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Chip morphology and hole surface texture in the drilling of cast Aluminum alloys

S.A. Batzer *, D.M. Haan, P.D. Rao, W.W. Olson, J.W. Sutherland

Department of Mechanical Engineering–Engineering Mechanics, Michigan Technological University, Houghton, MI 49931, USA
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Abstract

The effects of cutting fluid and other process variables on chip morphology when drilling cast aluminium alloys are investigated. The effects of workpiece material, speed, feed, hole depth, cutting-fluid presence and percentage oil concentration, workpiece temperature, drill type and drill overhang are studied using statistically-designed experiments. The measured responses of the experiments are the size and the shape of the generated chips. The effect of chip size on hole surface finish is also examined. The results show that the significant variables affecting chip size include the feed, material, drill type and to a lesser extent, cutting-fluid presence and drill speed. The drilled hole surface is shown to be correlated to chip size. © 1998 Published by Elsevier Science S.A. All rights reserved.

Keywords: Chips; Drilling; Machining; Surface finish; Cutting fluids

1. 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. In drilling, one of the most common industrial machining processes, there are three principal waste streams: chips, worn tooling and cutting fluids. The first two, chips and tooling, retain value and are routinely recycled. Chips are melted down, refined and returned to the same manufacturer or another industrial consumer for re-use. Drill bits, which are made of high speed steel (HSS) or carbide, are also recycled. For cutting fluids however, the cost of 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 tooling [1].

Dry machining is one option to reduce cutting-fluid usage. An important function of the drilling however, is to help to flush the chips out of the flutes. With an increased understanding of the mechanics of chip formation and transport mechanisms, cutting conditions can be specified which produce chips of the proper size, reducing the need for the flushing medium. This paper describes the analysis of 96 drilling experiments in cast aluminium alloy test bars, investigating the resulting chip sizes and shapes and hole surface finishes for varying workpiece materials, tools and cutting conditions. While much work has been carried out on process models [2] and basic research regarding the tool/work interactions [3], there has been little research to date into process inputs and resulting chip morphology. This paper presents basic research carried out on drilling process inputs to further extend the fundamental understanding of which process inputs actually affect the size and shape of resulting chips.

2. Chip morphology

In the drilling operation, small well-broken chips are desirable. This is because as the chips get larger, they cannot move easily through the flutes, which increases torque requirements, perhaps causing drill breakage. During formation, the chips rotate with the drill and impact the hole wall or interior of the flute. This impact produces a bending moment in the chip. Once the bending moment causes the chip to exceed a critical strain, it will fracture [4]. Thus, chip size/shape is being studied in order to identify the conditions which promote better chip evacuation.
Chip size is governed by its formation geometry at the cutting edge (thickness, curl) and the characteristic length, determined by the point at which the chip breaks in the generation cycle. Fig. 1 is after Nakayama [5] and details the three components of chip curl. First is the side-curl, which is due to velocity differences across the cutting lip, shown by $\omega_Z$. The second rotation, $\omega_Y$, is about the drill axis and accounts for the twisted, non-planar rake face (increasingly positive rake angle with radial distance from the drill axis). This term will also reflect the changes in rake angle caused by built-up-edge (BUE). The final rotation $\omega_Z$ is about the lip (cutting edge) of the drill. This component is caused by the natural up-curl of the chip due to its strain-hardening properties [5] and the obstruction of the web of the drill. It is this term which Nakayama shows as $\omega_Z$, perpendicular to both the Z- and Y-axis. Strictly speaking however, the chip will curl tangentially to the lip (L) axis and not the X-axis. The L-axis is perpendicular to the Z-axis but not the Y-axis. Nakayama attributed this last rotation only to the obstruction of the web of the drill. This statement is incomplete, as it does not account for the natural up-curl of the chip. Any physical rotation can be accounted for by the magnitudes and senses of rotations about three non-coplanar axes. Thus, rotations about $L$, $Y$ and $Z$ (this analysis), can be transformed into rotations about $X$, $Y$ and $Z$ (Nakayama’s analysis). The remaining dimensions required to fully describe the morphology of the chips are: the deformed chip thickness, which may vary along the lip; the characteristic length; and finally, any post-formation damage.

3. Experimental methodology

A set of drilling experiments was performed with a Fadal CNC 88HS vertical mill. Table 1 lists the eight experiment designs. As can be seen from Table 1, design A and designs E–H were full factorials [6]. Experiment designs B and D were fractional factorial experiments with resolution IV, while experiment design C was a fractional factorial with resolution V.

