduction for the margin relief, the cross sectional area of a two flute drill is equal to:

\[
A_D = \pi R_m^2 - \int_{x_H}^{x_F} \left( y_m - y_f \right) dx = \int_x^{x_H} \left( y_m - y_f \right) dx
\]

The three curves, margin, heel and face, are described by the equations:

\[
y_m = \sqrt{R_m^2 - x^2}
\]

\[
y_f = R_f + R_w - \sqrt{R_f^2 - x^2}
\]

\[
y_H = R_H + R_W - \sqrt{R_H^2 - x^2}
\]

\[
y_F = R_f + R_W - \sqrt{R_f^2 - x^2}
\]

(4)

where \( R_m \) is the heel radius and \( R_f \) is the face radius.

The x-coordinates, \( X_m \) and \( X_f \), denote the points of intersection between the heel and face radii and the drill radius, respectively. They can be found by the relations:

\[
X_m = \frac{4R_f^2R_W - 6R_f^2R_H + 4R_f^2R_W + 2R_f^2R_H - 4R_f^2R_H - R_W^2}{4R_H^2 + 8R_H R_W + 4R_W^2}
\]

\[
X_f = \frac{4R_f^2R_W - 6R_f^2R_H + 4R_f^2R_W + 2R_f^2R_H - 4R_f^2R_H - R_W^2}{4R_H^2 + 8R_H R_W + 4R_W^2}
\]

(5)

(6)

EXPERIMENT METHODOLOGY

A set of drilling experiments were performed with a Fadal CNC 88HS vertical mill at Ford’s Livonia Plant New Product and Testing Center. Table 1 lists the eight experiment designs. A total of 120 experiments were conducted. Table 2 gives a listing of drill geometries and drill materials. No coated or specialty drills (e.g., gun drills, spade drills, etc.) were used in these tests. Drill points were periodically inspected for wear. Wear was found to be negligible. The work materials were the cast aluminum alloys SAE 308 and 390 in the form of bars 11 mm x 215 mm x 25 mm.

The cutting fluid used was Chrysar M3C99A water soluble oil mixed at either 2% or 8% oil concentration by volume, and “off” (no cutting fluid used). When applied, the coolant was delivered via three jets at a combined volumetric flow rate of approximately 330 cm³/sec and a pressure of 44 kPa. Drilling speeds used were 765.5 M/min (250 ft/min) and 137.6 M/min (450 ft/min). Feeds per flute were .06 mm (.0015") and .12 mm (.003"). Holes were drilied up to 4.5 times the drill diameter (deep hole drilling). Both blind and through holes were examined. The drill overhang was held constant at 50 mm for each experiment design, except for design B, which examined the significance of this variable. The workpiece temperature was at the ambient temperature of 25°C except for experiment design E which had the workpieces heated to 100°C and cooled to -70°C. As can be seen from the table, designs A and E through H were full factorials. That is, the effects of the variables and interactions were directly shown by the data analysis. The remaining experiment designs were fractional factorial designs. Experiment designs B and D were fractional factorial experiments with resolution IV. Experiment design C was a fractional factorial with resolution V. An inherent confounding not explicitly shown in Table 3 is that caused by the varying drill geometries. Design B used “drill type” as a variable, which actually changes 5 drill characteristics as detailed in Table 2. Thus the effects due to point and helix angles, material, etc., are combined into an overall average. Design D also uses drill type as a variable, however only 2 characteristics are confounded.
GENERATED CHIP FORMS

The data measured for these experiments were the volumes of generated chips, and the surface finishes of the generated holes. Since the densities of these two alloys are approximately identical and were subject to fluctuations due to porosity, masses were used as a volume measure to compare chip sizes. Each set of chips were measured for mass using a Sartorius Model A20S precision scale with a resolution of .0001 g. Whenever possible, a sample of 20 chips was used to determine the average chip mass. For about 10% of the experiments, fewer than 20 chips were available.

These experiments showed that in every case, more than one chip type existed per sample. The total types of chips could include fan shaped, corkscrew, chisel edge and small dust like chips which are most likely broken off of the larger chips during formation or during handling. In drilling, due to the nature of the cutting conditions (increased cutting speed and rake angle with radial distance from the drill axis), fan shaped and corkscrew shaped chips are primarily produced.

If two or more types of chips were to be used in the analysis, the data would be of mixed types. It would be difficult to draw meaningful conclusions from the combined average weights of different types of chips. Thus the dominant chip components were chosen and studied. This means that if fan, corkscrew and dust like chips accumulated, and the if the fan shaped chips made up the majority of the volume, only the fan shaped chips would be studied. One other type of mixing which could not be removed was that due to the chips being produced by imperfectly made tooling. Each drill cutting edge produced a slightly different chip form. In one case, the two conical chips made during the initial cut (until steady state was achieved) showed a noticeably different size by simple inspection.

