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Effect of Hole Geometry and Electric-Discharge Machining (EDM) on Airflow Rates Through Small-Diameter Holes in Turbine Blade Material

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National Aeronautics
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Summary

An experimental investigation was conducted to determine the effect on air flow rate of two design parameters, electrode diameter and hole angle, and two machine parameters, electrode current and electrode current-on time. Test specimens were prepared from a typical turbine blade material (IN-100) of a typical thickness (1.6 mm). Holes were electric discharge machined individually in rows of 14 holes each using solid brass electrodes.

Electrode diameters were varied from 0.257 to 0.462 mm, and hole angles (angle between surface normal and centerline of the hole) were varied from 40° to 75°. The ranges of electrode current and electrode current-on time used were from 20 to 40 amperes and from 3 to 19 percent, respectively. Time to EDM individual holes (burn time), hole diameters, air flow-rates, and air-flow-rate deviations were determined as functions of the four control parameters. A cursory metallurgical examination was made of the recast layer and microcracks on the hole surfaces.

The results of the investigation showed an exponential increase in average burn time with increasing hole length (a function of hole angle) and a linear decrease in overburn (difference between finished hole diameter and electrode diameter) with increasing electrode diameter. Average air flow rates per hole increased linearly with the square of the electrode diameter (cross-sectional area) and with electrode current-on time, but changed little with changes in hole angle and electrode current. The average flow-rate deviation (from the mean flow rate for a given row of 14 holes) decreased with electrode diameter, increased with hole angle, and changed very little with electrode current and current on-time. The recast layer was less than 4 percent of the hole diameter, and the microcracks did not extend beyond the limits of the recast layer on the examined specimens.

Introduction

Film-cooled gas turbine vanes and blades often contain a multiplicity of small-diameter (as small as 0.25 mm) holes for ejecting cooling air onto surfaces exposed to the hot gas path. The most commonly used method for putting cooling holes in the

superalloy materials used for turbine components is electric discharge machining (EDM). Fabrication experience has shown that the size (diameter) of the EDM electrode or the hole is not a sufficient criterion for establishing the required cooling-air flow rates through the holes because of difficulties in measuring hole diameters accurately. Hole characteristics such as surface roughness, inlet and exit shapes, length, etc., may significantly affect the resulting hole flow rates. Since heat-transfer analyses of film-cooled components are based on hole cooling-air flow rates, a logical specification and inspection criterion for these holes would be air flow rates. However, no published information exists on the quantity and uniformity of coolant flow through EDM holes; nor is there any known published information on practical tolerances for specifying deviations in flow rates through such holes.

Inherent to the EDM process is the formation of a relatively rough surface where metal is removed by deplating and the creation of a recast layer on this surface as the remaining metal resolidifies. Surface roughness retards airflow and must be controlled or compensated for with a larger hole diameter. The recast layer is the source of microcracks that can propagate into the base metal and can result in structural failure. Therefore, controlling the thickness of the recast layer and the formation of microcracks within this layer are important considerations in the use of EDM for small-diameter cooling air holes.

This report describes an experimental study at the NASA Lewis Research Center to determine under controlled conditions the effect of two design and two machine parameters on the air flow rates through small-diameter EDM holes. The controlled design parameters were electrode diameter and hole angle, and the controlled machine parameters were electrode current and electrode current-on time. The design parameters (electrode size and hole angle) obviously determine the nominal cross-sectional area and length, respectively, of the hole. The machine parameters (electrode current and electrode current-on time) affect the nature of the EDM hole surface.

The study was conducted over ranges of electrode diameters from 0.257 to 0.462 mm, holes angles from 40° to 75°, electrode current from 20 to 40 A, and electrode current-on times from 3 to 19 percent. A typical turbine blade material (IN-100) of a typical thickness (1.6 mm) was used. The air flow rates were

measured for individual holes using room-temperature air discharging to atmospheric pressure at a constant pressure drop across the holes. The results are presented as plots of average-hole flow rate and average-hole flow-rate deviation as functions of each of the controlled parameters. Only a cursory metallurgical examination of the recast layer and its indigenous microcracks was performed.

Symbols

- B* barometric pressure downstream of holes, kPa
D diameter, mm
L hole length, mm
n hole number in row, 1 to 14
P total pressure upstream of holes, 55.2 kPa above barometric pressure
T absolute temperature, K
t burn time, sec
W flow rate per hole, mg/sec
 θ hole angle measured between the surface normal and the hole centerline, deg
 γ isentropic exponent, 1.40
 τ percent time that the electrode current is turned on
 Δ flow-rate deviation of the holes in a row, percent

Subscripts

- av* mean average in a row of 14 alike holes
e electrode
h finished hole
m measured condition
n hole number in row, 1 to 14
s standardized condition (temperature of 289.8 K and barometric pressure of 101.7 kPa)

Apparatus

Test Specimens

Test specimens were made from vacuum-cast IN-100 (nickel alloy) strips 1.6 mm thick, 4.7 cm long, and 3.5 cm wide. Identical round holes were electric discharge machined individually into these strips to form specimens rows of 14 holes each. In each specimen row the 14 holes making up the row were machined with all four control parameters held constant. Eighteen strips, with a maximum of 5 rows

per strip and a total of 62 rows, were prepared. All machining was done with solid brass electrodes. The diameters of the electrodes used in this study were measured within 0.00127 mm. Industry standards for these size electrodes allow ± 0.0127 -mm tolerance on the diameter.

