27
11/27/78
24071TIS

MASTER

BDX-613-1908 (Rev.)

SLOTING BY ELECTROCHEMICAL GRINDING

By R. W. Stiles

Published November 1978

Topical Report

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

**Kansas City
Division**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America

Available From the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Price:	Microfiche	\$3.00
	Paper Copy	\$4.00

BDX-613-1908 (Rev.)
Distribution Category UC-38

SLOTING BY ELECTROCHEMICAL GRINDING

By R. W. Stiles

Published November 1978

Topical Report
R. W. Stiles, Project Leader

Communications Services

**Kansas City
Division**

SLOTING BY ELECTROCHEMICAL GRINDING

BDX-613-1908 (Rev.), UNCLASSIFIED Topical Report, Published
November 1978

Prepared by R. W. Stiles

Cutting tests were performed with both Al_2O_3 copper-bond and diamond grinding wheels to determine tolerance capabilities in the production of narrow slots by electrochemical grinding. The effects of varying machining parameters were studied. Slot tolerance was $\pm 97.79 \mu\text{m}$ with the Al_2O_3 wheel and $\pm 106.68 \mu\text{m}$ with the diamond wheel. The diamond wheel is superior because of its wear resistance.

WAM-jap

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

The Bendix Corporation
Kansas City Division
P. O. Box 1159
Kansas City, Missouri 64141

A prime contractor with the United
States Department of Energy under
Contract Number EY-76-C-04-0613

CONTENTS

Section	Page
SUMMARY.	5
DISCUSSION	6
SCOPE AND PURPOSE.	6
PRIOR WORK	6
ACTIVITY	7
<u>Effects of Process Variables on Overcut</u>	7
<u>Slotting Tests With Al₂O₃ Copper-bond Wheel</u>	9
<u>Cutting Tests With Diamond Wheel</u>	12
<u>Analysis of Test Results</u>	14
ACCOMPLISHMENTS.	17
FUTURE WORK.	17
REFERENCE.	19
DISTRIBUTION	20

ILLUSTRATIONS

Figure		Page
1	Overcut From Measured Wheel Width at a Machining Voltage of 4 V.	8
2	Overcut From Measured Wheel Width at a Machining Voltage of 6 V.	9
3	Overcut From Measured Wheel Width at a Machining Voltage of 8 V.	10
4	Overcut for a Varying Machining Voltage at a Constant Feedrate of 1.27 mm/s.	11
5	Profiles of Cut at Entrance and Exit.	13
6	Tolerance Versus Feedrate	15
7	Overcut Versus Machining Voltage.	16
8	Overcut Versus Feedrate	16
9	Taper Versus Feedrate	17

TABLES

Number		Page
1	Test Results From Slots Produced With Al ₂ O ₃ Copper-bond Wheel	12
2	Test Results From Slots Produced With Diamond-Impregnated Aluminum Wheel.	14
3	Depth-Of-Cut Tolerances From Slots Produced With Diamond-Impregnated Aluminum Wheel	14
4	Comparison of Slots Produced by Al ₂ O ₃ Copper-bond and Diamond Wheels.	18

SUMMARY

Cutting tests were performed to determine tolerance capabilities in the production of narrow slots by electrochemical grinding. Also evaluated were the effects of machining voltage, feedrate, and spark suppression on overcut.

The slotting tests were conducted using Al_2O_3 copper-bond and diamond-aluminum-blade grinding wheels in the 0.508- to 0.762-mm range. The tests were run at a feedrate of 1.27 mm/s and a machining voltage of 3 V.

The results of the cutting tests made while varying the feedrate and machining voltage indicated that low voltage and high feedrate produce the best results; slot tolerance is affected by the feedrate, and, at feedrates below 1.058 mm/s, by the machining voltage; overcut is affected by both the machining voltage and the feedrate; and slot taper is affected by the feedrate, but not by the machining voltage.