Although various different types of chips were produced, one constant permeating the experiments was the randomness of the dominant chip shapes. A wrinkled surface existed on the concave surface of all chips, coupled with a burnished surface on the convex surface of the chips. The edges, however, showed remarkable irregularity. This either indicates randomness in the generation process, possibly caused by chips in the flute affecting the generation process, or damage after formation. Several of the experiment designs had individual chip weight measurements, and standard deviations of the weights for each test were calculated. For design A, the overall average dominant chip weight was 1.51 milligrams with a standard deviation average of 0.140 milligrams. Design D had an overall average dominant chip weight of 1.13 milligrams, with a standard deviation average of 0.205 milligrams. This shows a very large variation of the chips within fixed cutting conditions.

Figure 2 shows all chip forms which were created by the drilling experiments except for dustlike chips which were present in all experiment designs.

Figure 2-A shows conical chips. The diameter of the conical chip must be small enough to allow it to move through the flute/hole wall cavity without breaking [Kahng, et. al., 1978]. Notice the chip on the far right side of figure 2-A. This chip began with a spiral form when the drill contacted the workpiece, and grew as the entire lip became engaged. After several rotations, the chip fractured, and all newly developed chips were fan shaped.

Figure 2-B shows fan shaped chips. These are formed when the chips cannot curl sufficiently to follow the flute, and fracture.

Chisel edge chips, figure 2-C, form due to the extrusion of metal from the chisel edge [Oxford, 1955]. When these chips form there is also a second chip forming along the outer portion of the cutting edge. These chips are long and narrow, streaming out of the drill along the interior of the flute at the web.

Amorphous chips, which show a rather wrinkled, uncurled appearance, are shown in figure 2-D. These chips do not have enough consistent curl to take a fan shape, and are guided up the flutes.

Needle chips, figure 2-E, are caused by severe upcurling [Nakayama, 1978]. This happens when built up edge causes a change in the cutting surface.

Impacted chips, figure 2-F, are not a primary chip form. These are collections of chips which have become attached while moving up the flute. They are thus heavier than primary chip forms, and take on the shape of the flute.

STATISTICAL ANALYSIS OF EFFECTS

For this data, normal probability plots (NPPs) were constructed to determine which effects were statistically significant [DeJoy, et al., 1992]. The results of the data analysis are shown in Table 3 which lists the variables which were found significant. Variable significance is indicated by ordinal number ("1" being the most significant variable). Those variables not shown to be statistically significant are marked with an "X", while variables marked "-" were held constant.

From the data analysis, it was apparent that only primary effects analysis was warranted. No second order or higher effects were determined to be significant in this set of experiments. Table 2 shows only first order effects.

Individual effects

Feed. The feed was found to be the most significant variable affecting chip size. It was the most significant variable in all experiment designs except design E, which only found 1 significant variable. As the feed increased, so did the volume and weight of the produced chips.

Material. The two materials chosen for study, SAE 308 and SAE 390, had different material properties, and hence differing deformed chip thicknesses, resistance to bending moment, etc. The SAE 390, having the higher silicon content and therefore lower ductility, produced consistently smaller chips. Although it did not show in every case, in design E it was the most significant effect, and was the second most significant effect for designs F, G and H.

Drill Type. In design D, drill type was the second most significant variable. The two drills were similar, differing only in point angle and material. Drill type 4 was a HSS drill with a 135 degree included point angle. Drill type 5 was a carbide drill with a 118 degree included point angle. The type 5 drill
produced smaller chips. The point angle of the type 5 drill should produce wider, thinner chips. Carbide with its higher lubricity should also yield a thinner chip. This agrees with Cook, et al. [1963]. Experiment design B also changed drill type, with a total of 5 different characteristics. Design B did not conclusively show that "drill type" was significant. Notice that the diameter of the holes for type 2 drills are slightly larger than for type 1 drills (5.7 mm vs. 5.5 mm). It is unreasonable to suggest that drills of significantly different diameters will produce similarly sized chips. Also, it was possible to compare average chip sizes across the experiment designs. Designs C and G were identical except for drill type (if you neglect the hole depth variable which was varied in C, but never found to be significant). Design C chips were on average 54% larger than the design G chips.

**Cutting Fluid Presence.** Cutting fluid was the least significant effect which could still be identified as having an impact on chip size. It showed that cutting fluid presence decreased chip size. This gives evidence that the fluid is cooling the chips, reducing their ductility, or lubricating the rake face and producing thinner, more easily broken chips.