The two design parameters investigated were electrode diameter and hole angle (the angle between the surface normal and the hole centerline). Electrode diameter of 0.257, 0.272, 0.361, and 0.462 mm and hole angles of 40°, 60°, and 75° were used. These values covered the ranges of interest for typical holes in film-cooled turbine blades and vanes.

The two machine parameters investigated were electrode current and electrode current-on time. Currents of 20, 30, and 40 A and current-on times of 3, 6, 11, and 19 percent were used. The range of current levels covered slow to fast burn rates; burn rates affect surface roughness and the development of the recast layer with its attendant microcracks. The range of current-on times permitted an evaluation of the oil flushing effectiveness on burn rate and surface condition. Only the 3 percent current on time was used with all variations of each of the other control parameters. For the other current-on times, selected values of the other parameters were used.

EDM Equipment

The EDM machine used in the preparation of test specimens for this experimental investigation had a power supply that was adapted for the drilling of small-diameter holes.

Airflow Measuring System

The system used to measure the cooling-air flow rates through the small-diameter EDM film-cooling holes is shown in figure 1; this system is similar to and is based on experience from the one described in reference 1. Pressurized air at about 860 kPa entered the measuring system through a control valve and passed through a filter and a pair of pressure regulators which reduced the pressure to 206.8 kPa. The air then passed through a rotameter and a throttling valve to the test strip holder. Air exited the test strip through one of the EDM holes in one of the test specimen rows; all other holes in the test strip were sealed with vinyl tape during a given measurement. The accuracy of the rotameter was ± 1 percent of the full-scale reading, the accuracy of the pressure gages was ± 0.3 kPa, and the accuracy of the temperature gages was ± 0.3 K. Accuracy of the airflow measuring system was ± 1.5 percent.

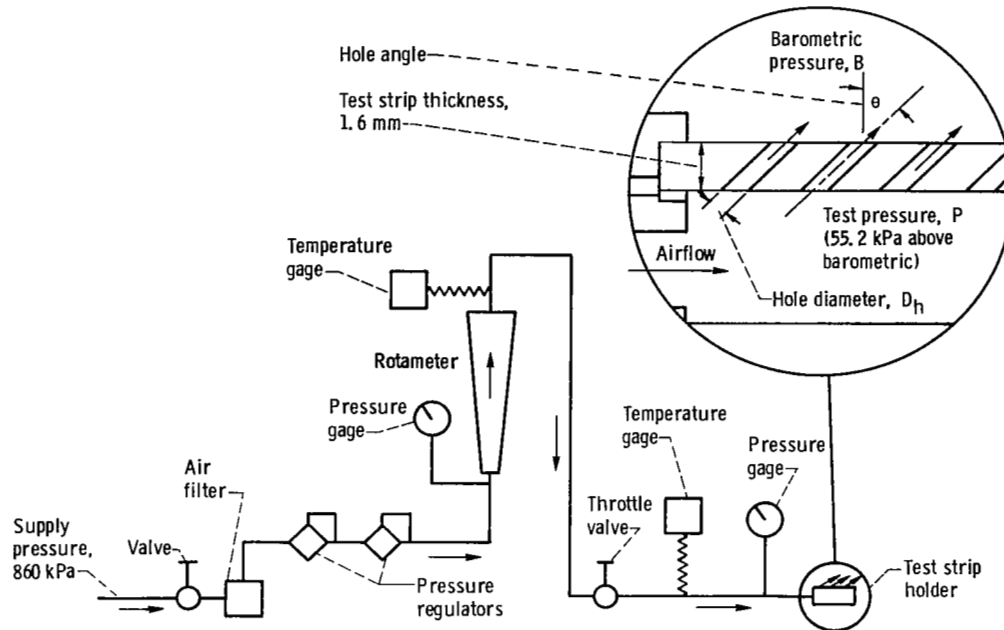


Figure 1. - Flow measuring apparatus with test strip holder.

Experimental Procedure

Measurement of Burn Time and Finished Hole Diameter

During the machining of the holes, burn time (in seconds) was measured for individual holes with a stop watch. Subsequently, hole diameter was measured using a set of round gage pins graduated in 0.0254-mm increments. The hole diameter was defined as the average of the diameter of the largest pin that would pass through a given hole and the smallest pin that would not pass through the hole. Accurate hole diameters are very difficult to measure because the surfaces of the EDM holes are very irregular and gage pins are calibrated in large increments compared with the hole diameters. Because of the inherent "overburn" in EDM, the hole diameter will always be larger than the diameter of the electrode used to make the hole.

Measurement of Air Flow Rates

Individual measurements of air flow rates through each of the EDM holes were made. All holes in the test strip except one were sealed with vinyl tape before testing. Then the strip was mounted in the specimen holder in the flow measuring system and

subjected to a constant pressure difference of 55.2 kPa between the pressure inside the holder and atmospheric (barometric) pressure. This value of constant pressure drop was chosen because experience has shown that the flow coefficients of the holes are less sensitive to pressure drop variations at this value (approximately half an atmosphere) than at other values. Temperature, pressure, and flow readings at the rotameter and temperature, internal pressure, and barometric pressure readings at the test specimen holder were recorded for flow through each individual hole.

