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POWER HACKSAW OPERATIONS ON TITANIUM AND ITS ALLOYS

BY

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Project M993

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SUMMARY SHEET

I. Engineering Research Institute, University of Michigan, Ann Arbor, Michigan

II. U. S. Army, Ordnance Corps.

III. Project No. TB4-15
Contract DA-20-018 ORD-11918, RAD No. ORDTB-1-12045.

IV. Report No. WAL 401/109-6

V. Priority No. - None

VI. Investigation of machinability of titanium-base alloys.

VII. Object:

The object is to investigate the machinability of commercially pure titanium and three alloys of titanium.

VIII. Summary:

Power hacksawing tests were run on titanium grades Ti 75A, RC 130B, and Ti 130A. All tests were made with 4 pitch saws on a commercial machine operating at three different speeds. The saw materials represented were tungsten high-speed steel and molybdenum high-speed steel. All tests were made with 1:20 emulsion of soluble oil in water.

IX. Conclusions:

(a) Titanium requires abnormally high feeding pressure.
(b) Molybdenum HSS blades have better even life.
(c) Tool wear is manifested in a gradual reduction in the feed rate at instant feeding pressure.
(d) There is little difficulty from broken teeth and blades in sawing titanium compared to some other metals.

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POWER HACKSAW OPERATIONS
ON
TITANIUM AND ITS ALLOYS

INTRODUCTION

Power hacksawing is not subject to as high a degree of control as most metal cutting operations and thus the effect of variables need to be studied only in a general way since it is difficult to make use of precise quantitative measurements. Proceeding on this basis, the program was set up under the following three headings:

1. To determine the optimum operating conditions for sawing titanium and its alloys on a standard power hacksaw with regard to:

    a. necessity of coolant, determined by the use of coolant and of no coolant;

    b. feeding pressure, determined by varying the feed value position; and

    c. cutting speed, determined by the use of low, medium, and high speeds.

2. To compare the relative effectiveness of sawblade materials:

    a. tungsten (high speed) and

    b. molybdenum (high-speed).

    The feed pressure and cutting rate were kept constant, with only the type of blade material varied. A comparison of the average feed rate vs. the amount of material cut revealed the effectiveness of each blade material.

3. To determine power consumption and forces present on the sawblades during hacksawing operations.

The forces were obtained by attaching two SR-4 strain gages, one on each side, mounted centrally between the holes and near the top edge of the blade. The gages were attached to a strain analyzer and then to a Brush recorder. The instantaneous feeding rate was obtained by attaching a wire from the movable frame of the saw to a potentiometer. Thus, a feeding movement of the frame would vary the output of the potentiometer, which output was recorded on an Illinois recorder.

TEST PROCEDURE

A 2 by 4 inch cross-section titanium specimen was locked in the clamping vise on the Standard Pereless power hacksaw so that a 3/16 inch thick section would be cut off. A counter device was mounted on the stationary frame and was actuated by the reciprocating cross head carrying the saw blade. The feeding rate was determined by attaching a counterbalanced wire to the nonreciprocating downfeed portion of the frame. The wire from the frame was attached at the other end to a pulley extending from a potentiometer, which was mounted on top of the stationary hacksaw frame. Another wire was attached to the pulley and carried a counterweight at the other end. Thus a movement of the cross head downward would carry the counterweight up, and when the cross head moved upward the counterweight would maintain a tension on the respective wires. This arrangement served to provide a positive movement of the potentiometer, whose changing resistance in a measuring circuit provided a variable voltage which could be translated into inches of feed. This changing voltage was fed into an Illinois recorder and recorded on a constant-speed chart from which the instantaneous feed rates could be taken. These instantaneous feed rate values were used in computations of the amount of metal removed for the determination of horsepower consumed per cubic inch of metal removed.

The countermechanism results were used in the computation of average feed rates in the wear tests. Since the material cut was 2 inches wide and 4 inches deep, the number of strokes from the counter divided into 4 inches would give the average feed rate per stroke for the 8 square inch cross section cut.

In the determination of the cutting forces and feeding forces, two SR-4 strain gages were mounted midway between the pin holes, as near the top of the blade as possible, and on opposite sides of each sawblade. The mounting of the gages on opposite sides of the blade was to eliminate air effects of lateral deflection. The bridge circuit consisted of the two gages mounted on the blade, used as opposite active gages, and two gages of a blade not in use. The results were recorded on a Brush recorder after being amplified. A calibration was obtained by inverting the blade and moving a known weight along the blade through the positions to be occupied by the stock to be cut. Thus, the brush deflections were converted into stress. Because the chart moved at a constant rate, the position of the work at the start and finish of the stroke could be determined on the charts. The stress recorded consisted of a horizontal cutting force and a vertical feeding force. However, by inserting the values of the stress from the Brush charts at the start and finish of a stroke into a formula for the stress at each of the respective positions, the horizontal and vertical forces were obtained. Thus, with the horizontal cutting force known, the horsepower was calculated. When this resultant horsepower was divided by the instantaneous volume of metal being removed, the power consumption per unit of metal removed was obtained.

EQUIPMENT AND MATERIAL

1. Machine

Peerless Hydracut Power Hacksaw
Size: 14 by 14 by 6 inch stroke
Speeds: 56, 98, and 140 strokes/min.

2. Blades

21 by 2 by .100 - 4T Hacksaw Baldes (Simonds Saw and Steel) of high-speed molybdenum and high-speed tungsten

3. Coolant

Soluble oil in water, 1:20

4. Material Cut: (2 by 4 by 18 inch long bars)

(a) Titanium Ti 75A
(b) Titanium alloy RC 130B
(c) Titanium alloy Ti 150A
(d) Hot-rolled SAE 1045 steel

5. Instruments

SR 4 Strain Gages, type 3-7, 500 Ohms

Strain Gage Amplifier (For feeding pressure)

(a) Brush BL320 Carrier Amplifier
(b) Brush Recording Oscillograph

Westinghouse D. C. recording voltmeter (For feed rate)

SUMMARY OF TEST RESULTS

Ti 75A

(1) This material could be cut at any of the three available speeds, 56, 98, or 140 strokes per minute. From a wear standpoint, the low speed is best.

(2) A coolant must be used; otherwise the material will gall and seize and quickly build up in the space between the sawblade teeth.

(3) Varying feed pressure can be used, but the full feed pressure results in greater feed rates without any noticeable increase in blade wear.

(4) A molybdenum high-speed blade gave a larger feed rate at the same pressure and did not wear any faster than a tungsten high-speed blade.

(5) This material cut faster and caused less wear on the saw blades than either Ti 150A or RC 130B.

(6) The power consumption is much less than the power consumed by Ti 150A and RC 130B.

(7) The effect of surface scale was not detectable.

Ti 150A

(1) This material could be cut at the two lower speeds, 56 or 98 strokes per minute. From a wear standpoint, the low speed is better.

(2) A coolant is necessary; otherwise the saw blade teeth are dulled at a rapid rate.

(3) A high feed pressure is necessary; otherwise the blade rides on the surface of the specimen and does not cut.

(4) A molybdenum high-speed blade gave a larger feed rate than a tungsten high-speed blade without any more wear shown.

(5) The material cut faster than RC 130B but slower than Ti 75A.

(6) Initially, this material consumed more power than Ti 75A and RC 130B, but after 32 square inches of cross section was cut it was intermediate between the other two.*

(7) The effect of surface scale on the wearing of saw blade teeth was tremendous. The surface should be free of scale to promote longer blade life.

RC 130B

(1) This material can be cut only at the slowest speed, 56 strokes per minute. At any higher speed the sawblade skews after a short period of use.

(2) A coolant is necessary for sawing to reduce the blade wear obtained on a dry cut.