The Al_2O_3 copper-bond wheel produced slots with 0.201-mm overcut, $\pm 97.79\text{-}\mu\text{m}$ tolerance, and 60.94- μm taper. The diamond wheel produced slots with 0.325-mm overcut, $\pm 106.68\text{-}\mu\text{m}$ tolerance, and 99.06- μm taper.

The depth-of-cut on the Al_2O_3 wheel exhibited a wear rate of 2.03 μm per pass, while the diamond wheel maintained a depth tolerance of $\pm 40.64\text{ }\mu\text{m}$.

DISCUSSION

SCOPE AND PURPOSE

Cutting tests were performed to determine tolerance capabilities in producing narrow slots by electrochemical grinding. During the development of the machining parameters, separate tests were conducted to determine the effects of machining voltage, feedrate, and spark suppression on overcut.

PRIOR WORK

Prior tests were performed on the electrochemical surface grinder to establish overcut, dimensional-variation, parallelism, flatness, and surface-finish guidelines for the electrochemical grinding of 17-4 PH stainless steel, 303 Se stainless steel, and 6061-T6 aluminum.¹ Based on that study, the following process standards were developed.

- Tolerance

Large Areas: $\pm 50.8 \mu\text{m}$.

Small Areas: $\pm 2.54 \mu\text{m}$.

- Surface Finish

254 to 762 nm.

- Metal Removal

Large Areas: Rough and finish.

Small Areas: Remove material in one pass.

- Current Density

Stainless Steel: 1.55 to 3.10 A/mm².

Aluminum: Approximately 1.55 A/mm².

- Voltage

Stainless Steel: Rough, 7 to 8 V; Finish, 4 to 5 V.

Aluminum: Rough, 5 to 6 V; Finish, 2 to 3 V.

ACTIVITY

Two different widths of Al_2O_3 copper-bond wheels were used in the tests: 0.508 and 0.762 mm. Both were 152.4 mm in diameter with a 76.2-mm-diameter hole. The diamond wheel was 0.813 mm wide and 177.8 mm in diameter, with a 76.2-mm-diameter hole.

The wheels were conditioned before the tests by making cuts in 17-4 PH stainless-steel bars at low voltages and slow feedrates. Both the feedrate and the voltage were progressively increased until the conditioning was complete.

The electrolyte used in the tests was 50 percent KCl and 50 percent KNO_3 , 239.65 kg/m³. The electrolyte was flooded onto the wheel at a rate of 31.5 to 35.8 cm³/s through a flexible plastic tube mounted against the wheel. (Earlier attempts to fit a rigid plexiglass nozzle to the wheel were abandoned. The wheels are so fragile that several broke in trying to set the nozzle.)

Effects of Process Variables on Overcut

Test cuts approximately 5.08 mm deep were made in 19.05-mm-square bars of 17-4 PH stainless steel while varying the feedrate and machining voltage. The machine voltage control provides from 2 to 20 Vdc in 0.2-V increments, and the feedrate control provides from 0.42 to 42.33 mm/s in 0.42-mm/s increments.

With a 0.762-mm-wide Al_2O_3 copper-bond wheel, cuts were made at a machining-voltage setting of 4 V with feedrates of 0.21, 0.42, 0.64, 0.85, 1.06, and 1.27 mm/s. Cuts then were made through the same feedrate progression at voltage settings of 6 and 8 V. The resulting slots were measured in two places: the entrance and the exit.

The results of the slot measurements are shown in Figures 1 through 3. In all cases, the measured overcut was less at the entrance, and it progressively increased through the cut. The slower feedrates produced a greater overcut spread from the entrance to the exit. Likewise, the higher voltages, along with the slow feedrates, resulted in a greater spread of overcut from the front to the back of the bars. No appreciable difference was noted in the overcut at the entrance for feedrates from 0.85 to 1.27 mm/s; however, there was a small difference in the overcut at the exit end. The higher the voltage, the greater effect the feedrate had on the overcut. The least amount of overcut was achieved at the lowest voltage setting with the fastest feedrate that was practical.