Analytical Procedure

Standardization of Measured Flow Rates

The measured air flow rates through the EDM holes were standardized to correct for the effect of air density variations. The following equation comes from the standard, one dimensional, isentropic flow equations to adjust for differences in pressure ratio in reference 2:

$$\frac{P_s}{P_m} \sqrt{\frac{T_m}{T_s}} \sqrt{\frac{(B/P)_s^{2/\gamma} - (B/P)_s^{(\gamma+1)/\gamma}}{(B/P)_m^{2/\gamma} - (B/P)_m^{(\gamma+1)/\gamma}}} \quad (1)$$

(All symbols are defined in Symbols.) Using a standard temperature of 289.8 K, a standard barometric pressure of 101.7 kPa, and a standard upstream pressure of 156.9 kPa, this correction factor becomes:

$$2.308 \sqrt{\frac{T_m}{P_m}} \sqrt{\frac{1}{(B/P)_m^{2/\gamma} - (B/P)_m^{(\gamma+1)/\gamma}}} \quad (2)$$

All measured flow rates were multiplied by this correction factor to arrive at a common basis for comparison.

Averaging of Standardized Flow Rates

The standardized flow rates for the individual holes in each row of 14 holes were averaged to obtain a single value of flow rate to be used in correlations with the controlled parameters. This averaging was done using the following relationship.

$$W_{av} = \frac{\sum_{n=1}^{n=14} W_n}{14} \quad (3)$$

Deviations of Standardized Flow Rates

The variation of flow rate in the individual holes in each row of 14 holes was evaluated by determining an average deviation of the standardized flow rate for each row using the following relationship:

$$\Delta_{av} = \frac{100 \sum_{n=1}^{n=14} (W_n - W_{av})/W_{av}}{14} \quad (4)$$

Statistical Analyses

Statistical analyses (analysis of variance of factorial experiments, ref. 3) were made of the hole flow rate, average flow rate deviation, and burn time data. This analytical technique shows whether variations in test results that are due to planned changes in the control parameters can be distinguished from variations that are due to system errors (ref. 4). Where variations due to the control parameters are distinguishable, the data will be presented as functions of these parameters.

Results and Discussion

The burn times, finished holes diameters, air flow rates, and flow-rate deviations for small-diameter, EDM holes in 1.6-mm-thick IN-100 strips using solid brass electrodes are presented herein as functions of the two design parameters, electrode diameter and hole angle, and the two machine parameters, electrode current and electrode current-on time. A brief discussion of the recast layer and the microcracks that resulted from the EDM process is also given.

Average Burn Time and Average Finished Hole Diameter

The average burn time (time in seconds to EDM an individual hole) for the experimental specimen rows are tabulated on table I. The analysis of variance for these data showed that the significant influencing parameter was hole length. Because the test strip thickness in this investigation was constant, hole length was directly related to hole angle. Figure 2 is a plot of the average burn times for all 3-percent electrode current-on time data against hole length. A least square curve fit of these data is

$$t_{av} = 18e^{0.35L} \quad (5)$$

The average burn time increased exponentially from 37 to 154 sec as the hole length increased from 2.07 to 6.13 mm. The maximum variation from the curve fit was ± 24 percent over the full range of control parameters.

The relationship between electrode diameter and finished hole diameter is shown in figure 3. Each plotted point represents several measurements of measured hole diameter. Because the "go, no-go" pin measurements for hole diameter were very approximate, the hole diameters recorded for the two smallest electrodes are identical. A least squares curve fit of the average finished hole diameter for each of the four electrode diameters is

$$D_h = 0.855 D_e = 0.129 \quad (6)$$

The maximum variation of the measured finished hole diameter from the curve fit was only 4.4 percent. This comparison is based on electrode diameters that were measured within 0.00127 mm. If industry standards of ± 0.0127 mm had been allowed, the variation would have been much greater.

