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**MACHINING STUDY OF A
URANIUM-4 WEIGHT PERCENT NIOBIUM ALLOY**

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MACHINING STUDY OF A URANIUM-4 WEIGHT PERCENT NIOBIUM ALLOY

John E. Fuller and John K. Lynch

Abstract. A machining study was made of a uranium-4.3 weight percent niobium alloy. Tool force and surface finish were determined as functions of six machining and tool-geometry variables. Parameters investigated were nose radius, top rake angle, front clearance angle, feed rate, surface speed, and depth of cut. Variables were changed according to an experimental plan dictated by statistical considerations. With each new combination of variables, tool force and surface finish could be observed. Two empirical equations, one for tool force and one for surface finish, have been derived as functions of the independent variables.

Advantageous tool-force minima were observed in surface speed and feed rate. Using mathematical models, optimum machining conditions have been developed for rough and finish cuts.

INTRODUCTION

The uranium-niobium alloy system offers an unusual combination of properties including corrosion resistance, favorable mechanical properties, and high density.

The material under study, a 4.3-weight percent niobium alloy, has a highly twinned monoclinic structure closely related to the orthorhombic structure of pure uranium.¹ The alloy can be age-hardened in order to get a wide range of mechanical properties.²

Because of a projected production application, a machining study of the alloy was undertaken. The parameters investigated were nose radius, top rake angle, front clearance angle, feed rate, surface speed, and depth of cut. Dependent variables included tool force and surface finish. Tool wear was observed, but not considered as a formal dependent variable in the mathematical analysis.

¹ M. Anagnostidis, M. Colombie, and H. Mont. "Phases Mestables dans les Alliages Uranium-Niobium." *Journal of Nuclear Materials*, 11:87. 1964.

² R. J. Jackson and D. V. Miley. "Tensile Properties of Gamma Quenched and Aged Uranium-Base Niobium Alloys." *Transactions of the American Society for Metals*, 61:2. 1968.

EXPERIMENTAL

The material used in the experiment was back-extruded into a closed-end hollow cylinder, 6 inches in diameter and 7 inches long, with a 0.75-inch wall thickness. (Metric conversion: 1 inch = 25.4 millimeters.) The extrusion was carried out at 788 °C. The cylinder was reheated to the same temperature and water-quenched. The piece was then age-hardened to a Rockwell-A reading of 59.

Wet-chemical analysis of the alloy yielded a niobium content of 4.30 percent. Emission spectroscopy yielded the following impurities in parts per million (ppm):

Aluminum	30	Silicon	150
Lead	5	Copper	10

All other impurities were below the detection limits.

The data for the experiment were collected according to a statistically designed experimental plan, known as a central composite design.³ The central composite design was made up of a 2⁶ factorial experiment (Points 1 through 64 in Table I), which permitted the estimation of curvature effects of the six variables.

A 14-inch swing Monarch⁴ engine lathe with continuously variable speed control was used. Tool forces could be determined on three orthogonal axes, one parallel to the spindle axis (x), one coincident with the tool and perpendicular to the work piece tangent plane (y), and the third tangent to the work piece (z). The experimental apparatus is shown in Figure 1. The forces were determined using a three-component dynamometer and were recorded with a multichannel recorder using light-beam galvanometers with photosensitive recording paper. During the experiment, an internal standard was used for frequent force calibrations. The standard was checked before and after the experiment with accurate weights. Surface finish was measured with a hand-held profilometer which had been checked against a master plate, certified by the Rocky Flats Standards Laboratory. The instrument used was accurate to ±5 percent on all scales.

³ O. L. Davies. *Design and Analysis of Industrial Experiments*. Hafner Publishing Company, New York. 1954.

⁴ Monarch Machine Tool Company, Sidney, Ohio.

TABLE I. Comparison of experimental and calculated values for tool force and surface finish.
(For Points 1 through 64, central composite design was made up of 2^6 factorial experiment.)