Figure 1. Overcut From Measured Wheel Width at a Machining Voltage of 4 V

Another test situation was devised to further determine the effect of the machining voltage on the overcut. For this test, the feed-rate was set at 1.27 mm/s, and cuts were made at machining voltages of 4, 8, 9, 12, and 16 V. The material, depth-of-cut, and other parameters remained the same as had been used in the previous tests. Again, the width of the slots was measured at the entrance and exit ends of the bar.

Figure 4 shows the effect of the machining voltage on the overcut. As indicated, the overcut increased as the voltage increased. Also, the spread in the amount of overcut increased between the entrance and the exit at the higher voltage settings.

Figure 2. Overcut From Measured Wheel Width at a Machining Voltage of 6 V

Using the same material, electrolyte, and grinding wheel, a series of cuts was made with the machining voltage set at 4 V, the feedrate set at 0.846 mm/s, and while varying the spark-suppression control from 0 through 100 percent. (The spark-suppression control modulates the voltage downward whenever excessive sparking or arcing occurs to prevent damage to the workpiece.) The results of these tests showed a reduction in the amount of overcut as the spark-sensitivity setting was increased. The minimum and maximum limits between the entrance and exit remained approximately the same.

Slotting Tests With Al_2O_3 Copper-bond Wheel

As a result of the test data that were obtained while varying the process parameters, the conclusion was reached that the slot

Figure 3. Overcut From Measured Wheel Width at a Machining Voltage of 8 V

tolerance and overcut could best be controlled at a machining voltage of 3 V and a feedrate of 1.27 mm/s. At these settings, a series of cuts was made approximately 5.08 mm deep in 19.05-mm-square bars of 17-4 PH stainless steel with a 0.508-mm-wide copper-bond wheel. The bars were held down by a magnetic chuck mounted on the table of the machine.

The machined slots were inspected for width at both top and bottom, depth, and fillet radius. All features were inspected at the entrance and exit of the cut. The inspection data then were analyzed to determine the overcut and the tolerance on the width, depth, and fillet radii. The results of these tests are shown in Table 1.

Figure 4. Overcut for a Varying Machining Voltage at a Constant Feedrate of 1.27 mm/s

The amount of overcut, dimensional variation, and taper was greater at the exit end of the bars than at the entrance. The slot-width limits at the entrance were 0.536 to 0.632 mm, and the limits at the exit end were 0.582 to 0.719 mm. Since the grinding wheel measured 0.533 mm in width, the maximum overcut of the slots was 0.122 mm at the entrance and 0.208 mm at the exit. The perpendicularity or angularity in the slots showed a left-to-right shift of 73.66 μm at the entrance and 137.16 μm at the exit. Figure 5 is a profile drawing of the cut at the

Table 1. Test Results From Slots Produced With Al₂O₃
Copper-bond Wheel

Slot Characteristic	Location		
	Entrance	Exit	Total Bar
Average Size (mm)	0.584	0.650	0.620
Upper Limit (mm)	0.632	0.719	0.711
Lower Limit (mm)	0.540	0.582	0.528
Minimum Tolerance, 95-Percent Confidence (mm)	0.096	0.137	0.195
Maximum Overcut (mm)	0.121	0.208	0.200
Average Size at Top (mm)	0.594	0.681	
Average Size at Bottom (mm)	0.574	0.620	
Average Taper (μ m)	20.32	60.96	

entrance and exit. The slots were wider at the top than at the bottom, having a taper of 0.020 mm at the entrance and 60.06 mm at the exit.

The fillet radii measured from 0.279 to 0.305 mm at both the entrance and exit ends.

The depth measurements of the slots showed a high rate of wheel wear--approximately 20.32 mm per pass. Because of this large amount of wear, frequent depth adjustment would be required to maintain control of the tolerance. Also observed on the test specimens was the fact that the depth-of-cut was shallower at the exit end than at the entrance. One test bar showed a 0.142-mm change in depth at the exit, while another showed an average change of 35.56 μ m.