TABLE I. - EXPERIMENTAL DATA

Specimen row	Design parameters		Machine parameters		Average burn time, sec	Average hole diameter ^b , mm	Average hole flow rate, mg/sec	Average hole flow rate deviation, percent		
	Electrode diameter ^a , mm	Hole angle, deg	Electrode current, A	Current on time, percent						
54	0.257	40	20	3	48.14	0.356	26.283	3.81		
55		40	30		41.23		27.531	5.41		
56		40	40		28.21		26.712	2.48		
57		60	20		54.43		24.607	4.50		
58			30		47.21		24.910	4.74		
59			30		52.00		25.313	5.83		
60			30		53.67		26.283	4.31		
61			75	40			56.07	25.464	6.16	
62				20			180.38	26.850	6.41	
46		0.272	40	30	3		-----	0.356	28.198	2.29
47	60		20		-----	26.901	3.57			
48			30		-----	29.786	4.44			
49					-----	28.047	3.48			
50					-----	29.055	6.43			
51					-----	29.131	7.58			
52					-----	27.316	4.54			
53					-----	28.035	3.09			
1	0.361	40	20	3	29.93	0.432	40.546	0.83		
2			30		35.07		42.008	1.90		
3				30			33.50	41.869	1.72	
4				30			36.79	41.819	1.76	
5				40			36.07	47.136	2.72	
6			60	20			53.86	40.723	2.06	
7							51.36	38.581	1.92	
8							64.36	40.105	2.52	
20							6	63.57	40.823	1.50
25							11	37.21	44.830	2.19
9					30		3	60.86	41.819	5.02
10							3	67.29	41.529	2.12
11								67.64	42.701	2.53
12								-----	42.234	1.56
13								-----	41.516	2.53
21					6		53.71	45.233	3.93	
22					6		48.29	44.024	2.29	
23					6		54.57	45.095	3.73	
26					11		66.29	45.069	1.86	
27					19		47.83	47.602	1.81	
28				19	44.77	47.438	2.88			
29				19	43.15	46.329	2.21			
14		75	40	3	60.36	42.915	2.53			
15				3	58.71	41.542	1.61			
16				3	63.29	42.159	1.92			
24				6	96.57	44.200	2.93			
30				11	75.43	45.032	3.41			
17				20	3	155.80	41.680	3.77		
18				30	3	158.93	42.839	4.51		
19				40	3	125.36	42.663	3.92		
31	0.462		40	20	3	42.86	0.533	60.025	0.54	
32					3			42.57	60.366	.76
33					3			44.07	60.114	.85
34					6			39.57	61.928	.84
35					11			28.29	64.020	.99
36					30	3		31.86	62.747	.90
37					40			29.14	62.936	.83
38				60	20			51.64	57.871	.41
39					30			47.36	59.471	1.26
40					30			46.93	60.340	1.37
41					30			49.64	61.109	1.20
42					40			56.21	61.122	1.07
43				75	20			146.92	57.37 ^c	.91
44				75	30			135.62	60.731	3.35
45				75	40			123.90	62.848	2.05

^a±0.00127 mm.

^b±0.0127 mm.

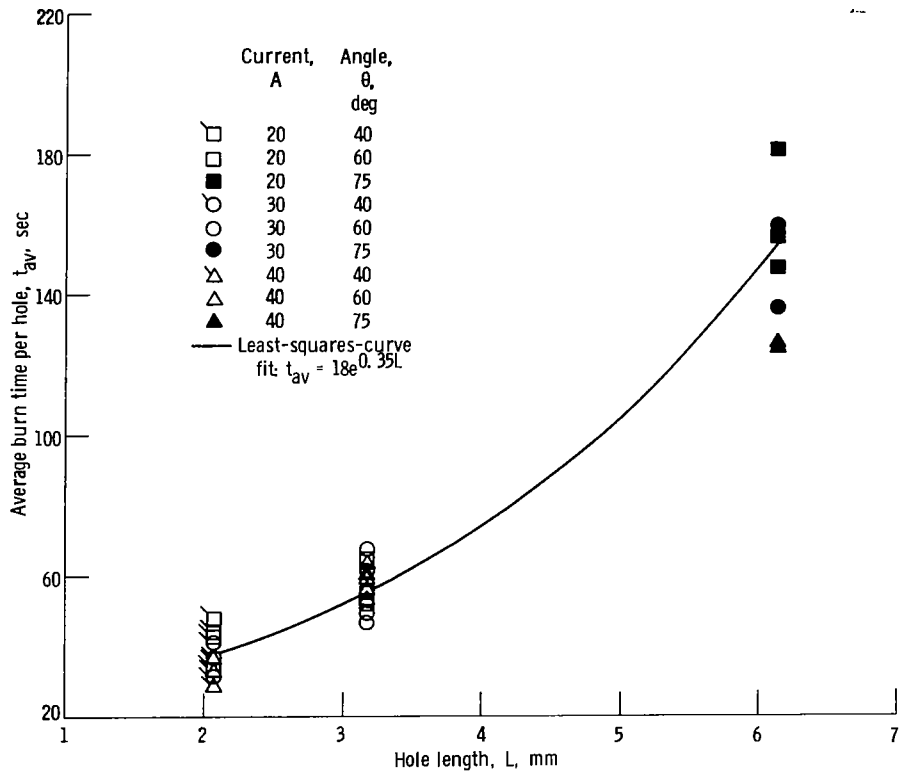


Figure 2. - Average burn time as function of hole length.

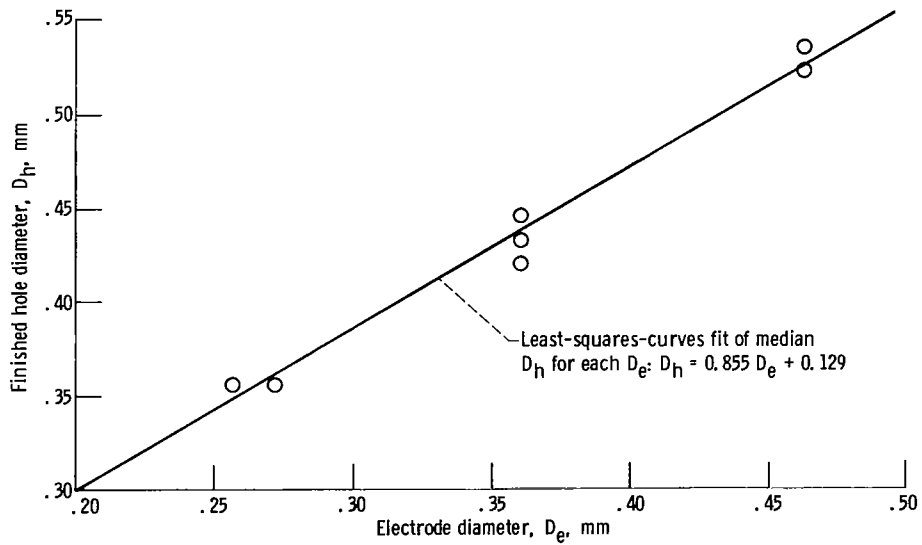


Figure 3. - Finished hole diameter as function of hole diameter.