Point No.	Nose Radius (inches) ($\times 10^{-2}$)	Rake Angle (degrees)	Clearance Angle (degrees)	Feed Rate (inches) ($\times 10^{-3}$)	Surface Speed (feet per minute)	Depth of Cut (inches) ($\times 10^{-3}$)	Tool Force		Surface Finish	
							Observed	Calculated	Observed	Calculated
							(pounds)		(microinches, AA)	
1	2	3	9	3.	250	1.92	8.02	10.99	15	16.64
2	4	3	9	3.			10.28	8.83	8	12.92
3	2	9	9	3.			4.90	4.19	7	8.13
4	4	9	9	3.			5.55	5.15	9	5.33
5	2	3	13	3.			7.13	7.08	15	9.83
6	4	3	13	3.			5.22	3.38	10	7.76
7	2	9	13	3.			3.75	3.42	9	11.97
8	4	9	13	3.			5.18	6.34	9	9.93
9	2	3	9	6.9			15.72	12.31	50	39.69
10	4	3	9	6.9			6.65	8.33	17	20.12
11	2	9	9	6.9			7.59	8.38	29	35.20
12	4	9	9	6.9			7.43	6.28	20	16.67
13	2	3	13	6.9			11.33	10.16	20	32.80
14	4	3	13	6.9			4.93	6.28	20	14.09
15	2	9	13	6.9			7.15	7.94	50	39.11
16	4	9	13	6.9			8.65	8.13	15	21.26
17	2	3	9	3.	650		9.64	13.93	15	15.93
18	4	3	9	3.			10.21	11.32	8	12.27
19	2	9	9	3.			7.61	6.28	7	8.15
20	4	9	9	3.			8.21	8.36	9	5.16
21	2	3	13	3.			8.47	8.47	15	10.19
22	4	3	13	3.			8.98	6.03	10	7.74
23	2	9	13	3.			6.10	5.54	9	12.80
24	4	9	13	3.			8.24	9.59	9	10.55
25	2	3	9	6.9			16.50	12.64	40	37.02
26	4	3	9	6.9			9.33	9.70	17	17.34
27	2	9	9	6.9			9.44	9.33	25	33.12
28	4	9	9	6.9			10.40	8.31	20	14.45
29	2	3	13	6.9			11.73	10.46	20	31.00
30	4	3	13	6.9			6.65	7.68	16	12.11
31	2	9	13	6.9			8.00	8.90	50	37.87
32	4	9	13	6.9			10.78	10.15	15	19.88
33	2	3	9	3.	250	7.03	17.32	17.74	12	15.54
34	4	3	9	3.			20.62	17.28	10	11.38
35	2	9	9	3.			12.22	11.41	11	6.85
36	4	9	9	3.			13.83	14.21	8	3.60
37	2	3	13	3.			12.44	12.93	12	8.84

TABLE I (continued)

38	4	3	13	3.	250	7.03	14.82	15.05	6	5.34
39	2	9	13	3.			10.97	9.56	6	10.83
40	4	9	13	3.			10.44	14.67	9	8.27
41	2	3	9	6.9			29.67	26.19	45	39.59
42	4	3	9	6.9			18.52	21.94	19	19.78
43	2	9	9	6.9			17.13	19.90	28	35.47
44	4	9	9	6.9			18.74	18.39	18	16.55
45	2	3	13	6.9			20.81	21.06	25	32.98
46	4	3	13	6.9			19.06	19.01	20	13.86
47	2	9	13	6.9			17.18	17.45	46	39.51
48	4	9	13	6.9			21.24	18.41	20	21.32
49	2	3	9	3.	650		19.52	18.75	12	15.51
50	4	3	9	3.			22.54	19.43	10	11.13
51	2	9	9	3.			16.25	13.09	11	7.37
52	4	9	9	3.			14.61	17.03	8	3.89
53	2	3	13	3.			13.92	13.98	13	9.60
54	4	3	13	3.			17.93	17.22	6	5.89
55	2	9	13	3.			13.68	11.29	6	12.14
56	4	9	13	3.			14.91	17.53	9	9.36
57	2	3	9	6.9			28.46	26.26	45	37.50
58	4	3	9	6.9			22.42	22.92	17	17.46
59	2	9	9	6.9			17.32	20.43	28	33.91
60	4	9	9	6.9			20.54	20.04	12	14.78
61	2	3	13	6.9			20.03	20.96	25	31.66
62	4	3	13	6.9			19.93	20.02	15	12.35
63	2	9	13	6.9			16.78	18.02	45	38.73
64	4	9	13	6.9			21.75	20.09	20	20.36
65	1	6	11	4.8	450	3.67	8.23	10.95	45	39.44
66	5	6	11	4.8			11.82	11.41	10	17.22
67	3	0	11	4.8			10.68	14.75	10	10.23
68	3	12	11	4.8			9.87	8.10	8	9.42
69	3	6	7	4.8			10.50	13.27	13	12.95
70	3	6	15	4.8			9.91	9.44	10	11.70
71	3	6	11	1.3			6.44	7.00	5	52.53
72	3	6	11	8.4			12.03	13.77	28	29.40
73	3	6	11	4.8	50		15.34	15.23	17	19.59
74	3	6	11	4.8	850		15.96	18.37	19	18.06
75	3	6	11	4.8	450	1.	1.42	3.99	11	11.52
76	3	6	11	4.8	450	13.4	25.33	19.20	12	11.13
77	3	6	11	4.8	450	3.67	11.00	12.25	12	10.69