(3) A high feed pressure is necessary; otherwise the blade rides on the surface of the specimen and does not cut.

(4) A molybdenum high-speed blade gave a larger feed rate than a tungsten high-speed blade and gave the same rate of wear.

(5) The material cut at a slower rate than Ti 75A or RC 130B.

(6) Initially the material consumed only as much power as Ti 75A, but quickly built up to a point where it consumed fifteen times the power consumed by Ti 75A.

(7) The scale on the surface reduces the blade life through greater wear; however., the variations in blade wear than the presence or absence of surface scale.

General Comments

When a coolant is used, with heavy feed pressure and a slow cutting speed, the saw blade wears gradually and the usable life depends on how small a feeding rate can be economically tolerated. At increased speeds or when

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*Based on feed rates at the same feed pressure, since no force data were taken on a blade cutting 32 square inches of cross section of a scale-free Ti 150A alloy.

no coolant is used, the heavy feed pressure necessary raises the temperature at the contact point of the material and sawblade teeth to a point where chip welding and seizure of material occur.

WEAR TESTS

In order to ascertain the effectiveness of the blade materials and to obtain a quantitative value of wear in terms of material cut, plots of average feed rate in inches per stroke against the number of square inches of cross section of metal cut were used. A conversion to other units can readily be made; for example, the width of kerf was .125 inch, so that the values of the abscissa divided by 8 yield the cubic inches of metal removed. Because a 6-inch stroke was used with a blade having 4 teeth per inch, the feed rates per tooth can be obtained by dividing the ordinate values by 24.

TABLE I

SUMMARY OF RESULTS

Material Cut	Permissible Cutting Speed	Influence of Surface Scale	Necessity of Coolant	* Feed Pressure Required	** Feed Rate-.001 inch/stroke			*** Power Consumption, Hp/cu in./min	
					Initial	After 32 sq in. cut Blade Material		Initial	After 32 Sq in. cut
						Molybdenum	Tungsten		
Ti 75A	Low Medium High	Negligible	Yes	Full	21	14	10	1.9	4.5
RC 130B	Low	Some	Yes	Full	14	9	6.5	2.0	59
Ti 150A	Low	Tremendous	Yes	Full	18	8.5	6.0	2.9	-
SAE 1045	-	-	-	-	40-	-	35	1.7	1.9

* Varied from 450 to 600 psi depending on cutting resistance.

** The feed rate is the result obtained at a slow cutting speed, with full feed pressure, and a 6-inch stroke

*** The power consumption was obtained while using tungsten blades, full feed pressure, slow cutting speed, and a coolant.

Power Consumption:

The power consumptions of Ti 75A, RC 130B, and SAE 1045 were comparatively the same at initial sawing. However, after 32 square inches of cross section were cut, the blade condition was reflected in the power consumption results, with SAE 1045 showing very little increase, Ti 75A doubling its initial value, and RC 130B increasing its power consumption thirty-fold. Although RC 130B consumed only as much power as Ti 75A at the beginning, it required twelve times as much power per cubic inch of metal removed after 32 square inches of cross section were cut.

TABLE II

SUMMARY OF POWER CONSUMPTION CALCULATIONS

Material	Blade Condition	Stress Recorded, psi		F_v, lbs	F_c, lbs	Feed rate, inches/ stroke	Metal Removed Cu in./min	Hp	Hp/cu in./min
		Beginning of Stroke	End of Stroke						
RC 130B	New	13,500	37,500	600	450	.014	.202	.4	2.0
RC 130B	After 32 sq in.	13,500	43,500	500	600	.0065	.009	.53	59.0
Ti 75A	New	13,500	40,500	450	675	.021	.303	.59	1.9
Ti 75A	After 32 sq in.	15,000	40,500	425	860	.0115	.167	.76	4.5
Ti 150A	New	16,500	48,000	525	860	.018	.258	.76	2.9
SAE 1045	New	18,000	45,000	450	1125	.040	.580	.99	1.7
SAE 1045	After 32 sq in.	18,000	45,000	450	1125	.035	.508	.99	1.9

$$\text{Hp} = \frac{(\text{F}_c,\ \text{lbs})(56\ \text{strokes/min})(\frac{6}{12}\ \text{ft/stroke})}{33{,}000\ \text{ft-lbs}}$$

$$\text{cu in./min} = (\text{length of cut, in.})(\text{feed rate, in.})/(\text{stroke, 56 strokes/min})(\text{width of cut, in.})$$

$$= (4\ \text{in.})(56\ \text{strokes/min})(.125\ \text{in.})(\text{feed-rate, in./stroke})$$

$$\frac{\text{Hp/cu in.}}{\text{min}} = \frac{\text{Hp}}{\text{cu in./min}}$$

DISCUSSION OF WEAR-TEST GRAPHS

Graph 1

In the power hacksawing of Ti 75A, the molybdenum high-speed blade removed approximately 30% more metal per cutting stroke than the tungsten high-speed blade and did not show any greater rate of wear.

Graph 2

In the power hacksawing of Ti 150A, the molybdenum high-speed blade removed approximately 30-35% more metal per cutting stroke than the tungsten blade in one test (A-A'); the figure was approximately 18% in another test (B-B'). The effect of scale on the Ti 150A specimen was not shown becuase it was so tremendous that the blade was completely worn out after one cut of 8 square inches of cross section with an average feed rate of only .002 inch/stroke.

Graph 3

In the power hacksawing of RC 130B, molybdenum high-speed blade removed 10-50% more metal per cutting stroke in test (A-A') and 30-40% more metal per stroke in another test (C-C'). A large difference in the cutting rates of both blade materials was obtained when different samples of RC 130B were cut.

Graph 4

In the power hacksawing of RC 130B with a scaled surface, the molybdenum high-speed blade removed from 6-50% more metal per cutting stroke than the tungsten blade. A comparison of Graph 4 with Graph 3 shows that the RC 130B itself has a greater effect in producing variations in cutting rate than the presence or absence of scale on the surface of the RC 130B.

A comparison of Graphs 1, 2, 3, and 4, shows that Ti 75A was cut at the fastest rate, followed by Ti 150A and then RC 130B.

Graph 5 - Graph 6

In the power hacksawing of Ti 75A at various speeds, the molybdenum high-speed blade removes metal at a faster rate than a tungsten blade at the same speed. In addition, Graph 6 shows that the blades' cutting ability is destroyed by gradual wear. Also, the curves indicate a higher feed rate for lower speeds.

PHOTOGRAPHS OF HACKSAW BLADES AT 5.5 DIAMETER MAGNIFICATION

Photo 1

The scale on the Ti 150A alloy broke down the sawblade teeth and caused extremely rapid wear to develop the lands on the teeth as shown here.

Photo 2

On a specimen of Ti 150A alloy which had the scale removed by a shaper, the sawblade teeth showed much less wear even though four times as much material had been cut as was cut with the blade in photo 1.

Photo 3

On a specimen of RC 130B with the surface scale present, the sawblade teeth showed the same type of wear on edge of the teeth as in photo 2.

Photo 4

On a specimen of RC 130B with the surface scale removed, the sawblade showed a slightly lesser wear than in photo 3 but the wear was still on the corners.

Photo 5

On a specimen of Ti 75A with the scale removed, the sawblade showed very little wear.