Cutting Tests With Diamond Wheel

Because of the large amount of wear experienced on the Al₂O₃ copper-bond wheels, a diamond wheel was purchased and additional cutting tests were made using the same machine settings that had been used on the previous cutting tests (a machining voltage of 3 V with a feedrate of 1.27 mm/s). This series of cuts was made approximately 5.08 mm deep in 6.35- by 19.05-mm bars of 304 stainless steel with a 0.813-mm-wide by 177.8-mm-diameter diamond-impregnated aluminum wheel.

Figure 5. Profiles of Cut at Entrance and Exit

The slots were inspected for width at both top and bottom, depth, and fillet radius. All features were inspected at the entrance and exit ends of the bar, and the inspection data were analyzed to determine the overcut and tolerance. The results of these tests are shown in Table 2.

The high rate of wheel wear that had been indicated by the test specimens cut with the copper-bond wheel was not evident in the bars machined with the diamond wheel. As indicated by Table 3, the depth-of-cut tolerances showed great improvement over the results from the previous tests. There was a 7.62- μm average change in depth from the entrance to the exit of the slots. The average fillet radius was 0.330 mm.

Table 2. Test Results From Slots Produced With
Diamond-Impregnated Aluminum Wheel

Slot Characteristic	Location		
	Entrance	Exit	Total Bar
Average Size (mm)	1.044	1.031	1.036
Upper Limit (mm)	1.146	1.143	1.143
Lower Limit (mm)	0.942	0.919	0.919
Minimum Tolerance, 95-Percent Confidence (mm)	0.203	0.232	0.213
Maximum Overcut (mm)	0.325	0.325	0.325
Average Size at Top (mm)	1.084	1.082	
Average Size at Bottom (mm)	1.003	0.983	
Average Taper (μm)	81.28	99.06	

Table 3. Depth-Of-Cut
Tolerances From
Slots Produced With
Diamond-Impregnated
Aluminum Wheel

Location	Minimum Tolerance, 95-Percent Confidence (μm)
Entrance	55.88
Exit	91.44
Total Bar	81.28

Analysis of Test Results

An analysis of the test results supports the following conclusions.

- Slot tolerance is affected by feedrate (time of electrolysis) and, at feedrates below 1.58 mm/s, by machining voltage (Figure 6).

Figure 6. Tolerance Versus Feedrate

- Overcut is affected by both machining voltage and feedrate (Figures 7 and 8).
- Slot taper is affected by feedrate (Figure 9), but not by machining voltage.
- The fillet radius of the slot is not affected by either the machining voltage or the feedrate; rather, it is affected by wheel conditioning. As the wheel conditioning progresses, the fillet radius decreases.

For control of the size and tolerance of electrochemically ground slots, low machining voltages and high feedrates produce the best results. The Al_2O_3 copper-bond wheels exhibited a high rate of peripheral wear. At the settings used in the tests (a machining voltage of 3 V and a feedrate of 1.27 mm/s), the cutting was predominately mechanical while the electrochemical reaction eliminated any burrs.

Although the diamond wheel did not produce as good a slot as did the Al_2O_3 copper-bond wheel (Table 4), the diamond wheel performed much better with regard to depth control and resistance to wear. The slots produced by electrochemical grinding using both the Al_2O_3 copper-bond and diamond wheels were completely free of burrs.

Figure 7. Overcut Versus Machining Voltage

Figure 8. Overcut Versus Feedrate

Figure 9. Taper Versus Feedrate

With the Al_2O_3 wheel, the amount of taper, tolerance, and overcut can be reasonably controlled at the entrance of the cut (7.62-mm taper, $\pm 48.26\text{-}\mu\text{m}$ tolerance, and 0.122-mm overcut). Variations in all of these parameters increase at the exit because of the electrolysis time.

ACCOMPLISHMENTS

A study to determine the effect of varying electrochemical-grinding parameters on slotting operations has indicated that low machining voltages and high feedrates produce the best results.