It can also be seen from the figure that the overburn (defined as $D_h - D_e$), decreased linearly from 0.09 to 0.06 mm (or from 35 percent to 13 percent) as the electrode diameter increased from 0.257 to 0.462 mm.

Average Hole Flow Rate

The average flow rate per hole as a function of electrode diameter squared is shown in figure 4 for the full ranges of hole angle and electrode current and for an electrode current-on time of 3 percent. A least-squares-curve fit of the average of the flow rates for each value of electrode diameter squared is

$$W_{av} = 232.74 D_e^2 + 11.06 \quad (7)$$

Based on this curve fit, the average flow rate per hole increased from 26.4 to 60.7 mg/sec, a 2.3-fold increase, as D_e^2 increased from 0.066 to 0.213 mm², a 3.23-fold increase. However, if the corresponding finished hole diameters from figure 3 are substituted for the electrode diameters, then the area ratio (or ratio of finished hole diameters squared) is 2.25. This ratio agrees closely with the ratio of the flow rates, as would be expected. The maximum variation from the curve fit of figure 4 was ± 5.8 mg/sec or ± 12.3 percent of the flow rate. As expected, the analysis of

variance confirmed that the flow rate per hole was a very strong function of electrode diameter.

The average flow rate per hole as a function of hole angle is shown in figure 5 for the full ranges of electrode diameters and electrode currents and for an electrode current-on time of 3 percent. The lines in the figure connect the mean values of points having the same electrode diameter and electrode current at each hole angle. It can be seen from the figure that hole angle (or hole length) has very little effect on average flow rate per hole, which remained within ± 6.3 percent for the full range of hole angles when the same electrode diameter and electrode current were used.

The average flow rate per hole as a function of electrode current is shown in figure 6 for the full ranges of hole angles and electrode diameters and for an electrode current-on time of 3 percent. The electrode current had little effect on the average flow rate per hole; the flow rate remained within ± 7.5 percent for the full range of electrode currents when the same hole angle and electrode diameter were used. The analysis of variance confirmed that the electrode current had little effect; it also showed that there was a very small effect of the interaction of electrode diameter and electrode current. This trend can be seen in figure 6 where the curves are not all parallel.

The average flow rate per hole as a function of electrode current-on time is shown in figure 7 for the full range of electrode currents and for electrode

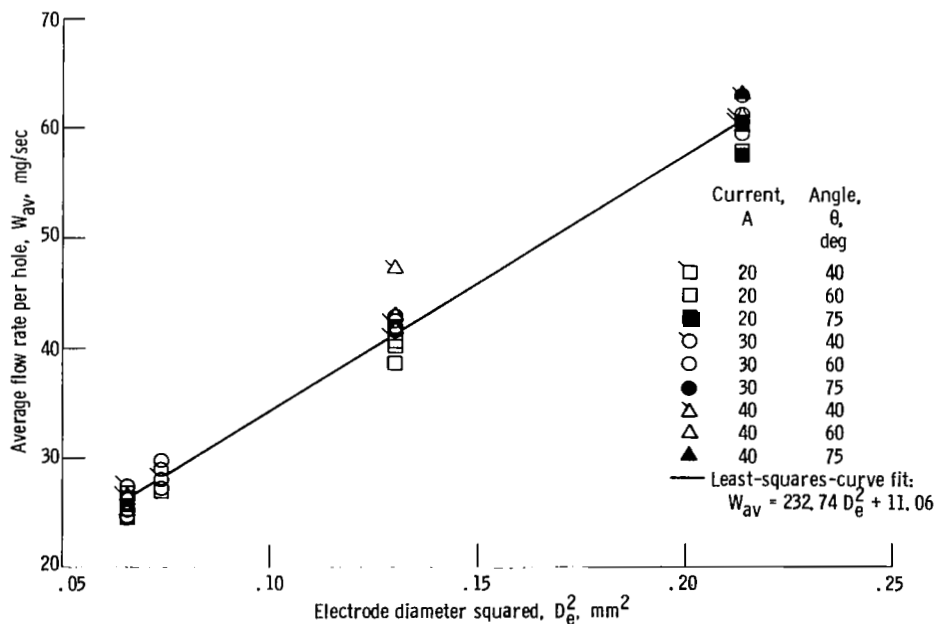


Figure 4. - Flow rate per hole as function of electrode diameter squared.