The work materials were cast aluminium alloys SAE 308 and 390 in the form of $11 \times 215 \times 25$ mm bars. The cutting fluid used was Chrysaz M3C99A water soluble oil, mixed at either 2 or 8% oil concentration by volume and ‘none’ (no cutting fluid used). When applied, the coolant was delivered via three jets at a combined volumetric flow rate of approximately 330 cm$^3$ s$^{-1}$ and a pressure of 44 kPa. The drilling speeds used were 76.5 m min$^{-1}$ (250 ft. min$^{-1}$) and 137.6 m min$^{-1}$ (450 ft. min$^{-1}$). The feeds per flute were 0.06 mm (0.0015 in.) and 0.12 mm (0.003 in.). Holes were drilled 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 initial workpiece temperature was at ambient temperature ($25^\circ$C) except for design E which employed workpieces heated to 100°C and cooled to $-70^\circ$C. Table 2 gives a listing of the drill geometries and drill materials considered in the eight designs. No coated or specialty drills (e.g. gun drills, spade drills)

<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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<tr>
<td>Type</td>
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<td>$2^3$</td>
<td>$2^2$</td>
<td>$2^1$</td>
<td>$2^0$</td>
<td>$2^1$</td>
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<td>Off/8%</td>
<td>Off/8%</td>
<td>Off</td>
<td>Off</td>
<td>Off/2%</td>
<td>Off/8%</td>
<td>2%/8%</td>
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<td>Drill type</td>
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<td>2</td>
<td>3</td>
<td>4/5</td>
<td>4</td>
<td>4</td>
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<td>308/390</td>
<td>308/390</td>
<td>308/390</td>
<td>308/390</td>
<td>308/390</td>
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<td>250/405</td>
<td>250/405</td>
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<td>250/405</td>
<td>250/405</td>
<td>250/405</td>
<td>250/405</td>
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<tr>
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<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>
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<td>Depth (diameters)</td>
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<td>2.5/4.5</td>
<td>2.5/4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
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<td>Overhang (mm)</td>
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<td>50</td>
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<tr>
<td>Temperature (°C)</td>
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<td>25</td>
<td>25</td>
<td>25</td>
<td>-70/100</td>
<td>25</td>
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<td>25</td>
</tr>
</tbody>
</table>
were used in the designs. The drill points were inspected periodically for wear, which was found to be negligible.

3.1. Generated chip forms

The response data measured for the drilling experiments were the masses of the chips generated and the surface finishes of the holes generated. Fig. 2 shows all of the chip forms which were created by the drilling experiments, except for dust-like chips.

Fig. 2A 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 [7]. Notice the chip on the far right of Fig. 2A: 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. All test plans and drill types exhibited this spiral chip form except for the type 2 drills used in test plan B, which had a zero helix angle (a straight flute). Fig. 2B shows fan shaped chips. These are formed when conical chips cannot curl sufficiently to follow the flute and fracture prior to a complete revolution. The fan shape was by far the predominant form and is considered the ideal chip for most drilling applications.

Chisel-edge chips, Fig. 2C, form due to the extrusion of metal from the chisel edge [8]. These chips are long and narrow, streaming out of the drill along the interior of the flute at the web. When this chip forms, there is also a second chip type forming along the cutting edge. These two chips may or may not interact. To eliminate the chisel-edge chip, it may be necessary to decrease the feed and thereby the amount of metal to be extruded. Amorphous chips, which have a rather wrinkled, uncurled appearance, are shown in Fig. 2D. These chips

---

**Table 2**

Drill geometrics and materials

<table>
<thead>
<tr>
<th>Drill Type</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>5.7</td>
<td>5.5</td>
<td>5.5</td>
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<td>HSS</td>
<td>Carbide</td>
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<td>Parabolic High</td>
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<tr>
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<td>2</td>
<td>2</td>
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<td>135°</td>
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<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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**Table 3**

Significant effects on chip mass

<table>
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<th>Design</th>
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<th>C</th>
<th>D</th>
<th>E</th>
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<td>x</td>
<td>x</td>
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<td>2</td>
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<tr>
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<td>x</td>
<td>x</td>
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<td>x</td>
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<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>Overhang</td>
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</tr>
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<td>Temperature</td>
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<td>x</td>
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<td>Drill type</td>
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<td>x</td>
<td>2</td>
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</tr>
</tbody>
</table>

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![Image](image1.png)![Image](image2.png)![Image](image3.png)![Image](image4.png)![Image](image5.png)

**Fig. 2.** Generated chip forms: (A) conical; (B) fan shaped; (C) chisel edge; (D) amorphous; (E) needle; (F) impacted.
do not have enough consistent curl to take a fan shape and are guided unbroken up the flutes. As is apparent from their size, they are the heaviest chip form and the least desirable.