Even though the diamond wheel produces greater overcut, tolerance, and taper than does the Al_2O_3 copper-bond wheel, it offers the better approach to slotting because of its better resistance to wear. Both wheels produced burr-free slots.

The utilization of electrochemical grinding as a production slotting process requires a liberal tolerance spread and a generous permissible fillet radius.

FUTURE WORK

Cutting tests will be performed to evaluate two-dimensional form grinding.

Table 4. Comparison of Slots Produced by Al_2O_3
Copper-bond and Diamond Wheels

Slot Characteristic	Type of Wheel	
	Al_2O_3 Copper-bond	Diamond
Overcut (μm)	200.66	325.00
Tolerance, 95-Percent Confidence (μm)	± 96.52	± 106.68
Taper (μm)	60.96	99.06

REFERENCE

¹R. W. Stiles, *Electrochemical Grinding* (Topical Report).
UNCLASSIFIED. Bendix Kansas City: BDX-613-1159, August, 1976
(Available from NTIS).

DISTRIBUTION

	Copy
R. Bulcock, DOE-KCAO	1
A. G. Erny, D/261, FU34	2
H. L. Price, D/261, FU34	3
J. E. Long, D/531, 1B46	4
H. T. Barnes, D/554, BD50	5-6
L. Stratton, D/554, 2C44	7-9
R. P. Frohmberg, D/800, 2A41	10
J. A. Knuth, D/800, 2A40	11
F. J. Boyle, D/821, 2A36	12
W. G. Cooper, D/821, 2A36	13
D. P. Roberts, D/821, 1A27	14
D. R. Wachter, D/821, 2A36	15
C. A. Bier, D/822, 2A36	16
J. P. Dycus, D/822, 2A36	17
J. C. McCoy, D/822, MA40	18
D. D. Oswald, D/822, 2A36	19
R. W. Stiles, D/822, 2A36	20
J. L. Couchman, D/823, 1A27	21
C. E. Spitzkeit, D/823, 1A27	22
R. E. Kessler, D/865, 2C40	23

BDX-613-1908 (Rev.)

SLOTING BY ELECTROCHEMICAL GRINDING, R. W. Stiles, UNCLAS Topical, November 1978.

Cutting tests were performed with both Al_2O_3 copper-bond and diamond grinding wheels to determine tolerance capabilities in the production of narrow slots by electrochemical grinding. The effects of varying machining parameters were studied. Slot tolerance was $\pm 97.79 \mu\text{m}$ with the Al_2O_3 wheel and $\pm 106.68 \mu\text{m}$ with the diamond wheel. The diamond wheel is superior because of its wear resistance.

MECHANICAL: ELECTROCHEMICAL GRINDING

SLOTING BY ELECTROCHEMICAL GRINDING, R. W. Stiles, UNCLAS Topical, BDX-613-1908 (Rev.), November 1978.

Cutting tests were performed with both Al_2O_3 copper-bond and diamond grinding wheels to determine tolerance capabilities in the production of narrow slots by electrochemical grinding. The effects of varying machining parameters were studied. Slot tolerance was $\pm 97.79 \mu\text{m}$ with the Al_2O_3 wheel and $\pm 106.68 \mu\text{m}$ with the diamond wheel. The diamond wheel is superior because of its wear resistance.

SLOTING BY ELECTROCHEMICAL GRINDING, R. W. Stiles, UNCLAS Topical, BDX-613-1908 (Rev.), November 1978.

Cutting tests were performed with both Al_2O_3 copper-bond and diamond grinding wheels to determine tolerance capabilities in the production of narrow slots by electrochemical grinding. The effects of varying machining parameters were studied. Slot tolerance was $\pm 97.79 \mu\text{m}$ with the Al_2O_3 wheel and $\pm 106.68 \mu\text{m}$ with the diamond wheel. The diamond wheel is superior because of its wear resistance.