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Effects of Cutting Conditions on Drilling of Aluminum 380

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The major purpose of this project was to determine the effects of cutting conditions on drilling of aluminum alloy 380. Measurements of tool wear and surface finish were taken for two cutting speeds and feed rates, respectively. In each of the four tests, a high-helix, high-speed steel drill, ¼ in. (6.35 mm) in diameter, was used to produce 460 holes 1.00 in. (25.4 mm) deep. The speeds used were 195 and 390 ft/min (99 and 198 cm/s), and the feeds were 0.016 and 0.032 in./rev (0.406 and 0.812 mm/rev). Cutting speed had a greater influence on tool wear than feed rate. However, mean surface roughness increased approximately the same amount when the speed was doubled, as it did when the feed rate was doubled.

1. Introduction

SOME automotive plants can become more flexible by converting from special-purpose machines to computer numerical control (CNC) machines. However, computer numerical control machine tools have fewer spindles, and productivity could decrease. Productivity commonly is expressed as the labor input required for a physical unit of measured output.[1] The following factors may affect productivity: operator wages, labor hours, setup costs, tooling costs, material costs, and finish specifications.

To maintain a reasonable production rate, speeds and feeds normally are increased. Increasing these cutting conditions may lead to increased tool wear and a rougher surface finish. The total manufacturing cost could rise due to higher setup costs and scrap costs because quality specifications cannot be met.

A testing program was established to study the effects of increasing cutting speed and feed rate. The measured variables in the drilling tests were tool wear and surface finish on the walls of the drilled holes.

Drilling is the most common metal cutting process used in industry. Most high-speed steel (HSS) drills have two cutting edges and two helical flutes. These flutes allow the chips to be pushed out of the hole and the cutting fluid to flood the cutting edges.[2]

Drill feed is the rate at which the drill is forced into the workpiece material and can be expressed as in./rev (mm/rev). Cutting speed is the velocity at which a point on the circumference of the drill passes the wall of the hole being drilled and can be expressed as surface ft/min (cm/s).[3]

As a metal is cut with high-speed steel drills, the cutting edges will start to wear, mainly due to the abrasive action. The increasing drill wear generates more heat at the interface between the tool and the workpiece. Workpiece material will weld to the cutting edge, causing a built-up edge (BUE), which in turn produces a rougher surface. To assist in controlling these actions, a cutting fluid is essential when using high-speed steel drills.[4]

Water-base cutting fluids are effective in reducing the heat generated due to friction. Use of oil in the cutting fluid can help reduce the lubricity problem.[5] The flushing action of the cutting fluid helps to keep the chips from packing in the flutes, which would lead to a rougher surface.

During a drilling operation, the workpiece under the chisel edge at the center of the drill is under severe deformation. Chips forced across the cutting edges cause them to wear along their entire lengths. Maximum wear occurs at the outer ends of the cutting edges along the margins, the locations of maximum surface speed.

As worldwide competition increases, manufacturing becomes more concerned about improved product quality and performance. During the development of a product, surface finish may be a critical factor. When a product contains moving parts, performance and efficiency depend highly on the compatibility of surfaces in contact. The texture of the contacting surfaces will affect lubrication, friction, wear, load-bearing, and sealing functions of the mating parts.[6]

Surface finish consists of three components: roughness, waviness, and error of form. Waviness is the result of vibration of the machine tool. Error of form is related to the straightness of the surface, and a machine tool that is misaligned will produce a long wavelength condition. If the process is "in-control," waviness and error of form can be ignored. Surface-measuring equipment is used to quantify the roughness component. These results can be used to monitor the stability of machining processes such as drilling, turning, milling, boring, and grinding.[7]

The most commonly used parameter for measuring surface finish is the arithmetic average roughness, R_a. This parameter is the arithmetic average height of surface irregularities, y_i, from the mean line, measured within the sampling length:

$$R_a\,(\text{approx}) = \frac{\sum_{i=1}^{n} y_i}{n}$$

where n is the number of irregularities within the sampling length.[8]

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Table 1 Metallurgical Analysis of Aluminum 380

Alloy	Composition, % Cu	Fe	Mg	Mn	Ni	Si	Sn	Zn
Aluminum alloy 380	3.00-4.00	1.30(a)	0.10(a)	0.50(a)	0.50(a)	7.50-9.50	0.35(a)	3.00(a)
Workpiece	3.41	1.10	0.03	0.22	0.08	7.77	0.20	2.63

(a) Maximum percentage allowed.

