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ELECTROCHEMICAL MACHINING DEEP THROUGH
HOLES IN 304 STAINLESS STEEL

By L. K. Gillespie

Published August 1978

Final Report
L. K. Gillespie, Project Leader

Prepared for the United States Department of Energy
Under Contract Number EY-76-C-04-0613.

**Kansas City
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Housings for electromechanical switches often require deep non-circular shapes in hard-to-machine materials. In a study to determine if electrochemical machining (ECM) could increase production, it was found that ECM was twice as fast as conventional broaching. ECM was able to maintain tolerances of $\pm 152 \mu\text{m}$ (0.006 in.) on surfaces and $\pm 304 \mu\text{m}$ (0.012 in.) on fillet radii. These are three times and six times respectively less consistent than conventional broaching.

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SUMMARY

Electrochemical machining (ECM) is a relatively fast method of removing material. By this method, electrical energy causes a chemical reaction which, in turn, dissolves metal from a work-piece into an electrolytic solution. This reaction, which can be faster than conventional machining methods, is particularly important on long, deep noncircular holes in hard-to-machine materials. These conditions exist in many electromechanical mechanism housings.

A study was made of the tolerance capabilities of ECM to produce rectangular holes approximately 25.4 mm (1 in.) square through a depth of 76 mm (3 in.) in 304 stainless steel. It was observed that on the straight sides the $\pm 2\sigma$ limits required to use ECM were $\pm 152 \mu\text{m}$ (0.006 in.). Fillet radii were repeatable within $\pm 304 \mu\text{m}$ (0.012 in.). The surface finish produced was $1.3 \mu\text{m}$ (50 $\mu\text{in.}$).

ECM generated this cavity twice as fast as conventional broaching and generated no burrs. Broaches are extensively employed for machining squares and hexagonal holes and splined shaft fittings. Broaching is a machining process whereby one or more cutters with a series of teeth are pushed or drawn entirely across a surface consisting of straight-line elements. Conventional broaching was three times more consistent on straight sides and six times more consistent on fillet radii than ECM.

DISCUSSION

SCOPE AND PURPOSE

The object of this study was to determine the tolerance capability of electrochemical machining (ECM) of deep through holes in 304 stainless steel.

ACTIVITY

The production of rectangular through holes (Figure 1) traditionally has been performed by drilling a pilot hole then broaching. For this configuration at least three different broaches are required to remove all the material left after drilling.

In a small lot production application it is sometimes difficult to maintain the combination of size, location, and fillet radii shown in Figure 1. Since the hole is defined by a contour tolerance, any broach variation above nominal size reduces the allowable positional tolerance. Variations below nominal size incur the risk of the fillet radii being out of tolerance. The broaching operation itself leaves tapered holes, and gouges when chips weld to a broach tooth. Broached hole locations vary significantly from part to part in some setups for as yet unexplained reasons. In short, the tolerances shown in Figure 1 are only slightly above the state-of-the-art limits of broaching capability for this configuration and material.

Electrochemical machining inherently eliminates many of the problems experienced when using broaching. It is a noncontact process, so tool and part deflections are not as critical as in broaching. Sharp broaches exert 133 N (300 pounds force) on the part and fixture and dull broaches increase this to 400 N (900 pounds force).

Tool size is easily changed since it is a short milled segment. Broaching, in contrast, requires 4 to 6 weeks for obtaining new broaches. Tool costs are in the order of 100 dollars while broach sets cost 1200 dollars or more per set. ECM tooling does not require resharpener or replacement except in the case of accidents. In the case of this hole shape, machining times are roughly equivalent to broaching and setup times are significantly less for ECM.

Because of these obvious advantages, this study was initiated to determine the tolerance capabilities of ECM and the relative economics of ECM and broaching for the configuration identified in Figure 1. This figure is characteristic of the internal shape

Figure 1. Rectangular Hole Produced by Broaching and ECM

of an actual production part which experienced the broaching problems previously identified.

Test Approach

Thirty-six samples were machined conventionally to the configuration shown in Figure 2. These parts were then electrochemically machined by Rockwell International (Golden, Colorado) to the configuration shown in Figure 1. The parts were then measured and this data was subjected to a best fit analysis according to the Sandia Laboratories developed program known as Coincident Coordinate Measurement Program (COCOMP). The repeatability of dimensions was then compared to that of broaching. The general characteristics of the ECM process were also noted. Two sizes of the round pilot hole were evaluated, as was the potential of eliminating the need for a pilot hole. The basic production rate desired was 40 minutes per part or faster.