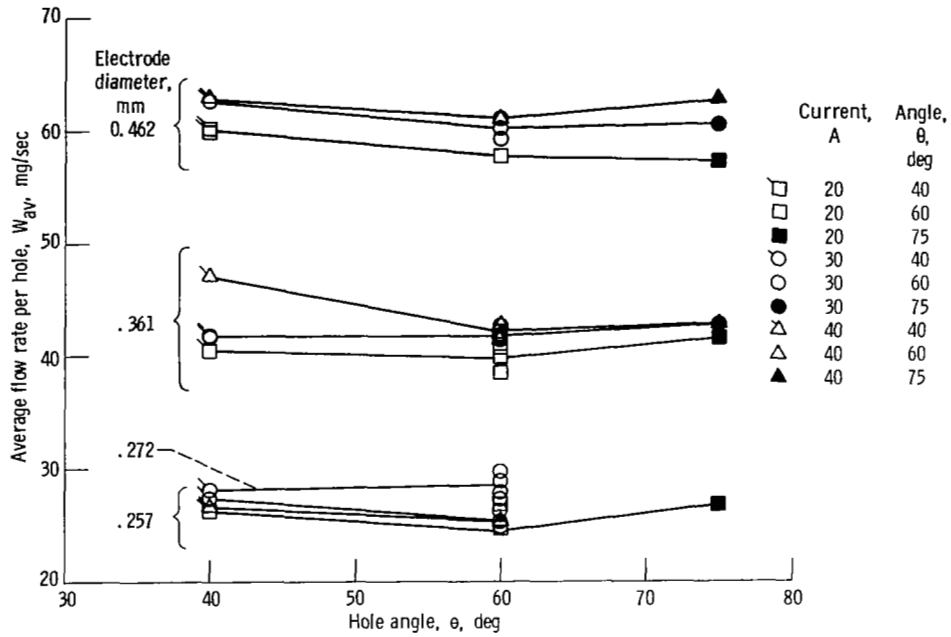


Figure 5. - Flow rate per hole as function of hole angle (measured between the surface normal and the hole centerline). Lines are mean of average flow rate per hole (same electrode diameter and current).

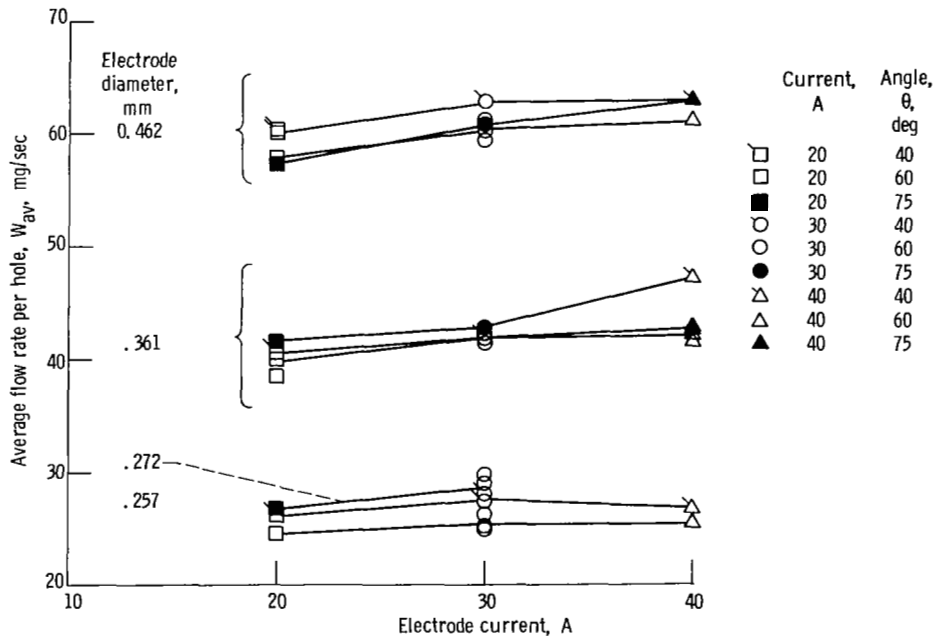


Figure 6. - Flow rate per hole as function of electrode current. Lines are mean of average flow rate per hole (same electrode diameter and angle).

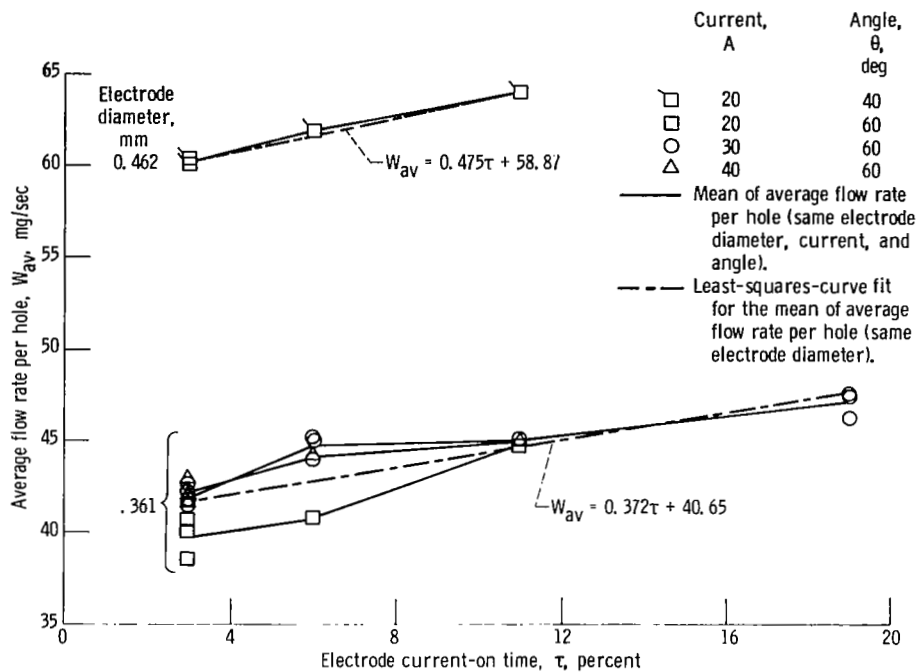


Figure 7. - Average flow rate per hole as function of percent electrode current-on time.