FIGURE 1. Plan view of experimental setup.

FIGURE 2. Tool geometry shows the experimental variables: nose radius, rake angle, and front clearance angle. The relationship of the three orthogonal axes (x, y, z) to the tool is noted also.

TABLE II. Experimental ranges of machining parameters.

	Low	Median	High
Nose Radius, inches	0.01	0.03	0.05
Rake Angle, degrees	0	6	12
Clearance Angle, degrees	7	11	15
Feed Rate, inches per revolution	0.0013	0.005	0.0084
Surface Speed, feet per minute	50	450	850
Depth of Cut, inches	0.001	0.0037	0.0134

NOTE: 1 inch = 25.4 millimeters, and
1 foot = 30.48 centimeters.

The experimental ranges of the independent variables are given in Table II. Figure 2 shows tool geometry. A 2.5-volume percent water-soluble oil solution was used as the coolant. The tool-bit material consisted of 97-percent tungsten carbide and 3-percent cobalt, the hardest commercially available grade.

DISCUSSION AND RESULTS

The direction of the resolved force varied considerably with differences in feed, speed, and depth of cut, as noted from Figure 3. In this figure, the three tool-bit geometry variables are held constant. In the subsequent data analysis, only the total resultant force will be used.

The data from a central composite design can normally be analyzed using analysis of variance, but the feed rates possible on the lathe were not evenly spaced as required for this determination. Therefore, the results of the experiment (Columns 8 and 10 in Table I) were analyzed using a multiple-regression program.⁵

To place the variables on a convenient scale for computation, each variable is transformed as follows:

$$V_i = \frac{X_i - X_0}{(\Delta X)} \quad (1)$$

In Equation 1, V_i is the variable to be used in the mathematical model for tool force or surface finish, X_i is the untransformed variable, X_0 is the median variable value (see Table II), and ΔX is the difference in successive values of the variables. For example, the nose radii considered in this study were 0.01, 0.02, 0.03, 0.04, and 0.05 inches. Thus:

$$V_i = \frac{0.04 - 0.02}{0.01} = 1 \quad \text{for a nose radius of 0.04} \quad (2)$$

Resulting values of V_i for the nose radii considered are as follows:

X_i Nose Radius (inches)	V_i Transformed value of X_i (inches)
0.01	-2
0.02	-1
0.03	0
0.04	1
0.05	2

Using transformation values for all the independent variables resulted in all the variables having a range of from -2 to 2, with a median value of zero.

The force and surface finish data were fitted to a second-order mathematical model of the type:

Force or Surface Finish =

$$b_0 + b_1 V_1 + b_2 V_2 + b_{11} V_1^2 + b_{22} V_2^2 + b_{12} V_1 V_2 \quad (3)$$

Equation 3 illustrates a second-order model for two variables. The experimentally determined constants are the b terms. The complete equation, using the summation convention,⁶ is given below:

Force or Surface Finish =

$$b_0 + b_i V_i + b_{ii} V_i^2 + \frac{(b_{ij} V_i V_j - b_{ii} V_i^2)}{2} \quad (4)$$

NOTE: $i, j = 1$ to 6

$$b_{ij} = b_{ji}$$

The regression coefficients determined for the actual models are given in Table III. Also given are the mean

⁵N. R. Draper and H. Smith. *Applied Regression Analysis*. John Wiley and Sons, Incorporated, New York. 1966.