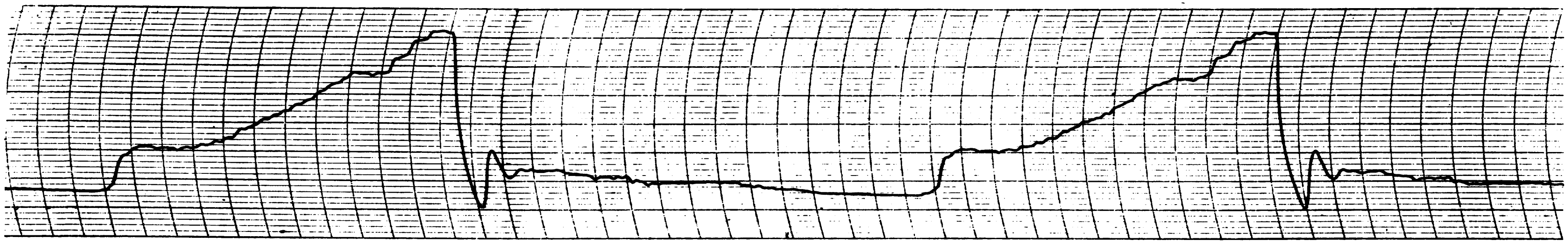
Photo 6

On a speciman of RC 130B with the surface scale present, the sawblade skewed badly and was removed. Cutting speed was 98 strokes per minute.

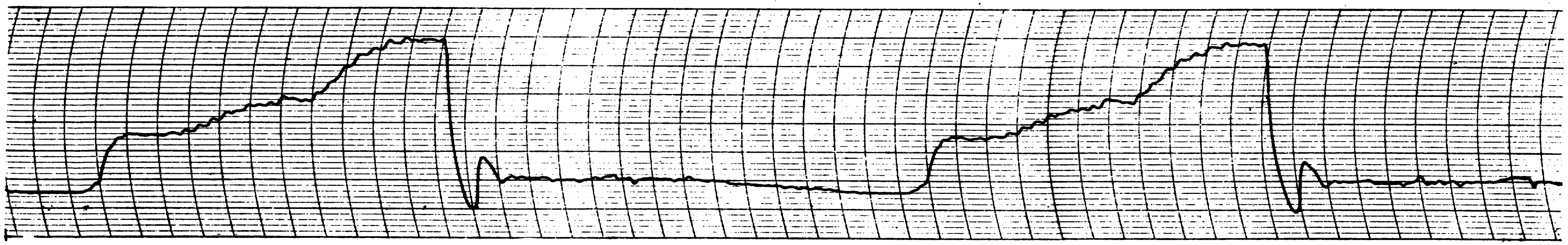
STRESS CHARTS FOR HACKSAW TESTS

The stress patterns shown on the following charts involve both the horizontal cutting force and the vertical feeding force. The configuration obtained is the result of the shifting of the point of application of the vertical force during a cutting stroke, resulting in a greater bending stress produced near the end of the stroke than at the beginning of the stroke.

The analysis of the forces involved during a cutting stroke are shown with equations for the stress recorded at the start and finish of the cutting stroke in terms of horizontal and vertical forces. By inserting the values of stress obtained at the start and finish of the stroke in their respective equations, the horizontal and vertical forces involved in the sawing of the various materials was obtained.



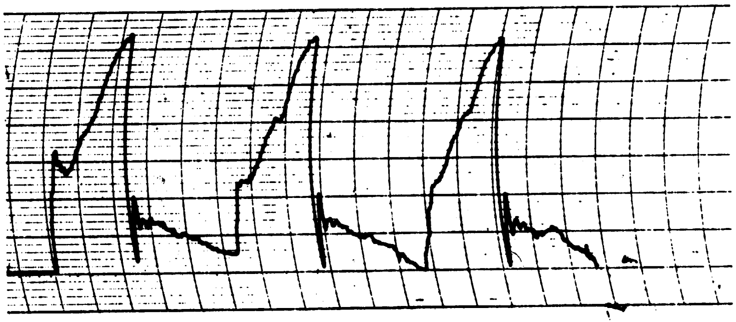
ALLOY 150A NEW BLADE NO SCALE 1500 PSI/LINE
COMPLETE STROKE = 5 1/4"



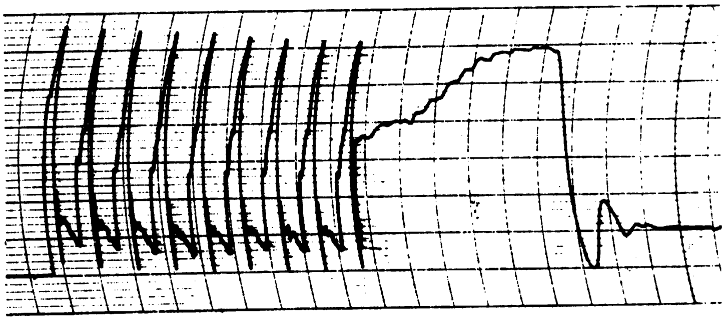
1045 STEEL NEW BLADE NO SCALE 1500 PSI/LINE
COMPLETE STROKE = 5 1/4"

MATERIAL

CALIBRATION
1500 PSI/VERTICAL LINE
COMPLETE STROKE = 1 1/8 " HORIZONTAL



NEW BLADE
MATERIAL 304 SS
BROKE AT START OF 4 TH. STROKE

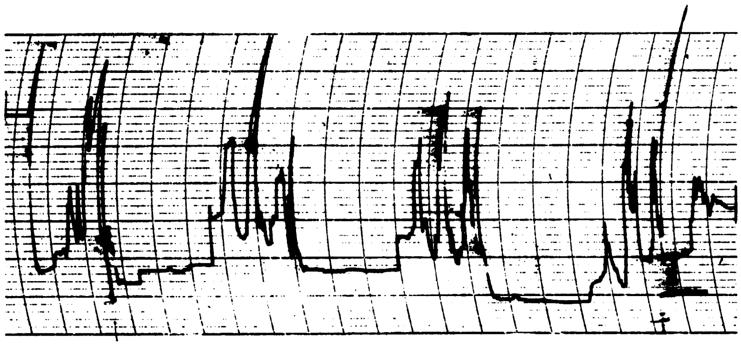


NEW BLADE
MATERIAL 1045 STEEL
(CHART SPEED ACCOUNTS FOR THE HORIZONTAL SPACING OF THE RECORD)

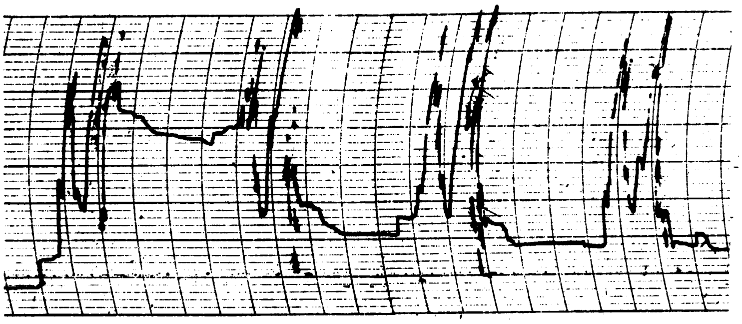
NEW BLADE
MATERIAL 1045 STEEL
(CONTINUATION OF ABOVE RECORD AT THE STD. SPEED USED AT OTHER MATERIALS)