Significance was tested for five times, however, and only proven once. In design A it was the third most significant variable. It suggests that the impact of cutting fluid on chip size is really quite minimal in the case of deep drilling. In design C there was evidence at the time of the experiments that cutting fluid was being effectively circulated into the hole. This evidence was a reduction in BUE during these experiments. Thus it is very important that cutting fluid was not found to be significant in this design. It is known, however, that cutting fluid can affect the surface finish of the hole in drilling. We can therefore conclude that cutting fluids do have an effect at the margin where the chips are dragging, but that the fluid does not always reach the cutting zone and affect the size of the generated chips.

**Remaining Experiment Variables.** It is important to recognize what did not affect chip size. The variables of fluid concentration, hole depth, drill overhang and initial temperature of the workpiece did not significantly change the chip weights. Since fluid presence was so weakly tied to chip size in deep drilling, it is not unusual that fluid concentration was not found to be significant. It was only tested in one experiment design (H), so this can in no way be declared conclusive. That the hole depth did not affect chip size suggests that the process quickly reaches steady state (in 2 or fewer diameters of drilling). Drill overhang did not prove to be significant, but this also may not suggest anything conclusively. The runout of the drills were measured, and were not found to be appreciably different between tests, regardless of the length of overhang. The workpiece temperature tests, in which the temperature differed by 170°, showed that the drilling cutting temperatures were high enough to make this temperature difference insignificant with respect to chip size.

**SURFACE FINISH ANALYSIS**

Chip size versus hole surface finish data were plotted to investigate any possible correlation. No correlation was found. From visual analysis of the holes, it appears that the retraction of the still-rotating drill scores the hole and produces the final surface texture. Circumferential lines ring the holes. Possible explanations are that either chips, BUE or the drill itself impacts the sides of the hole and causes the damage. Inspection of the drills showed that the BUE formed at the center of the drill, and was absent at the margins. This indicates that the chips are being dragged along the hole wall and scoring the surface.

Figure 3 show the profile heights of the sidewall for one of the experiments, from the bottom of the hole to the top. The peak to peak values are spaced at the same distance as the retraction feed per flute. This gives conclusive evidence that the drill retraction is affecting the surface finish. The torque values for the entire cut are shown in figure 4. The trace shows initial travel from rest to contact, increasing torque to full drill engagement, steady hole production, with a slight upward trend due to friction along the margins, end of cut, dwell time with reversal of drill, and finally retraction of the drill. Notice the large spikes contained in the retraction portion. Since no cutting is occurring along the drill lips, it must be interference which is causing the large torque requirements.

The results show that hole surface quality is not adversely affected by chip size, and that chip size is governed primarily by the feed, material, and to a lesser extent other variables. These results agree with the findings of Furness [1992] who studied hole location, roundness and dimension errors with respect to feed and speed, finding that for hot rolled steel that hole quality could not be significantly affected by manipulating cutting conditions.

**SUMMARY AND CONCLUSIONS**

There is a need for increasingly environmentally friendly machining processes in American industry. Numerous sets of designed experiments were conducted on cast aluminum alloys, studying the effects of cutting conditions on the drilling process in order to better understand chip formation mechanics and hole surface quality effects. Process variables chosen included the presence and concentration of coolant, material, speed, feed, and size of drilled hole. The response variables studied were the size and shape of the generated chips. It was shown that the significant variables include the feed, material, drill type and cutting fluid presence. Since the cutting fluid presence was shown to be such a minor factor in chip size, further investigation into dry drilling should be undertaken. It was determined that dominant chip size had no significant effect on hole surface finish. It was further shown that chip sizes and shapes were very random, detracting from their ability to act as indicators of the workings of the drilling process.

**ACKNOWLEDGEMENTS**

The authors wish to gratefully acknowledge the financial support received for this research from the Machine Tool Agile Manufacturing Research Institute and Ford Motor Corporation. Special thanks to Chris Wentland of Michigan Technological University for help with the figures.
REFERENCES


FIG. 3 SURFACE FINISH PLOT - DESIGN A.

FIG. 4 TORQUE PLOT - DESIGN A.
Table 1: TEST VARIABLES FOR EACH EXPERIMENT DESIGN.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>5.5</td>
<td>5.7</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Carbide</td>
<td>Carbide</td>
<td>HSS</td>
<td>Carbide</td>
<td>HSS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helix</td>
<td>High</td>
<td>Straight</td>
<td>Parabolic</td>
<td>Medium</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flutes</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point Style</td>
<td>140 deg S-Point</td>
<td>135 deg Straight</td>
<td>135 deg Split</td>
<td>118 deg Straight</td>
<td>135 deg Straight</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: DRILL GEOMETRIES AND MATERIALS.

Table 3: SIGNIFICANT EFFECTS.