⁶W. Prager. *Introduction to Mechanics of Continua*. Ginn and Company, Boston, Massachusetts. 1961.

Legend

<u>Point</u>	<u>Feed Rate</u>	<u>Surface Speed</u>	<u>Depth of Cut</u>
4	Low	Low	Low
12	High	Low	Low
20	Low	High	Low
28	High	High	Low
36	Low	Low	High
44	High	Low	High
52	Low	High	High
60	High	High	High

Relationship of Machining Parameters for Points Noted in Figure.

FIGURE 3. Illustrated is the effect of machining parameters on the direction of the total resolved force on the tool. Tool geometry was held constant at all points noted (nose radius, 0.04 inches; rake angle, 9 degrees; and clearance angle, 9 degrees).

TABLE III. Analysis of variance of effects of machining parameters in tool force.

<u>Determined Constants</u>	<u>Source of Variability</u>	<u>Tool Force</u>		<u>Surface Finish</u>	
		<u>Mean Square</u>	<u>Regression Constants</u>	<u>Mean Square</u>	<u>Regression Constants</u>
b_0	Mean	12,829	12.02	24,198	10.70
<u>Linear Effects</u>					
b_1	Nose Radius (NR)	0.01	0.028	2419.77	-5.552
b_2	Rake Angle (RA)	122.33	-1.292	3.12	-0.218
b_3	Clearance Angle (CA)	68.42	-1.049	6.12	-0.306
b_4	Feed Rate (FR)	233.03	1.963	4753.12	8.431
b_5	Surface Speed (SS)	46.13	0.761	10.12	-0.354
b_6	Log _e Depth of Cut (DC)	715.94	4.292	0.20	-0.171
<u>Interactions</u>					
b_{12}	NR and RA	44.03	0.774	2.61	0.233
b_{13}	NR and CA	13.33	-0.533	2.66	0.175
b_{14}	NR and FR	53.25	-1.136	1004.15	-3.907
b_{15}	NR and SS	4.57	0.280	0.13	-0.050
b_{16}	NR and DC	9.57	0.486	0.54	-0.106
b_{23}	RA and CA	41.11	0.743	446.03	2.670
b_{24}	RA and FR	0.20	-0.069	77.33	1.135
b_{25}	RA and SS	1.48	0.167	1.29	0.137
b_{26}	RA and DC	8.13	-0.259	0.94	0.047
b_{34}	CA and FR	0.04	-0.137	0.02	0.019
b_{35}	CA and SS	0.00	0.010	2.66	0.198
b_{36}	CA and DC	5.85	-0.182	0.01	0.019
b_{45}	FR and SS	5.64	-0.289	16.97	-0.520
b_{46}	FR and DC	839.98	0.814	1.66	0.344
b_{56}	SS and DC	0.80	0.089	1.02	0.107
<u>Curvature Effects</u>					
b_{11}	(NR) ²	2.47	0.210	439.07	4.408
b_{22}	(RA) ²	0.05	0.074	15.75	-0.228
b_{33}	(CA) ²	0.90	-0.046	0.78	0.400
b_{44}	(FR) ²	0.31	0.790	12.94	0.534
b_{55}	(SS) ²	71.78	1.482	88.89	2.016
b_{66}	(DC) ²	119.76	-0.331	41.99	0.196
Residual	— — — — —	6.40	— — — — —	36.74	

square values for each coefficient, which may be used to judge the relative importance of each variable or combination of variables. As a rough guide, any mean square value greater than six denotes a variable which has a statistically significant effect on force or surface finish. The greater the mean square, the more important the effect.

As noted in Table III, depth of cut and feed rate produce the greatest effect on tool force, while nose radius and feed rate have the most important effect on surface finish.

A logarithmic scale was used for depth of cut, in order to span a large range of values and to concentrate the data in the low range where most machining would be done.

The second-order models can be used to predict tool force and surface finish for any combination of machining parameters, as long as the parameters are kept reasonably close to the experimental ranges (see Table II). Because of measurement errors in the data, the predicting equations will not predict perfectly.

The standard error of estimate (one standard deviation) on the predicted value is ± 2.5 pounds and ± 6.1 microinches arithmetic average (AA) for the tool force and surface finish models, respectively (1 pound of force equals about 5 newtons).