ALLOY 150A

CALIBRATION
7500 PSI / VERTICAL LINE
COMPLETE STROKE = 1 1/8" HORIZONTAL



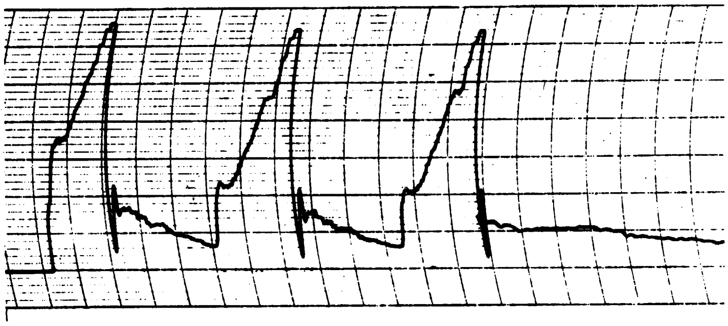
BLADE NO. 19
(AFTER CUTTING 32
SQ. IN. CROSS SECTION)
SCALE ON ALLOY
X 1/5



BLADE NO. 19
(AFTER CUTTING 32
SQ. IN. CROSS SECTION)
SCALE ON ALLOY
X 100

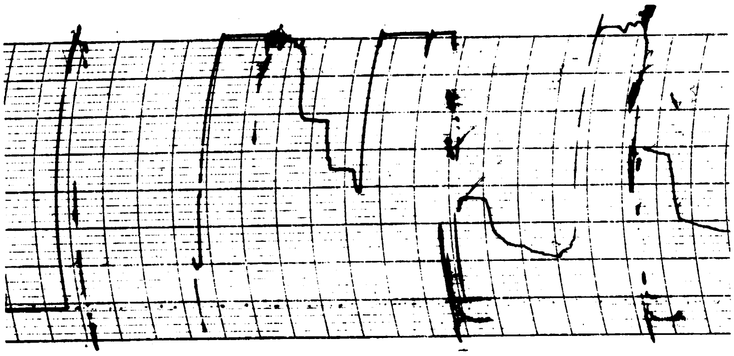
ALLOY 150 A

CALIBRATION
1500 PSI/VERTICAL LINE
COMPLETE STROKE = 1 1/16 HORIZONTAL



NEW BLADE
NO SCALE ON ALLOY

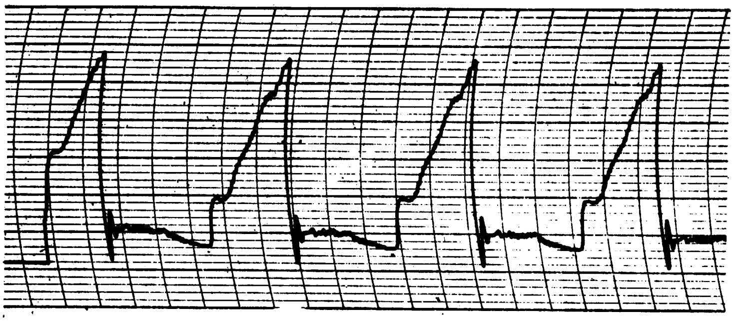
NEW BLADE
SCALE ON ALLOY



BLADE NO. 19
(AFTER CUTTING 32
SQ. IN. CROSS SECTION)
SCALE ON ALLOY

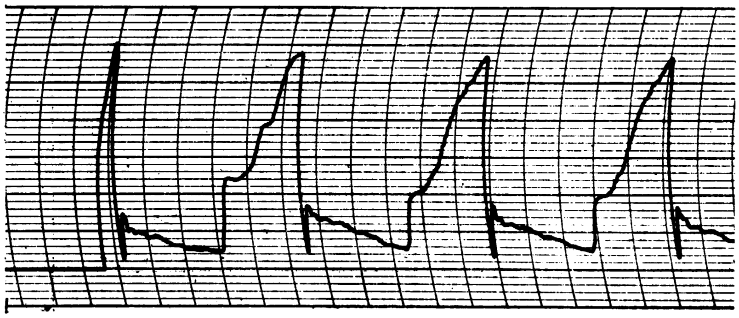
ALLOY 130 B

CALIBRATION
1500 PSI / VERTICAL LINE
COMPLETE STROKE = 1 1/16" HORIZONTAL

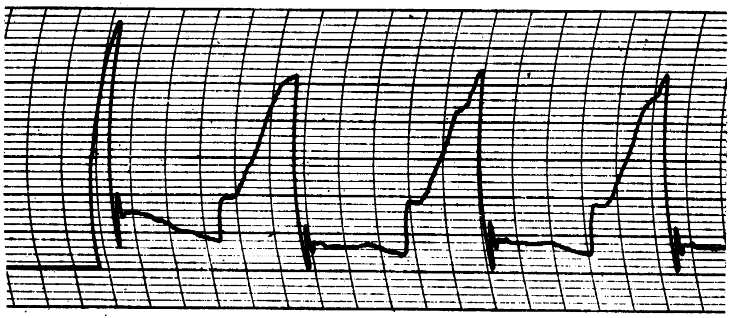


NEW BLADE
NO SCALE ON ALLOY

BLADE NO. 20
(AFTER CUTTING 32
SQ. IN. CROSS SECTION)
NO SCALE ON ALLOY



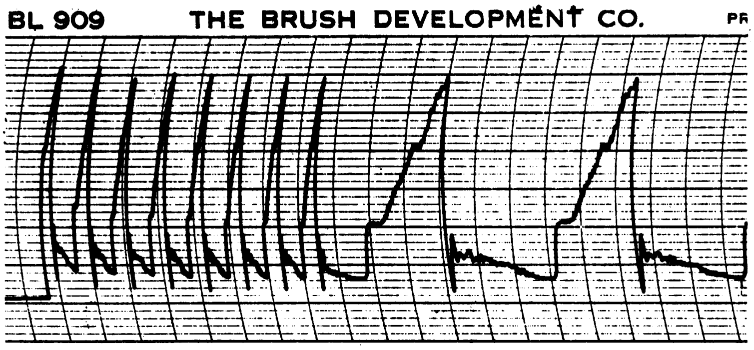
NEW BLADE
SCALE ON ALLOY



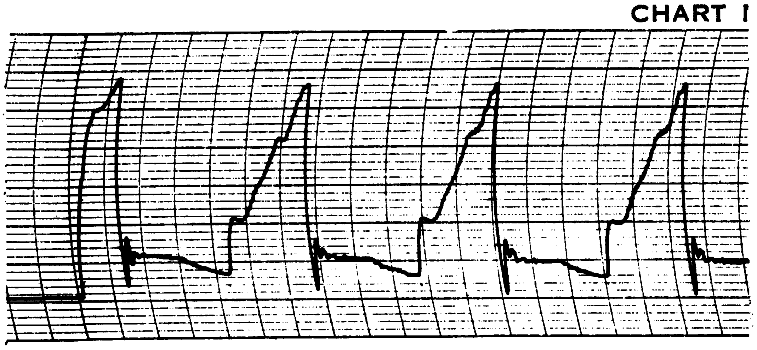
BLADE NO. 20
(AFTER CUTTING 32
SQ. IN. CROSS SECTION)
SCALE ON ALLOY

MATERIAL 75 A

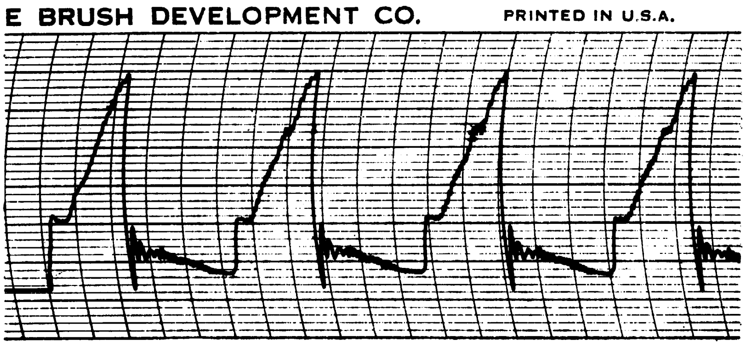
CALIBRATION
1500 PSI/VERTICAL LINE
COMPLETE STROKE = 1 1/16 HORIZONTAL



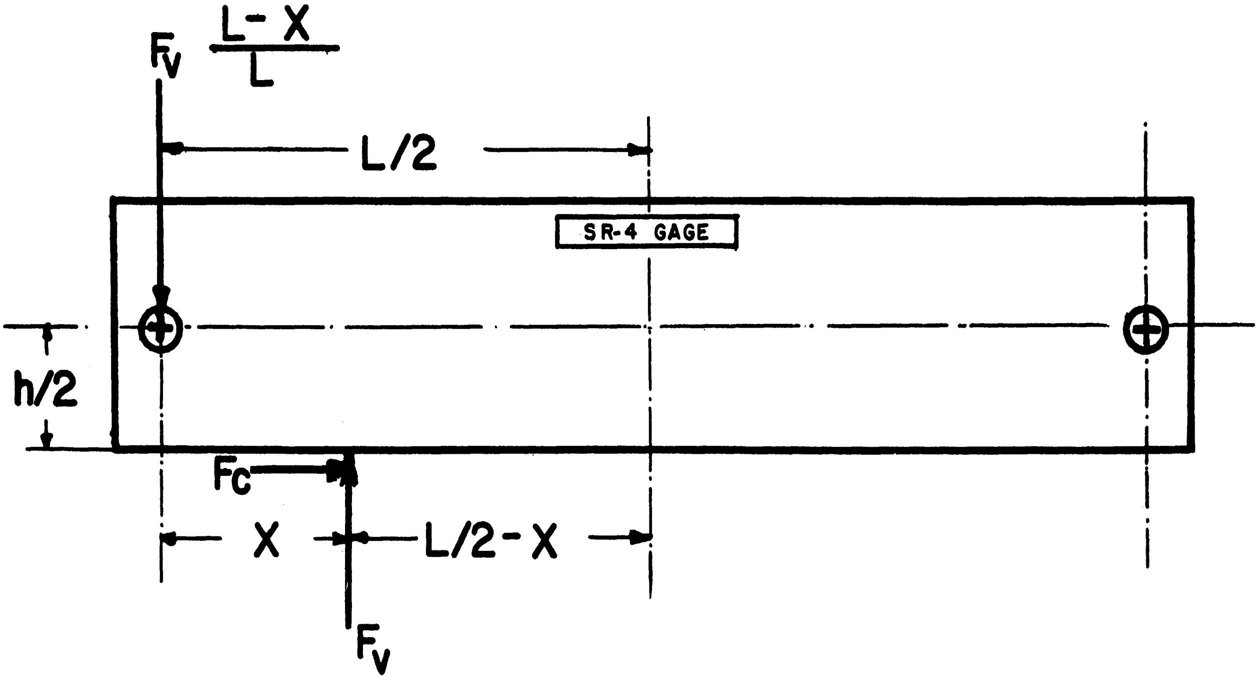
NEW BLADE
NO SCALE ON METAL



BLADE
(AFTER CUTTING 32 SQ. IN. CROSS SECTION)