The sampling length, usually referred to as cutoff length, must be short enough to eliminate any waviness component, but long enough to include at least five irregularities (tool marks) caused by the machining operation. Six cutoff lengths, ranging from 0.003 to 1.00 in. (0.0762 to 25.4 mm), are specified in the ANSI B46.1-1978 surface-texture standard. The suggested value for most surfaces is 0.003 in. (0.762 mm). The surface-measuring equipment calculates the least-squares mean line and then measures the perpendicular distances from the mean line to the peaks and valleys of the profile. R_a is the average of these distances.

Aluminum alloy 380 is used in die casting carburetors, transmissions, gear cases, cylinder heads, and other automotive components. The complete alloy chemistry of aluminum 380 and the metallurgical analysis of the workpiece material are shown in Table 1. The hardness of the silicon phase gives the die casing excellent wear characteristics. However, the abrasive nature of the hard particles of free silicon causes rapid tool wear, which is influenced by both particle size and silicon content.[9]

Burant and Skingle studied the drilling of aluminum alloys containing silicon.[10] One of their objectives was to determine the drilling conditions for a high metal removal rate with aluminum 380. The conditions recommended for a high-speed steel drill with parabolic flutes were a speed of 250 ft/min (127 cm/s) and a feed of 0.013 in./rev (0.330 mm/rev). These values were obtained by drilling 1000 holes five- to six-drill diameters deep using a soluble oil at a concentration of 4.8 vol%. Under these cutting conditions, the drills showed only a slight built-up edge and no appreciable margin wear. A nitride case on the drills improved tool life. Also, chips packed the flutes at three drill diameters deep when high-speed steel drills with a regular or low-helix angle (24 to 33°) were used.

Leep and Sims conducted drilling experiments on aluminum alloy 390, a high-silicon alloy with 16 to 18% silicon.[11] The feed rate and the hole depth were held constant at 0.040 in./rev (1.02 mm/rev) and 1.00 in. (25.4 mm), respectively. The authors found that doubling the cutting speed from 50 to 100 ft/min (25.4 to 50.8 cm/s) caused a 12% increase in tool wear when a soluble oil was used at concentrations of 4.0 and 8.0 wt%. The tradename of this commercially available soluble oil was Microcut™ 19-NP-H (Quaker Chemical Corporation).

Halbleib examined the effects of cutting conditions on the surface finish of holes drilled into aluminum alloy 390.[12] Doubling the feed rate from 0.012 to 0.024 in./rev (0.305 to 0.610 mm/rev) resulted in a 36% increase in surface roughness. Cutting speed was not a significant factor in affecting surface roughness for the range 125 to 250 ft/min (63.5 to 127.0 cm/s). The cutting fluid used was CIMCOOL® 400. This cutting fluid was recommended for heavy-duty machining and contained a synthetic lubricant, MSL™, developed and patented by Cincinnati Milacron.

Henderer evaluated the performance of TiN-coated high-speed steel drills with AISI 4340 as the workpiece material.[13] TiN tools drilled an equivalent number of holes before failure for speeds from 100 to 125 ft/min (50.8 to 63.5 cm/s) as uncoated tools did at 50 ft/min (25.4 cm/s). Feeds varying from 0.0022 to 0.0125 in./rev (0.056 to 0.317 mm/rev) were used with the ¼-in. (6.35-mm) drills. Henderer suggested that the increased tool life was the result of reduced spindle power and built-up edge.

2. Experimental Setup

A computer numerical control drilling and tapping machine was used to perform the drilling tests. This machine tool had a maximum programmable spindle speed of 6000 rev/min (100 rev/s) and an accuracy of 0.0004 in. (0.010 mm).

The high-speed steel drills were made from type M7 tool steel. This tool steel contained the following nominal percentages of identifying elements: 1.00% carbon, 1.75% tungsten, 8.75% molybdenum, 4.00% chromium, and 2.00% vanadium. The "M" classification refers to the element molybdenum as the principle alloying constituent. The M tool steels were developed to reduce the amounts of tungsten and chromium, thereby replacing the tungsten-base tool steels. Major properties for the M7 cutting tool material include excellent abrasion resistance at elevated temperatures and uniform hardness throughout the drill (61 to 65 HRC).[14] These drills had the following specifications: ¼-in. (6.35-mm) diameter, high-helix angle (36°), straight shank, and jobber's length. Center drilling was done to ensure proper alignment of the drill point as it penetrated the workpiece.