Needle chips, Fig. 2E, are caused by severe upcurling [9]. There is no clear demarcation between needle and fan-shaped chips. It is the marked change in the radius of the chip about the lip axis which results in the needle shape. This radius change occurs when built-up edge alters the drill cutting surface geometry. BUE is caused by strain-hardening workpiece material welding itself to the rake face and becoming a new cutting surface. The geometry of BUE and its tendency to form are a function of workpiece and tool material, cutting speed, rake angle and other factors [10]. While these are the smallest chip form next to dust-like chips, they may be undesirable, since in general, BUE is undesirable. An increase in cutting speed will usually reduce the formation of BUE and lead to the formation of fan-shaped chips. Impacted chips, Fig. 2F, are not a primary chip form, being aggregations of smaller chips which have amalgamated while moving up the flute. They are thus heavier than primary chip forms and take on the shape of the flute. They are an undesirable chip form precisely because they clog the flutes. Impacted chips were found both with and without cutting fluid and thus cannot be accounted for by an adhesion effect of the fluid. To eliminate this type, it may be necessary to reduce the feed, speed or both, or to use a drill with a larger flute cavity.

Sets of chips from each experiment were weighed using a Sartorius Model A200S precision scale with a resolution of 0.0001 g and a sample of approximately 20 chips was used to determine the average chip mass. These experiments showed that in every case, more than one chip type existed per sample. Types of chips could include fan-shaped, corkscrew, chisel-edge and small ‘dust-like’ chips, which latter are most likely broken off from the larger chips during their formation or transport through the flute.

If two or more types of chip had been used in this analysis, the data would be of mixed types. It would be difficult to draw meaningful conclusions from the combined average masses of these different types. Thus, the predominant chip type was identified for each test and studied in greater detail. This means that if fan, corkscrew and dust-like chips were produced and if fan-shaped chips were predominant, then only the fan-shaped chips would be studied. One other type of mixing which could not be removed was that due to the chips having been 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.

One constant throughout the experiments was the random nature of the predominant chip shapes. A wrinkled surface existed on the concave (top) surface of all chips, coupled with a burnished surface on the convex (bottom) 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 newly-created chips, or damage after formation (i.e. the formation of dust-like chips). To quantify this phenomenon, several of the experiment designs had individual chip-mass measurements performed. Design A showed an overall average predominant chip-mass of 1.51 mg, with an estimated standard deviation of 0.140 mg. Design D had an overall average predominant chip mass of 1.13 mg with an estimated standard deviation of 0.205 mg.

The formation of the dust-like chips was investigated. Fig. 3 shows a section of a drilled hole. The dark spots (shadows) are chips which have become embedded in the wall. By moving the light source directly above the specimen, the embedded chips appear shinier than the surrounding hole wall, suggesting that the chips have been burnished by the drill margin after becoming embedded. This gives strong evidence that chips are being caught between the hole wall and drill margin, creating these smaller chips and accounting for some of the randomness of chip masses.

3.2. Statistical analysis of effects

For this data, normal probability plots (NPPs) were constructed to determine which effects were statistically significant [11]. In general, probability plots are graphic tools designed to enable the user to judge whether or
Fig. 4. Normal probability plot of effects; experiment design H

not data points are part of a specified probability distribution. If a set of sorted effects, data is graphed on a normal probability plot. These points falling as a generally straight line, centred at zero, are well described by a single normal distribution with a mean of zero, i.e. they are from an error distribution with a mean of zero. Points that lie off the line do not come from the error distribution and thus have a non-zero mean effect. Fig. 4 shows the NPP developed for experiment design H, utilizing resulting predominant chip mass as the response. The two effects, material and feed, are determined as being significant. Since the material term is to the left of the line, by changing material from the low value (SAE 308 Aluminum) to the high value (SAE 390 Aluminum), the predominant chip mass decreases. The opposite is true for feed: increasing the drill feed from the low to the high value will result in an increase in the predominant chip mass.

The results of the NPP data analysis are shown in Table 3. Variable significance is indicated by an 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 not studied in this set of experiments. Table 3 shows the first-order effects.

3.3. Individual effects

Not every effect was found to be significant, nor were the effects which were determined to be significant shown to be so in every experiment in which they were tested. The analysis results and possible mechanisms causing significance are discussed below.

3.3.1. Feed

The feed was found to be the most significant variable affecting chip size, being the most significant variable in all experiment designs except for design E. As the feed increased, so did the mass of the chips produced. This was due to increased cutting edge engagement leading to a greater undeformed chip thickness and also possibly due to increased strength of the resulting chip in relation to bending, delaying fracture.