NO SCALE ON METAL



NEW BLADE
SCALE ON METAL



Bending Stress at SR-4 Gage - $\frac{Mc}{I}$

where

$$M = F_c \frac{h}{2} + F_v \frac{L - x}{L} \frac{L}{2} - F_v \left(\frac{L}{2} - x\right)$$

$$I = \frac{bh^3}{12} = \frac{(.1)(8)}{12} = 0.067$$

F_V - vertical force on blade
F_c - horizontal cutting force
X - distance of F_V from pin hole
h - height of blade, 2 inches
b - thickness of blade, 0.100 inch
L - length of blade, 21 inches
Strain gage located at midpoint at top edge
c - distance of strain gage from neutral axis, 1 inch

S - total stress at gage $= \frac{M_c}{I} - \frac{F_c}{bh}$

At beginning of stroke x = 2 inches $S_B = 15 F_V + 10 F_c$

At end of 6" stroke x = 8 inches $S_E = 60 F_V + 10 F_c$

By using the values of S_B and S_E, obtained from the Brush charts, the values of F_V and F_c are computed.

56 STROKES/MIN.
FULL FEED PRESSURE

AFTER 32 SQ. IN. CUT
MAG. X 5.5

CLEANED SURFACE

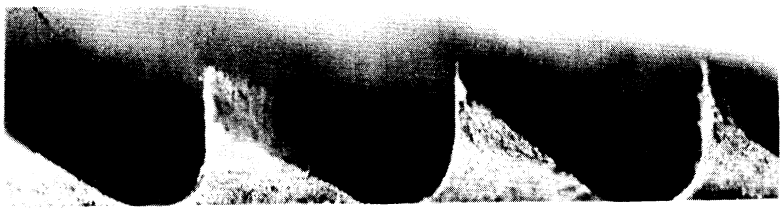


FIG.4

98 STROKES/MIN.
FULL FEED PRESSURE

AFTER 32 SQ. IN. CUT

CLEANED SURFACE

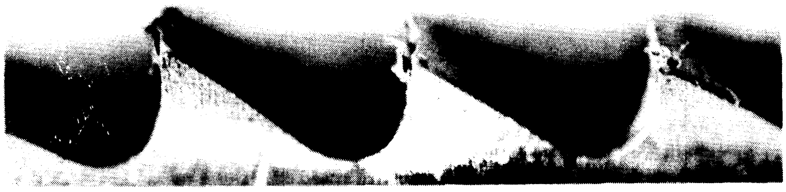


FIG.5

OXIDIZED SURFACE

(ONLY 2 SQ. IN.
CROSS SECTION
CUT)

FIG.6

56 STROKES / MIN.
FULL FEED PRESSURE

AFTER 32 SQ. IN. CUT
MAG. X 5.5

OXIDIZED SURFACE

(ONLY 8 SQ. IN.
CROSS SECTION
CUT)