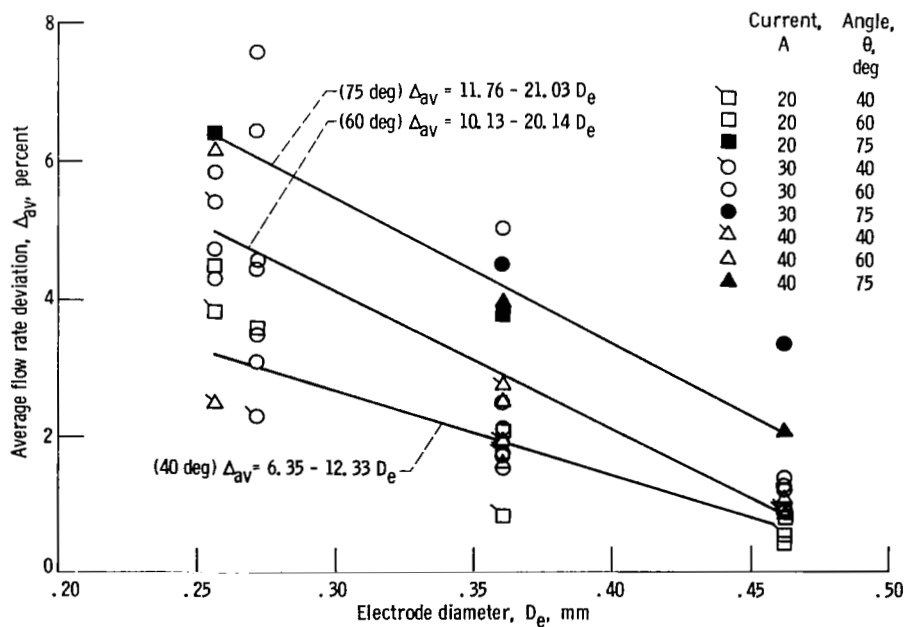
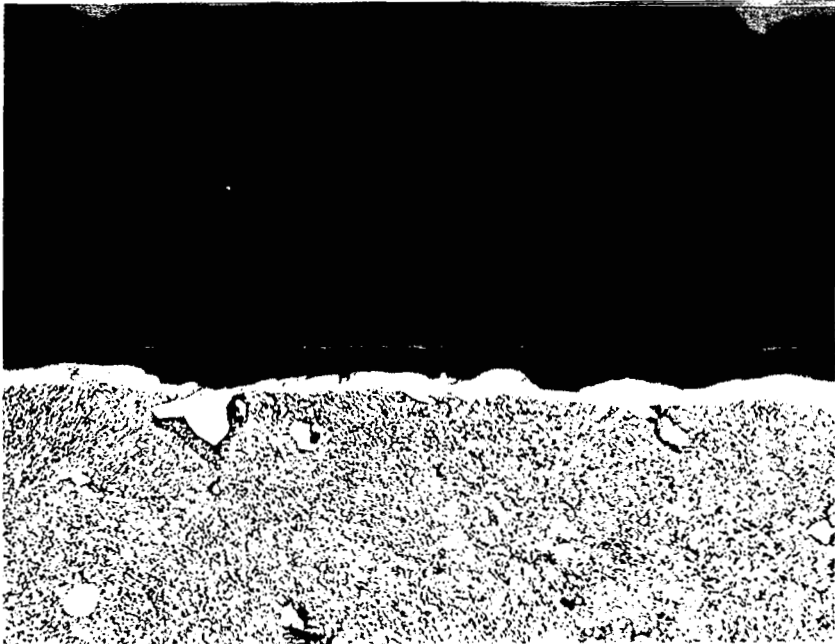


Figure 8. - Average flow rate deviation (from mean among all holes in a row) as function of electrode diameter. Lines are least-squares-curve fits of mean of average flow rate deviation at same hole angles.



(a) Magnification, X50.



(b) Magnification, X250.

Figure 9. - Microphotographs of cross section of typical EDM hole in IN-100 material.



diameters of 0.361 and 0.462 mm and hole angles of 40° and 60°. The solid lines in the figure connect the mean values of points having the same electrode diameter, hole angle, and electrode current at each electrode current-on time. Least square curve fits of these mean values are

$$W_{av} = 0.372 \tau + 40.65 \quad (8)$$

for an electrode diameter of 0.361 mm and

$$W_{av} = 0.475 \tau + 58.87 \quad (9)$$

for an electrode diameter of 0.462 mm. For the smaller electrode and a hole angle of 60°, the average flow rate per hole, based on these curve fits, increased 14.2 percent for an increase in electrode current-on time from 3 to 19 percent. For the larger electrode diameter, a hole angle of 40°, and an electrode current of 20 A, the average flow rate per hole increased 6.3 percent for an increase in current-on time from 3 to 11 percent.