Effect of Pilot Hole Size

The initial test parts contained a pilot hole with a diameter of 25.15 mm (0.99 in.). This was the size of hole used for a pilot in the broaching operation. This hole size was too large for successful electrochemical machining. When a tool large enough to produce the correct conditions in the corners is used, a dished out area occurs (Figure 3). The rectangular tool was 25.35 by 26.63 mm (0.998 by 1.009 in.). With this size hole the electrochemically machined rectangular hole had dished out areas at the four points from which the least amount of material was to be removed (Figure 3).

Efforts to ECM the hole without using any pilot hole were not successful because of the more than 80 minutes per part required to produce the hole. The remaining 30 samples were produced beginning with a pilot hole of 23.8 mm (0.937 in.).

Dimensional Consistency

Twenty-one electrochemically machined parts were inspected for dimensional conformance. Each part was checked in a single setup with a Comar measuring machine using a probe to provide three point measurements on each straight line (Figure 4). A single measurement was made of a point on each fillet radius. Both the entrance and the exit ends of all parts were inspected. This provided 44 measurements for each part. The data was then submitted for analysis by the COCOMP program. For this study the

Figure 2. Initial Part Configuration

theoretical intersections of all lines were used to provide point definitions of key locations. COCOMP then used these points for determining the amount of translation and rotation required. The transformed locations of all measured points were printed out in addition to these theoretical points of intersection.

The following net results of this data manipulation are given:

- The nominal ECM cavity size for each part for one end,
- The nominal location of the cavity within each part for one end,
- Measured points out of tolerance for each part for one end,

Figure 3. Effect Produced With Pilot Hole Diameter of 25.1 mm (0.99 in.)

- Nominal size and location for the entire lot of parts for one end,
- Standard deviation of each measurement for one end, and
- Comparisons between the two ends of the parts.

Table 1 presents the data for 21 electrochemically machined housings chosen at random from those produced in the second group of parts. Comparative data is also presented for a sample of five parts produced by broaching. Since three measurements were taken for each line (Figure 4), the standard deviation is based on 63 measurements for these features. COCOMP actually prints out a standard deviation corresponding to the 21 first measurements, and then for the 21 second point measurements, and another for the 21 measurements which were the third of the three taken on each line. As seen in Table 1, the standard deviation of line location for L1 through L4 was in the order of $38.1 \mu\text{m}$ (0.0015 in). This end corresponds to the end the ECM tool entered the part. The actual location of the measurements made was roughly 6.35 mm (0.25 in.) below the top surface. From a statistical standpoint one would expect 95.44 percent of these measured features to fall

FEATURE	X	Y	R
L1	27.1 (1.067) *		
L2		27.3 (1.075)	
L3	1.45 (0.057)		
L4		1.27 (0.050)	
L5	(0.000)		
L6		57.5 (2.265)	
L7	29.8 (1.175)		
L8		(0.000)	
L9	1.45 (0.057)		
L10		1.27 (0.050)	
L11	27.1 (1.067)		
L12		27.3 (1.075)	
C1	3.05 (0.120)	2.87 (0.113)	1.57 (0.062)
C2	3.05 (0.120)	25.7 (1.013)	1.57 (0.062)
C3	25.5 (1.004)	25.7 (1.013)	1.57 (0.062)
C4	25.5 (1.004)	2.87 (0.113)	1.57 (0.062)
C5	25.5 (1.004)	2.87 (0.113)	1.57 (0.062)
C6	25.5 (1.004)	25.7 (1.013)	1.57 (0.062)
C7	3.05 (0.120)	25.7 (1.013)	1.57 (0.062)
C8	3.05 (0.120)	2.87 (0.113)	1.57 (0.062)

*.mm (IN.)

Figure 4. Designation for Lines and Fillet Radii

Table 1. COCOMP Results for Geometry Shown in Figure 4
(The intersections of L1 and L2, L2 and L3,
L3 and L4, and L4 and L1 were used as the
primary features for the COCOMP analysis for
this table.)

Feature	Standard Deviation of Line and Radius Location*			
	ECM Hole		Broached Hole	
	(μm)	(in.)	(μm)	(in.)
L1	34.8	0.00137	10.9	0.00043
L2	44.2	0.00174	15.0	0.00059
L3	32.5	0.00128	27.4	0.00108
L4	26.4	0.00104	18.5	0.00073
L5	118.4	0.00466	30.2	0.00119
L6	87.4	0.00344	53.3	0.00210
L7	122.4	0.00482	30.2	0.00119
L8	86.4	0.00340	25.1	0.00099
L9	78.7	0.00310	10.2	0.00040
L10	127.3	0.00501	26.9	0.00106
L11	86.6	0.00341	11.2	0.00044
L12	153.9	0.00606	27.2	0.00107
C1	162.3	0.00639	22.4	0.00088
C2	183.1	0.00721	28.4	0.00112
C3	154.7	0.00609	28.7	0.00113
C4	136.1	0.00536	19.3	0.00076
C5	123.7	0.00487	25.9	0.00102
C6	283.7	0.01117	31.8	0.00125
C7	251.5	0.00990	22.1	0.00087
C8	127.3	0.00501	20.6	0.00812