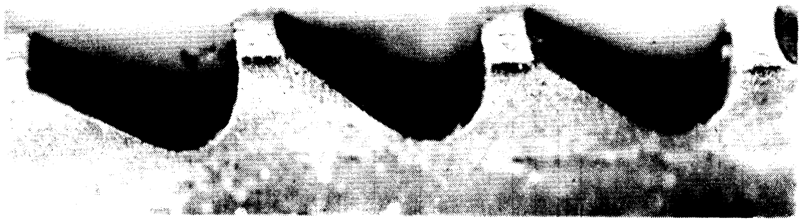


FIG. 1

CLEANED SURFACE

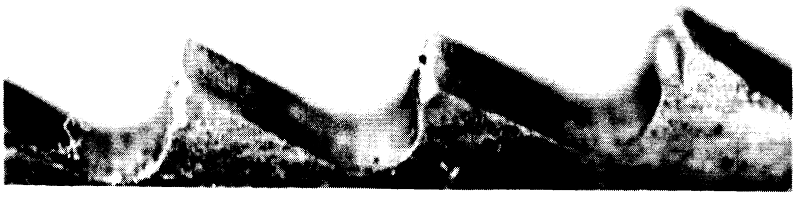


FIG. 2

OXIDIZED SURFACE

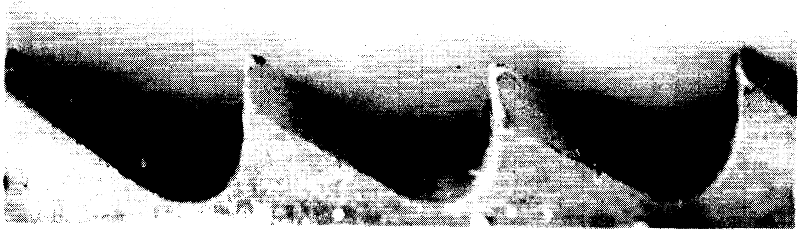
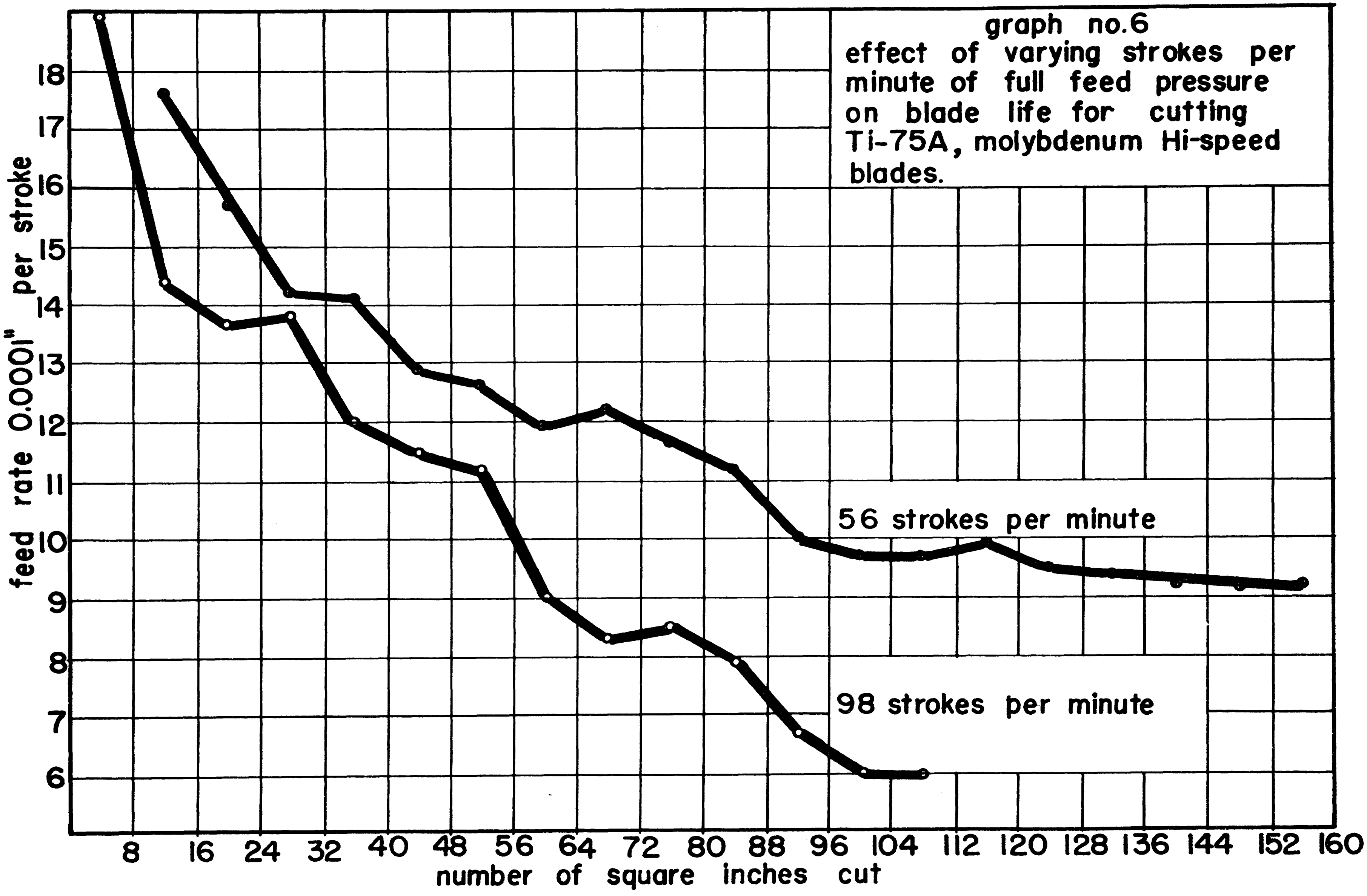
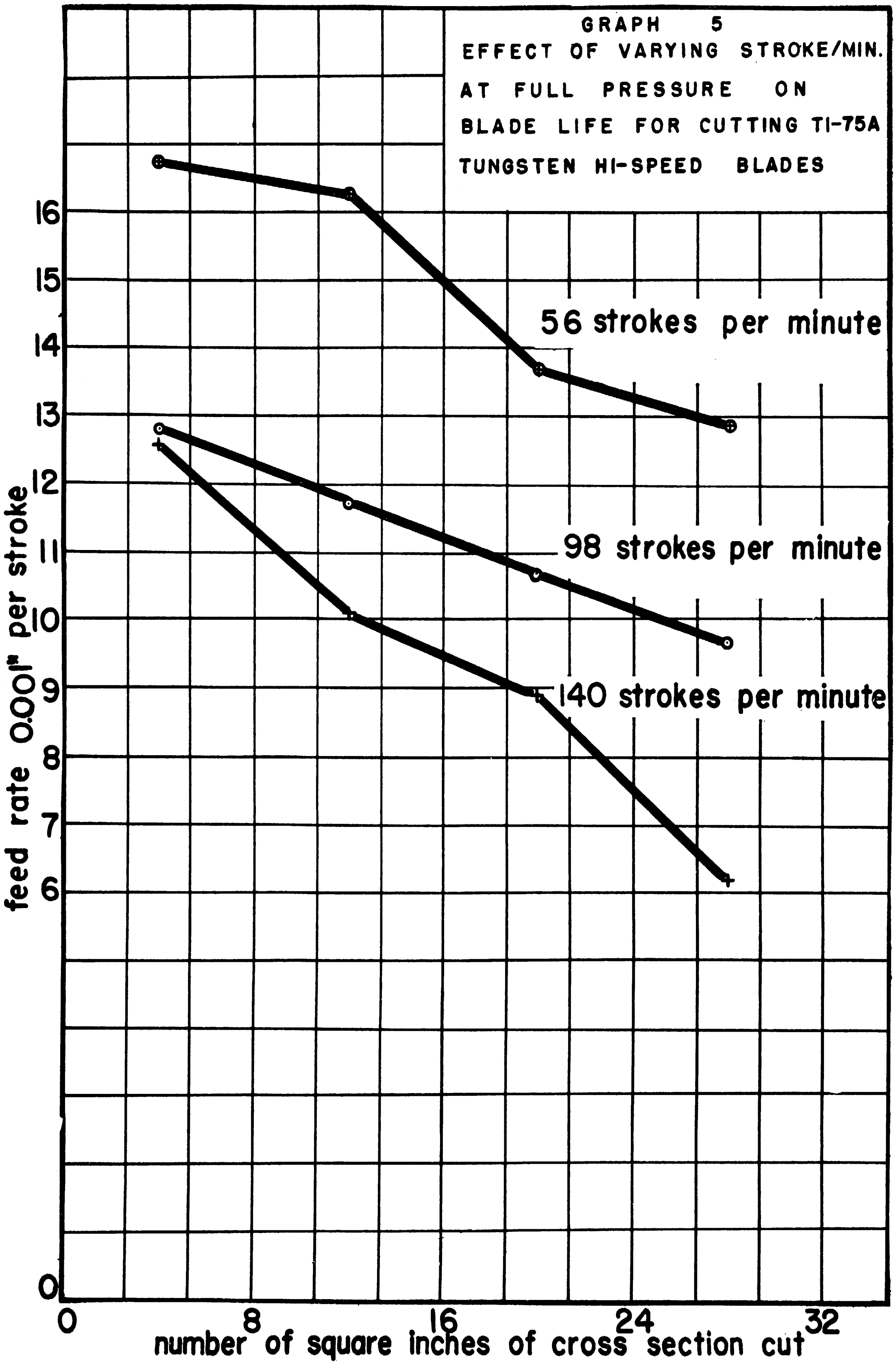
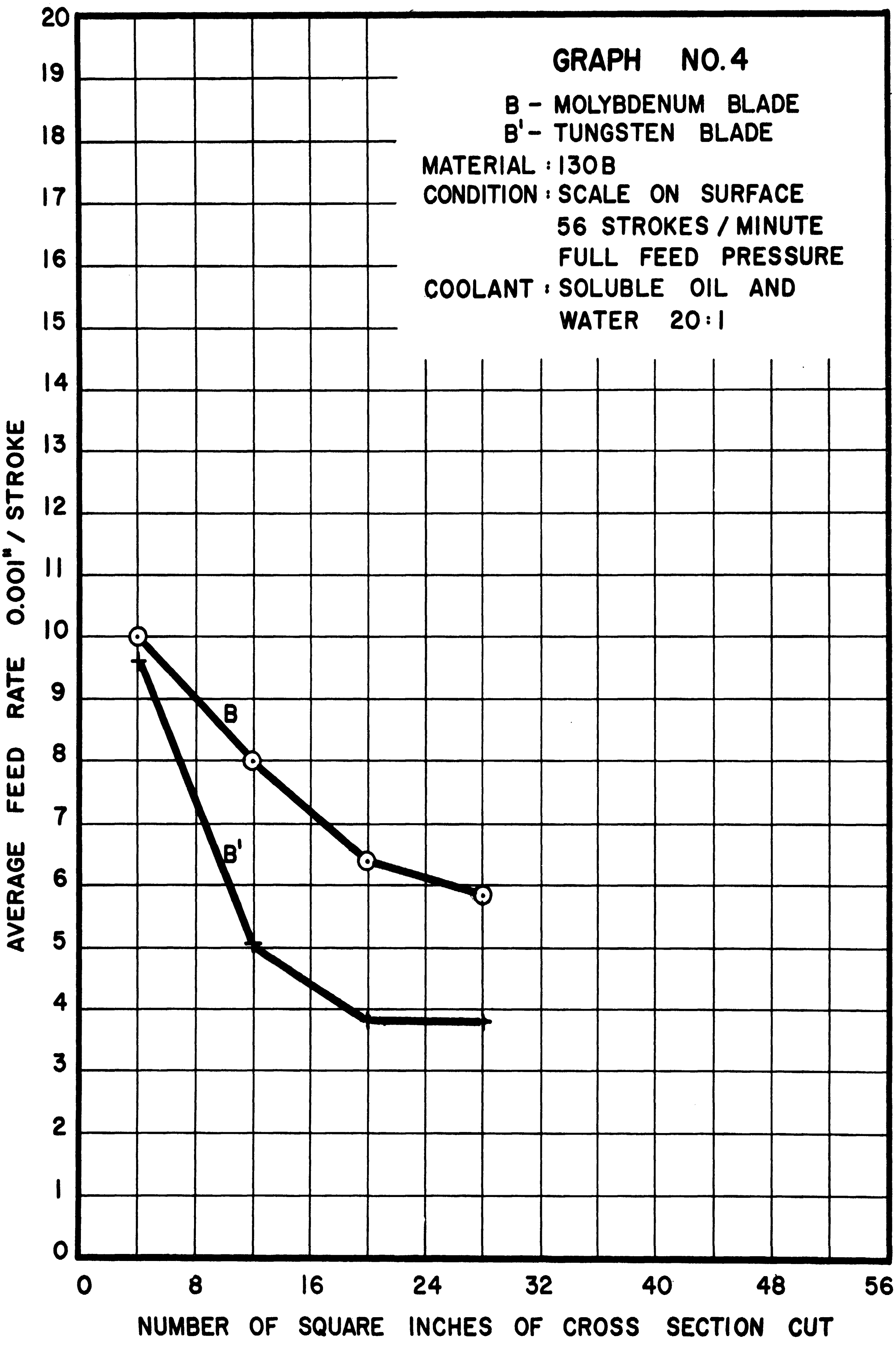