Average Hole Flow Rate Deviations

The variation in flow rates through the 14 holes in each row (average flow-rate deviations from the mean flow rate for the row) were determined by using equation (4). The analysis of variance showed that the average flow-rate deviation was affected significantly by electrode diameter, slightly by hole angle (or hole length), and little by electrode current and current-on time. Therefore, the data were plotted as a function of the electrode diameter. This relationship is shown in figure 8 where all points are at an electrode current-on time of 3 percent. Least square curve fits of the data are

$$\text{for } 40^\circ \text{ hole angle, } \Delta_{av} = 6.35 - 12.33 D_e \quad (10)$$

$$\text{for } 60^\circ \text{ hole angle, } \Delta_{av} = 10.13 - 20.14 D_e \quad (11)$$

$$\text{for } 75^\circ \text{ hole angle, } \Delta_{av} = 11.76 - 21.03 D_e \quad (12)$$

It can be seen from the figure that the average flow-rate deviation decreased linearly with electrode diameter and increased with hole angle. For the full range of parameters tested, the maximum average flow rate deviation was less than 7.6 percent.

Recast Layer and Microcracks

The scope of this experimental investigation did not include an in-depth study of the formation of a recast layer and microcracks that are inherent in the EDM process. However, some samples of EDM holes in IN-100 specimens were subjected to metallographic inspection to determine the general nature of these factors. Figure 9 shows microphotographs of a sample. For the electrode currents, electrode current-on times, electrode diameters, and hole angles used for these samples, the recast layer did not exceed 0.016 mm (4 percent of the hole diameter), and the microcracks did not extend beyond the limits of the recast layer. (Note: Some slight taper in an EDM hole is normal, but the apparent exaggerated taper of the hole in figure 9(a) is due to the fact that the specimen was not cut exactly on the centerline of the hole.)

Concluding Remarks

On the basis of the results from this experimental investigation of air flow rates through small diameter EDM holes, it can be concluded that for the range of parameters tested flow rates are reproducible within acceptable tolerances and that the effects of the control parameters used (electrode diameter, hole angle, electrode current, and electrode current-on time) can be evaluated accurately or are negligible. In this investigation the electrode diameters were measured within 0.00127 mm. If industry standards of ± 0.0127 mm had been allowed, the variation in flow rate would have been much greater.

All of the holes in this experimental investigation were electric discharge machined individually, and the average burn times presented are on an individual hole basis. In a production effort, rows of holes with like diameters and angles would possibly be machined simultaneously. Therefore, the recorded average burn times per hole may not be meaningful for production estimates. However, these times are applicable to model making and do show that, from a manpower/machine time standpoint, individual-hole electric discharge machining is a feasible way to produce test models.

Summary of Results

The results of an experimental investigation to determine the effects of two design parameters (electrode diameter and hole angle) and two machine parameters (electrode current and electrode current-on time) on the airflow and physical characteristics of small-diameter holes that were machined

individually into superalloy material by electrical discharge machining (EDM) are summarized below. The ranges of the parameters tested were electrode diameter from 0.257 to 0.462 mm, hole angle from 40° to 75°, electrode current from 20 to 40 A, and electrode current-on time from 3 to 19 percent. Over these ranges of the control parameters

1. The average flow rate per hole was found
 - a. to increase linearly with the square of the electrode diameter (by a factor of 2.3 for an 80 percent increase in diameter)
 - b. to be affected little (± 6.3 percent) by hole angle (related to hole length)
 - c. to be affected little (± 7.5 percent) by doubling the electrode current
 - d. to increase linearly by 14.2 percent for a 6.3 times increase in electrode current-on time.
2. The average flow rate deviation (from the mean flow rate for a given row of 14 holes) was found
 - a. to decrease linearly by a factor of about 3 as the electrode diameter increased by a factor of 1.8
 - b. to increase as the hole angle increased
 - c. not to be affected significantly by electrode current and electrode current-on time
 - d. to have maximum deviations of less than 7.6 percent for all tested values of the control parameters.
3. The average burn time per hole increased exponentially (from 37 to 154 sec) with an increase in hole length from 2.07 to 6.13 mm.

4. The electrode overburn (difference between finished hole diameter and electrode diameter) decreased linearly from 0.09 to 0.06 mm with an increase in electrode diameter from 0.257 to 0.462 mm.

5. A cursory metallographic examination showed that the thickness of the recast layer was less than 4 percent of hole diameter and that the microcracks present did not extend beyond the limits of the recast layer.

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National Aeronautics and Space Administration,
Cleveland, Ohio, April 14, 1980,
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16. Abstract The effects of two design parameters, electrode diameter and hole angle, and two machine parameters, electrode current and current-on time, on air flow rates through small-diameter (0.257 to 0.462 mm) electric-discharge-machined (EDM) holes were measured. The holes were machined individually in rows of 14 each through 1.6-mm-thick IN-100 strips. The data showed linear increase in air flow rate with increases in electrode cross-sectional area and current-on time and little change with changes in hole angle and electrode current. The average flow-rate deviation (from the mean flow rate for a given row) decreased linearly with electrode diameter and increased with hole angle. Burn time and finished hole diameter were also measured.			
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