*In the case of fillet radii, this is a radial standard deviation.

within $\pm 2\sigma$ which in this case is $\pm 127.2 \mu\text{m}$ (0.003 in.). The repeatability of lines L5 through L8 appears noticeably worse ($101.6 \mu\text{m}$ or 0.004 in.). Lines L5 and L8 correspond to the locating surfaces used during machining and inspection. Since the outer contour was allowed to vary without close monitoring of size, it is not surprising that these outer lines have a large standard deviation. In production, the actual variation is smaller. Part of this apparent standard deviation is the result of the COCOMP program. Since, in this instance, the program was instructed to make a least squares best fit to lines L1 through L4 only, any mislocation of the tool with respect to L1 would not appear in the COCOMP output. The net result of this analysis illustrates the very best standard deviation which was observed on these parts. The actual standard deviation is probably larger.

The large values of standard deviation for L9 through L12 is in part due to runout in the tooling, in part due to the process and in part due to the COCOMP program. For these points, the part was inspected with L5 and L8 serving as the locating surface. In this case, all the variation in setup appears in these four lines. Subsequent paragraphs will illustrate the effect of using lines L1 through L4 and L9 through L12 as the primary features for best fit. The values for the fillet radii indicate a $\pm 2\sigma$ spread of $\pm 0.31 \text{ mm}$ (0.012 in.) which is considerably worse than the repeatability required to assure a 0.15 mm (0.006 in.) tolerance band.

The repeatability of the broached hole in most cases is three times better than that of the electrochemically machined hole (Table 1). In the case of the fillet radii, the broached holes had a repeatability up to 10 times better.

The nominal position of each feature is not presented in this report since it is easily changed by minor setup changes or tool size changes.

As seen in Table 2, when a best fit is obtained to both ends of the cavity, the repeatabilities of lines L9 through L12 improve slightly and those for L1 through L4 worsen slightly. The net result is not significantly different, however.

Factors Affecting Tolerances

During these tests it was observed that on some parts the bottom end of the part was not fully machined to the desired contour. This is apparently the result of electrical resistance differences between the part and the electrolyte caused by changing part configuration. This could be eliminated on the part by making the length 6.35 mm (0.25 in.) longer initially then machining it off after the ECM operation. The second approach would be to utilize

Table 2. COCOMP Results for Least Squares Fit to Both Ends of Parts (The intersections of L1 through L4 and L9 through L12 were used as the primary features for this analysis.)

Feature	Standard Deviation of Line and Radius Location*			
	ECM Hole		Broached Hole	
	(μm)	(in.)	(μm)	(in.)
L1	48.5	0.00191	11.2	0.00044
L2	81.8	0.00322	12.4	0.00049
L3	54.9	0.00216	24.9	0.00098
L4	74.7	0.00294	16.5	0.00065
L5	135.6	0.00534	31.2	0.00123
L6	62.2	0.00245	52.1	0.00205
L7	152.1	0.00599	30.7	0.00121
L8	43.7	0.00172	21.3	0.00084
L9	44.2	0.00174	11.9	0.00047
L10	62.7	0.00247	22.6	0.00089
L11	50.3	0.00198	17.3	0.00068
L12	86.6	0.00341	30.0	0.00118
C1	213.9	0.00842	22.6	0.00089
C2	160.3	0.00631	31.0	0.00122
C3	126.5	0.00498	29.2	0.00115
C4	169.2	0.00666	17.0	0.00067
C5	128.3	0.00505	24.1	0.00095
C6	230.9	0.00909	31.8	0.00125
C7	207.3	0.00816	26.7	0.00105
C8	137.7	0.00542	20.1	0.00079

*In the case of fillet radii, this is a radial standard deviation.

a sacrificial backup just below the actual part. This backup would provide the electrical resistance required to maintain a constant electrical pattern. The latter method was used for the last 10 parts produced.

Somewhat better tolerances probably could have been obtained with additional tooling and electrolyte evaluation.

Physical Appearance

Six characteristics of electrochemically machined parts are obvious by visual examination. The first characteristic is a dull surface. When sodium nitrate is used as an electrolyte, a white hydroxide is produced by electrolysis. The parts also had a rusty appearance when they were removed from the electrolyte. After electrochemical machining, the parts were blasted with glass beads to remove this rusty appearance. A frosty or dull surface resulted. An Auger analysis of this cleaned surface was made and compared to a normal bright, shiny surface. The results indicate the presence of silicon (probably from glass beads) and sodium on both surfaces (Table 3). Neither sample demonstrated any unusual contaminants other than these. SEM and EDAX analyses were also made with no different results.