Another method in evaluating and applying the models is to hold all but two of the variables constant and plot force and surface finish contours as a function of the two variables. Such plots for tool force and surface finish are illustrated by Figures 4 through 33. Corresponding plots (the same two variables) for force and surface finish are at the same positions on facing pages for comparisons.

A computer optimization program was used also for selection of the best parameters for application in typical rough- and finish-machining operations. The approach was to find points of minimum tool force consistent with a specified removal rate; and in the case of finish machining, a specified surface finish.

The criteria and the results obtained are given in Tables IV and V. With respect to the roughing parameters, a nose radius of 0.01 inches showed excessive wear, even though initially yielding a low tool force. Therefore a larger radius would have to be used in a production process. A nose radius of 0.03 inches raises the force to 13.9 pounds, but lowers the surface finish to 28.7 microinches.

TABLE IV. Optimum machining parameters for roughing cuts. (Removal rates greater than 0.30 cubic inches per minute.)

Nose Radius	0.010 inches
Rake Angle	12 degrees
Clearance Angle	15 degrees
Feed Rate	0.0028 inches per revolution
Surface Speed	355 feet per minute
Depth of Cut	0.0154 inches

Resulting Tool Force	= 8.68 pounds
Resulting Surface Finish	= 30.1 microinches (AA)
Resulting Removal Rate	= 0.30 cubic inches per minute

TABLE V. Optimum machining parameters for finish cuts. (Removal rates greater than 0.03 cubic inches per minute; surface finish less than 15 microinches AA.)

Nose Radius	0.049 inches
Rake Angle	11.8 degrees
Clearance Angle	8.2 degrees
Feed Rate	0.0049 inches per revolution
Surface Speed	254 feet per minute
Depth of Cut	0.002 inches

Resulting Tool Force	= 4.38 pounds
Resulting Surface Finish	= 11.3 microinches (AA)
Resulting Removal Rate	= 0.03 cubic inches per minute

The most significant findings of the study relate to the tool force minima found in surface speed and feed rate. Effects can be noted clearly in contour plots in which speed and feed are plotted against other variables with which they have little interaction, such as in Figures 6, 7, and 13 (Pages 10 and 12).

The minimum values provide an advantage when optimizing parameters. Nothing unusual was noted in the surface finish model, with the finishes generally falling close to the theoretical values predicted by the geometry of feed and nose radius. Of interest is the finding that the surface speed tool-force minimum had an effect on the surface finish, as evidenced by similar minima in Figures 13 and 17 (Pages 12 and 13). The finding was evident even though surface speed is not considered a factor in predicting the theoretical surface finish from geometrical considerations.

ILLUSTRATIONS

Figures 4 through 33

Figure 4

Figure 5

NOSE RADIUS (inches $\times 10^3$)

Tool Force Contours in Pounds.

Figure 6

Figure 7

NOSE RADIUS (inches $\times 10^3$)

Legend

All variables except those plotted on the abscissa and ordinate are held constant at the median values (refer to Table II, Page 5). For comparison, the contour plots for a given pair of variables for tool force and surface finish are placed in the same position and on facing pages. Plots in which dense contours end abruptly, such as in Figures 10 and 14, Pages 11 and 12, actually continue to climb steeply. The contours are omitted as a convenience in application of the automatic plotter program. The contour intervals are: 1 pound on the force plots, and 2 microinches, arithmetic average (AA), on the surface finish plots.

FIGURES 4 through 33. Contour Plots of Total Tool Force and Surface Finish.

Figure 8

Figure 9

Surface Finish Contours in Microinches (arithmetic average).

Figure 10

Figure 11

NOSE RADIUS (inches $\times 10^3$)

Figure 12

Figure 13

Tool Force Contours in Pounds.

Figure 14

Figure 15

Figure 16

Figure 17

Surface Finish Contours in Microinches (arithmetic average).

Figure 18

Figure 19

Figure 20

Figure 21

Tool Force Contours in Pounds.

Figure 22

Figure 23

Figure 24

Figure 25

Surface Finish Contours in Microinches (arithmetic average).

Figure 26

Figure 27

RAKE ANGLE (degrees)

Figure 28

Figure 29

Tool Force Contours in Pounds.

Figure 30

Figure 31

Figure 32

Surface Finish Contours in Microinches (arithmetic average).

Figure 33