3.3.2. Material

The two materials chosen for study, SAE 308 and SAE 390 aluminum, had different material properties and hence differing deformed chip thicknesses, resistance to bending moment, etc. The SAE 390, having the greater silicon content and therefore lower ductility, produced consistently smaller chips. Although the material did not demonstrate significance 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.

3.3.3. 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. The more acute point angle of the type five drill, with its longer cutting edge, should produce wider and hence thinner chips. Drill type five, made of carbide rather than the HSS of type four, should demonstrate a greater rake face lubricity and again yield a thinner crop. Thinner chips should in general be weaker and break earlier in the generation cycle. The type five drill did indeed produce smaller chips, these findings agreeing with those of Cook et al. [11]. Experiment B also changed drill type, with a total of five different characteristics. Design B did not conclusively show that ‘drill type’ was significant. This is remarkable since the diameter of the type two drill is slightly larger than that of type one (5.7 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 (neglecting the hole-depth variable, which was varied in design C, but not found to be significant). Due to the aliasing strategy used, it would not be valid to simply combine the two experiments into a larger design and check for variable significance. Design C chips however, were on average 54% heavier than design G chips. This may be due to the significantly larger flute cavity space of the type three drills used in design C, allowing larger chips to travel unbroken through the flute.

3.3.4. Cutting-fluid presence

Cutting-fluid presence significantly decreased the predominant chip size in design A. This provides 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 five times however and only shown once. In design A, it was the third most significant variable. This 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, evidenced by a reduction in BUE during these experiments. Therefore, it is very important that cutting fluid was not found to be significant in this design. It is known however, that cutting fluid can effect the surface finish of the hole in drilling. It can therefore be concluded that cutting fluids do not 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 chips generated.

3.3.5. Speed

Speed was found to be significant only in design A, even though it was tested for in every experiment design. In design A, it was found that increasing the speed increased the chip mass. This can be explained by the increase in the heat generated in the deformation zone, which will cause the chips to be more ductile and fall later in the generation cycle. Since significance was not proven in seven out of eight experiment designs, this suggests that the predominant chip size is largely insensitive to changes in cutting speed for the range of cutting conditions chosen.

3.3.6. Remaining experiment variables

The variables of fluid concentration, hole depth, drill overhang and initial temperature of the workpiece did not significantly affect the average predominant chip mass. Since fluid presence was so weakly tied to chip size in deep drilling, it is not surprising that fluid concentration was not found to be significant. It was only tested in one experiment design (H) however, meaning that 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 two or less diameters of drilling). Drill overhang did not prove to be significant, but this may not suggest anything conclusively either. The run-out of the drills was measured and 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°C, showed that the drilling cutting temperatures were high enough to make this temperature difference insignificant with respect to chip size.

3.3.7. Surface finish analysis

One measure of drilling process quality is the surface finish of the resulting hole wall. To investigate any link between chip size and hole surface finish, predominant chip size versus hole surface finish data were plotted and regression analyses was performed. In each experiment design, the 95% confidence interval of the slope of the regression line included zero, indicating no statistically significant relationship. When all experiment data is combined into a single plot however, a moderately positive correlation between predominant chip size and surface roughness is demonstrated (Fig. 5). It is evident that when the largest chips are formed, a relatively high surface-roughness results. If conditions are chosen which produce smaller chips (less than 2.5 mg), then the roughness appears to be a largely random phenomenon with respect to chip size.

4. Conclusions

There is a demonstrated need for increasingly environmentally-friendly machining processes in industry. By studying the various chip forms in the drilling process, it is possible to draw meaningful conclusions about the process and the resulting hole surface texture, providing necessary insights leading to a reduction in the use of cutting fluid. Numerous sets of designed experiments were conducted on cast aluminum alloys, studying the effects of the cutting conditions on the drilling process in order to better understand chip-formation mechanics and hole-surface-quality effects. The process variables chosen included the presence and concentration of coolant, workpiece material, speed, feed and size of drilled hole. It was shown that the significance variables include the feed, material and drill type and to a lesser extent, cutting-fluid presence and drilling speed. Since cutting-fluid presence was shown to be such a minor factor in chip size, further investigation into dry drilling should be undertaken. It was also determined that predominant chip size had no significant effect on hole surface finish when relatively small chips were produced, but also that relatively large chips would produce a consistently rougher surface finish.
Evidence was presented showing that dust-like chips are formed by post-formation damage at the flute margin, embedding the newly-formed dust-like chips into the sides of the hole.

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