The second characteristic is a "die roll" like radius on the tool entrance side of the part. This is apparently the result of overcutting. The electrolyte passes over the top surface throughout the cut, whereas on the back surface the electrolyte only flows over the part for 1 or 2 minutes. On some parts this pseudo die roll ranges from 50.8 to 203.2 μm (0.002 to 0.008 in.).

The third characteristic is the presence of many striations along the axis of the ECM feature. These apparently are the result of preferential flow paths (Figure 5).

The fourth characteristic is a relatively smooth surface finish. Table 4 illustrates the results of profilometer traces made axially and transversely in the cavity of both ECM and broached cavities.

The fifth characteristic was the absence of burrs on the ECM parts.

The sixth item of note was the variation of fillet radii from one end to the other. Figure 6 portrays the actual conditions seen on two parts. On a single part the difference was less dramatic but still easily observed.

Table 3. Auger Results of Surface Dulled by ECM and Normal Bright Surface (Values shown indicate the peak height of the given element as a ratio of the sum of peak heights of all elements.)

Element	Before Sputtering (Percent)	After Sputtering	
		1 Minute (Percent)	2 Minutes (Percent)
Dull Surface			
Silicon	5	8	5
Sodium	22	2	1
Carbon	52	39	12
Iron	11	43	78
Oxygen	11	7	5
Nickel	0	1	2
Bright Surface			
Silicon	7	0	0
Sodium	0	1	0
Carbon	66	27	12
Iron	14	71	80
Oxygen	1	0	0
Nickel	0	1	8

Economics

Electrochemically machining these features required approximately 10 minutes per part setup time and 40 minutes per cycle machining time. The maximum feedrate available is 2 mm/min. (0.080 in./min.). The tests were performed at 2 mm/min. (0.080 in.), 0.414 MPa (60 psi) electrolyte pressure, 43°C electrolyte temperature, and a concentration of NaNO₃ of 28.4 gram mols/liter (2 pounds/gallon) of water.

Although only one part was run per cycle, it is possible to produce six parts in the same length of time by ECM. As a result, it is possible to ECM six parts per hour. Table 5 illustrates

Figure 5. Striations Caused by Preferential Flow Paths (2.5X)

the relative comparisons between ECM and broaching for this part. The ECM process is obviously much faster and less expensive. Unfortunately, in this study this process would not meet the tolerance requirements (Table 6).

The data in this report was based on what is believed to be a normal processing approach. With additional effort, improved tolerances are probable but not to the extent that they would equal that of broaching.

Table 4. Surface Finish Results in Cavities

Sample Number	Axial Profilometer Trace		Transverse Profilometer Trace	
	High (μm) ($\mu\text{in.}$)	Low (μm) ($\mu\text{in.}$)	High (μm) ($\mu\text{in.}$)	Low (μm) ($\mu\text{in.}$)
ECM Cavity				
1	2.29 (90)	0.64 (25)	1.27 (50)	0.89 (35)
2	1.52 (60)	0.51 (20)	1.65 (65)	1.02 (40)
3	2.41 (95)	0.51 (20)	1.52 (60)	0.89 (35)
Broached Cavity				
1201	2.41 (95)	0.10 (4)	2.03 (80)	0.51 (20)
1327	3.43 (135)	0.51 (20)	1.40 (55)	0.56 (22)
1366	2.79 (110)	0.89 (35)	1.52 (60)	0.51 (20)

FILLET RADII AT ENTRANCE OF CAVITY

FILLET RADII AT EXIT OF CAVITY

Figure 6. Variations in Fillet Radii on Two Parts

Table 5. Relative Economics of ECM and Broaching for the Cavity Shown in Figure 1

Condition	ECM	Broached
Parts/Hour	6	3
Tool Cost/Part (Dollars)	2	4
Electrolyte or Lubricant Cost/Part (Dollars)	0.10	0.25
Machine Setup (Hours)	1	3
Deburr (Minutes/Part)	0	5
Cleanup of Parts (Minutes/Part)	1	3

Table 6. Summary Comparisons of Typical Tolerances Produced

Characteristic	ECM Tolerance		Broaching Tolerance	
	(μm)	(in.)	(μm)	(in.)
Straight Lines ($\pm 2\sigma$)	± 152	(± 0.006)	± 51	(± 0.002)
Fillet Radii ($\pm 2\sigma$)	± 304	(± 0.012)	± 51	(± 0.002)
Edge Radius	51/203	(0.002/0.008)	Burrs	
Surface Finish	1.3	(50 $\mu\text{in.}$)	1.3	(50 $\mu\text{in.}$)

ACCOMPLISHMENTS

It has been shown that while the ECM process can double current production rates by broaching, it is approximately three times less consistent in terms of machining tolerances than broaching.

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