A commercially available soluble oil formulated for drilling aluminum was used as the cutting fluid. The tradename of this soluble oil was Trim-Sol™, from the Master Chemical Company. The concentration of the concentrate in the water-base fluid was maintained at 5 vol% by monitoring it with a refractometer and adding the proper amount of make-up water.

Aluminum alloy 380 was selected as the workpiece, because the company at which the experimentation was performed uses this material for most of its carburetor components. The silicon content for this alloy was in the range from 7.5 to 9.5%. Each of the four blocks was approximately 12.7 in. (323 mm) long, 1.9 in. (48 mm) wide, and 2.5 in. (64 mm) thick. The average surface hardness was measured to be 33 HRB, which is equivalent to 69 HB.

After each drilling segment of 115 holes, the drills were dipped into muriatic acid to remove the built-up edge. Then,

Table 2 Mean Tool Wear

Test 1: 195 ft/min, 0.016 in./rev (99 cm/s, 0.406 mm/rev)
Test 2: 390 ft/min, 0.032 in./rev (99 cm/s, 0.812 mm/rev)
Test 3: 195 ft/min, 0.016 in./rev (198 cm/s, 0.406 mm/rev)
Test 4: 390 ft/min, 0.032 in./rev (198 cm/s, 0.812 mm/rev)

No. of holes	Tool wear: Test 1 in.	(mm)	Test 2 in.	(mm)	Test 3 in.	(mm)	Test 4 in.	(mm)
345	0.0103	(0.262)	0.0108	(0.274)	0.0154	(0.391)	0.0161	(0.409)
460	0.0113	(0.287)	0.0114	(0.290)	0.0162	(0.411)	0.0177	(0.450)

Table 3 Mean Surface Finish

Test 1: 195 ft/min, 0.016 in./rev (99 cm/s, 0.406 mm/rev)
Test 2: 390 ft/min, 0.032 in./rev (99 cm/s, 0.812 mm/rev)
Test 3: 195 ft/min,0.016 in./rev (198 cm/s, 0.406 mm/rev)
Test 4: 390 ft/min, 0.032 in./rev (198 cm/s, 0.812 mm/rev)

No. of holes	Surface finish: Test 1 μin.	(μm)	Test 2 μin.	(μm)	Test 3 μin.	(μm)	Test 4 μin.	(μm)
460	144	(3.66)	168	(4.27)	170	(4.32)	192	(4.88)

Note: Each mean was calculated from five measurements for each test.

tool wear was measured with a toolmaker's microscope, which had a magnification of 30× and an accuracy of 100 μin. (2.54 μm). Tool wear was the average of the two values measured on the lands at the margins of the drill.

A surface measurement system was used to measure the finish of the drilled holes. This system used a small-bore probe that moved linearly along the wall of the drilled hole. Surface finish was measured for each test at 92, 184, 276, 368, and 460 holes. These values were then averaged to obtain a surface measurement for a particular test. The probe, which included a stylus and a skid, traversed the length of a hole. A cutoff value of 0.300 in. (0.762 mm) and a meter sensitivity of 300 μin. (7.62 μm) were used. The average deviation from the mean line, R_a, was recorded for each reading.

A preliminary study was performed to determine the smallest drill diameter that could be used to drill a reasonable number of holes at the maximum cutting conditions without tool failure. After breaking five drills with a diameter of $\frac{7}{64}$ in. (2.78 mm), larger drills were tested. A diameter of $\frac{1}{4}$ in. (6.35 mm) was selected for blind holes, which were 1.00 in. (25.4 mm) deep to the shoulders of the drill, or four times the drill diameter. The machine tool limits for this drill size were a speed of 394 ft/min (200 cm/s) and a feed of 0.033 in./rev (0.838 mm/rev).

High and low values of speed and feed were selected for the main drilling tests. The high values for speed and feed were 390 ft/min (198 cm/s) and 0.032 in./rev (0.812 mm/rev), respectively. These values were slightly less than the maximum values for the machine tool. To obtain a sizable variation in the test results, the high values were multiplied by $\frac{1}{2}$ for the second set of cutting conditions. The low values for speed and feed were 195 ft/min (99 cm/s) and 0.016 in./rev (0.406 mm/rev), respectively.

The drilling cycle automatically center-drilled and drilled holes according to the part program. The holes were spaced 0.300 in. (7.62 mm) from center to center in a row, and the distance from the center line of one row to the center line of the next row was also 0.300 in. (7.62 mm). Holes were drilled into the tops and bottoms of four blocks, with one test on each block.

3. Results and Discussion

Averaged tool wear for 345 and 460 holes of each test is summarized in Table 2. The mean surface finish for a test was the mean value of five measurements. A measurement was taken every 92 holes. Averaged surface finish values for 460 holes are summarized in Table 3.

The results for mean tool wear and surface finish after 460 holes from Tables 2 and 3, respectively, were used to perform an analysis of means. The means were calculated to establish quantitative relationships between the cutting conditions (speed and feed) and the performance criteria (tool wear and surface finish). The results are shown in Table 4. The mean values of tool wear and surface finish at a particular feed rate were based on the values associated with the two levels of cutting speed. Likewise, the mean values at a particular cutting speed were associated with the two levels of feed rate. Using the mean values in Table 4, ratios of the higher value of wear or finish to the lower value of the same dependent variable were calculated for constant feed and speed. These ratios are shown in Fig. 1.

The analysis of means demonstrates how the performance criteria are influenced by the cutting conditions. By doubling the feed rate, the land wear at the margin increased by only 7%. Doubling the feed rate would cause the chisel edge to wear faster. Doubling the cutting speed caused a 50% increase in

Table 4 Results from Analysis of Means

Constant feed	**0.016in./rev**	**(0.406 mm/rev)**	**0.032 in./rev**	**(0.812 mm/rev)**
Mean wear, in. (mm)	0.0137	(0.349)	0.0146	(0.370)
Mean finish, µin. (µm)	157	(3.99)	180	(4.57)
Constant speed	**195 ft/min**	**(99cm/s)**	**390 ft/min**	**(198 cm/s)**
Mean wear, in. (mm)	0.0113	(0.288)	0.0170	(0.431)
Mean finish, µin. (µm)	156	(3.96)	181	(4.60)

Ratios of Means for Constant Feed

Tool wear:

$$\frac{High\text{–}feed\ mean}{Low\text{–}feed\ mean} = \frac{0.0146}{0.0137} = \frac{(0.370)}{(0.349)} = 1.07$$

Surface roughness:

$$\frac{High\text{–}feed\ mean}{Low\text{–}feed\ mean} = \frac{180}{157} = \frac{(4.57)}{(3.99)} = 1.15$$

Ratios of Means for Constant Speed

Tool wear:

$$\frac{High\text{–}speed\ mean}{Low\text{–}speed\ mean} = \frac{0.0170}{0.0113} = \frac{(0.431)}{(0.288)} = 1.50$$

Surface roughness:

$$\frac{High\text{–}speed\ mean}{Low\text{–}speed\ mean} = \frac{181}{156} = \frac{(4.60)}{(3.96)} = 1.16$$

Fig. 1 Ratios of means.

land wear. At the high levels of the cutting conditions, the drill was less than 40% worn after 460 holes. This observation suggested that either more holes could have been drilled or more severe cutting conditions could have been used before the drill would fail.

Surface roughness increased due to the accelerated cutting conditions. A 15% increase in surface roughness occurred when the feed rate was doubled, while a 16% increase was related to the higher cutting speed.

4. Conclusions

The following conclusions were drawn from the results of the drilling tests. When the cutting speed was doubled from 195 to 390 ft/min (99 to 198 cm/s), the drill wear increased 50%. Drill wear increased only 7% when the feed rate was increased from 0.016 to 0.032 in./rev (0.406 to 0.812 mm/rev). When 460 holes were drilled 1.00 in. (2.54 cm) deep into aluminum alloy 380 at a cutting speed of 390 ft/min (198 cm/s) and a feed rate of 0.032 in./rev (0.812 mm/rev), the drill wear was less than 40% of the margin. A 16% increase in surface roughness was associated with increasing the cutting speed from 195 to 390 ft/min (99 to 198 cm/s). Increasing the feed rate from 0.016 to 0.032 in./rev (0.406 to 0.812 mm/rev) caused the surface roughness to increase by 15%. When using drills with a diameter of $^7\!/_{64}$ in. (2.78 mm), increasing the cutting speed and the feed rate above the recommended values resulted in sporadic drill breakage.

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