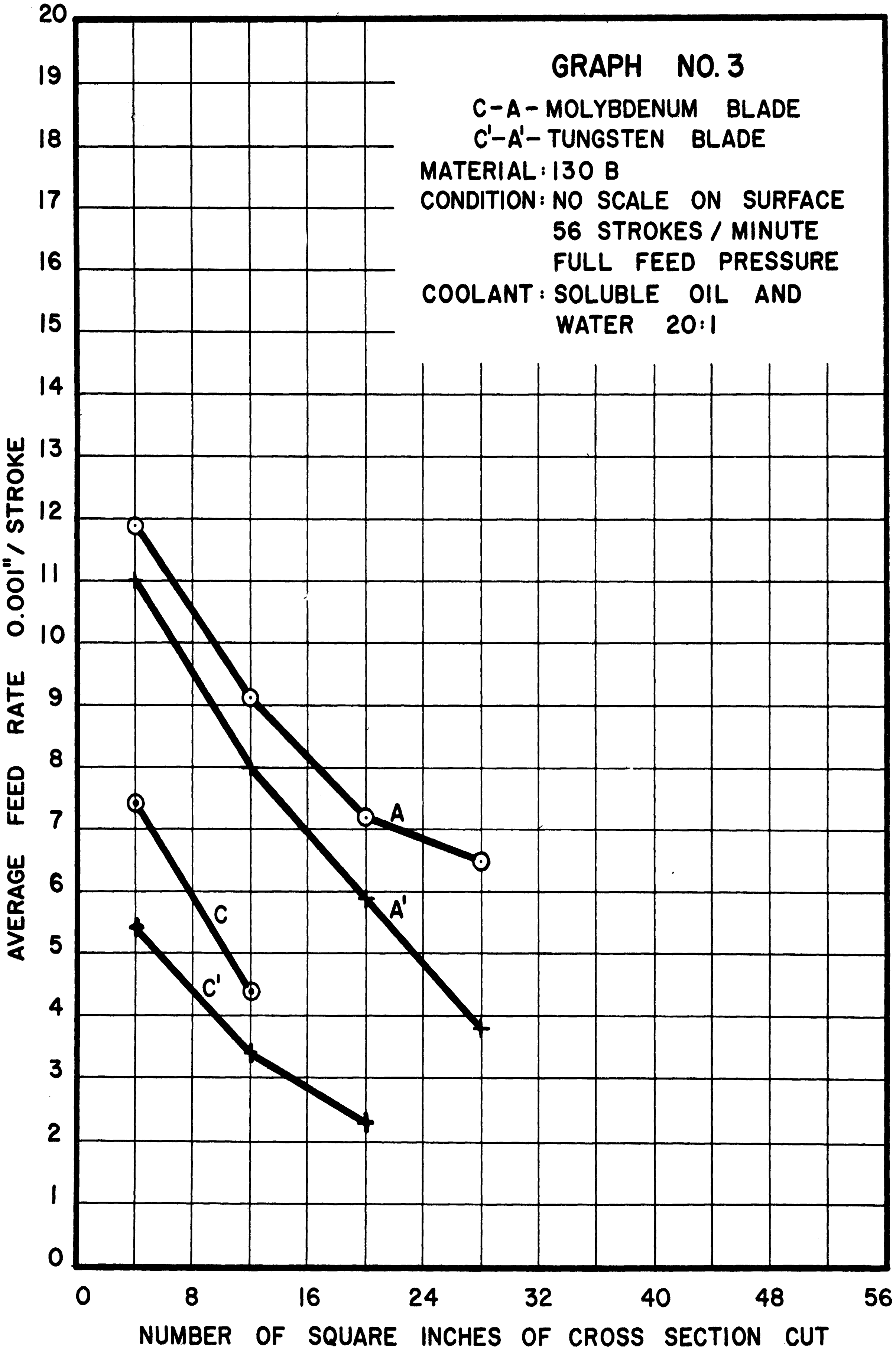
FIG. 3

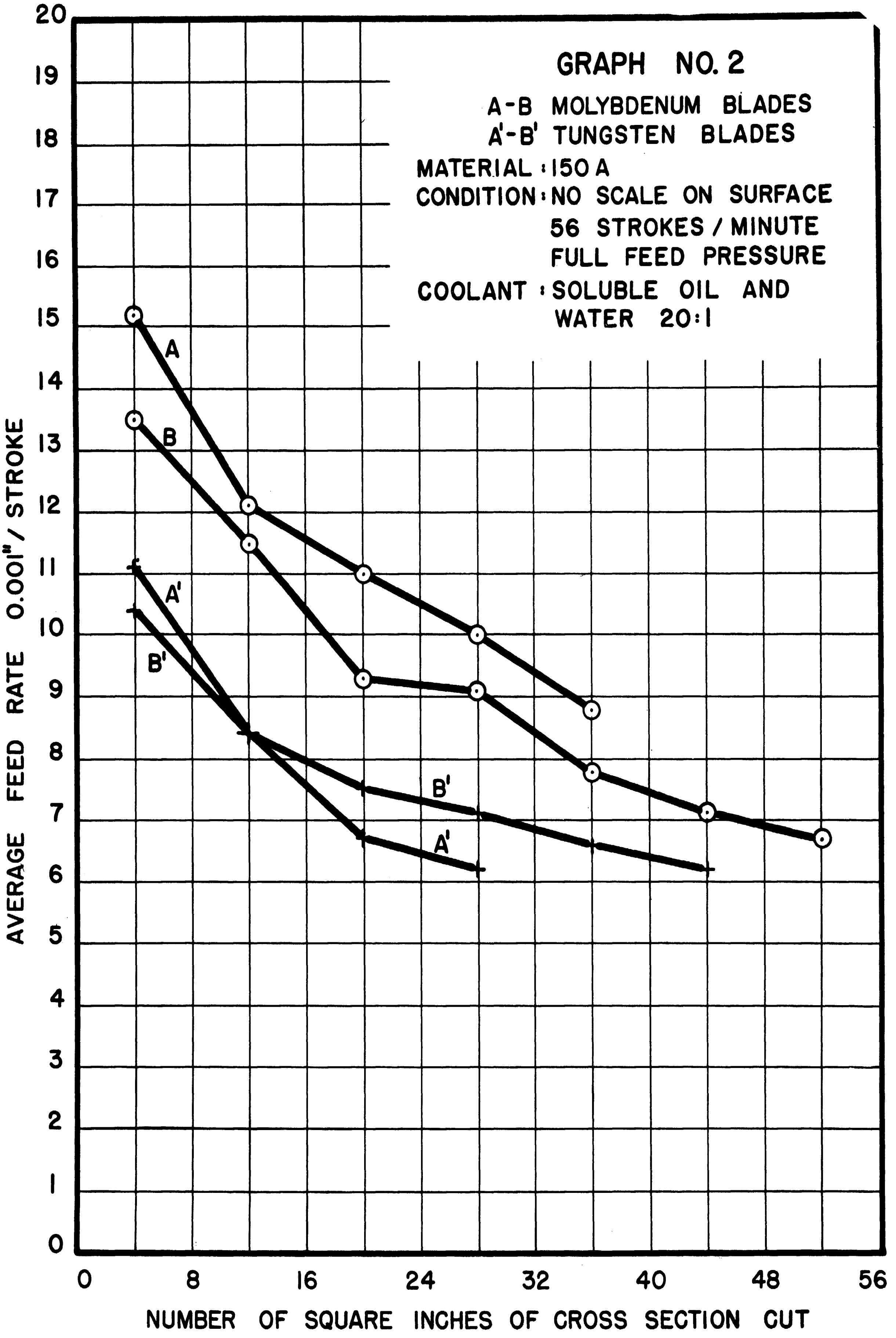


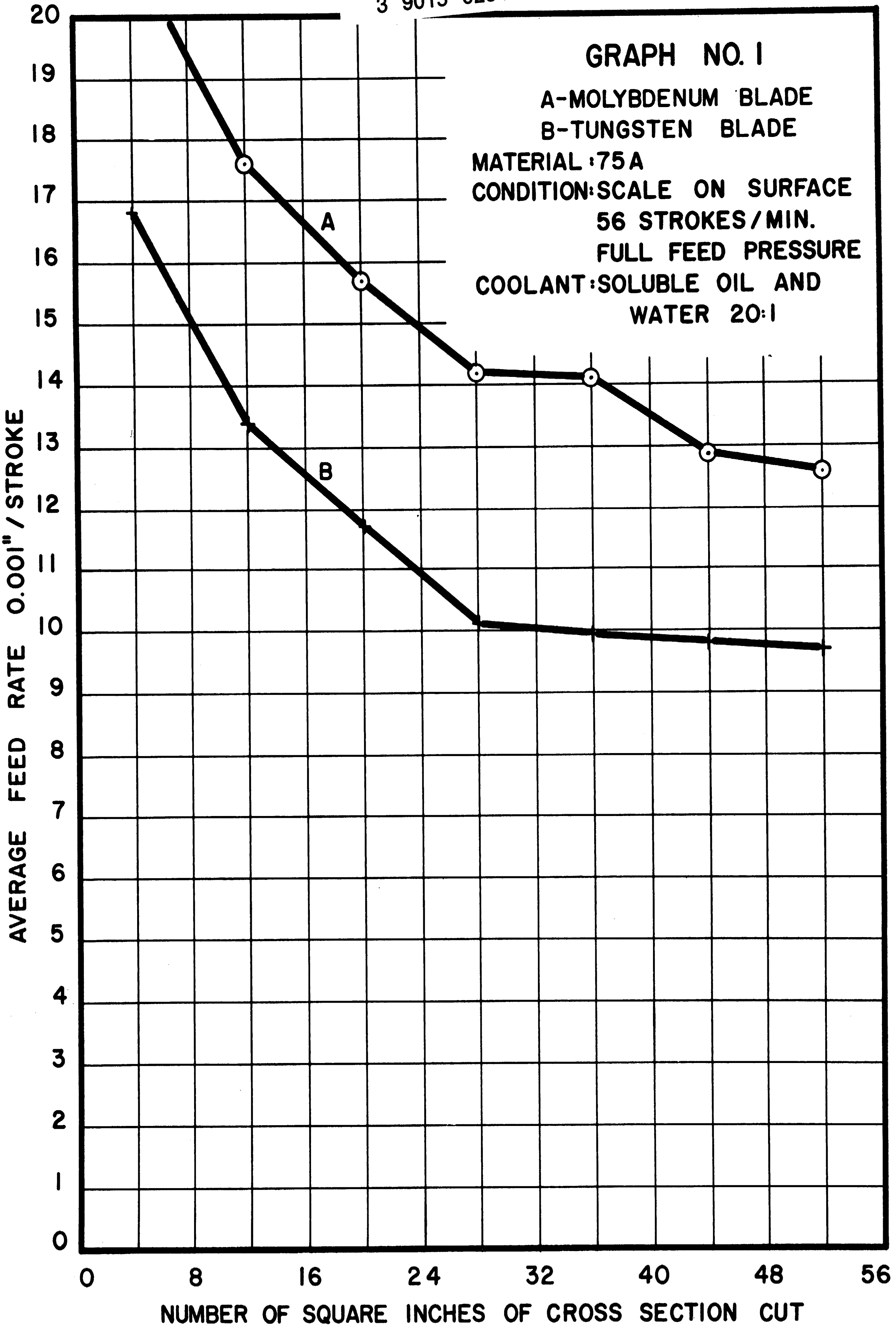
graph no.6
effect of varying strokes per minute of full feed pressure on blade life for cutting Ti-75A, molybdenum Hi-speed blades.


GRAPH 5
EFFECT OF VARYING STROKE/MIN. AT FULL PRESSURE ON BLADE LIFE FOR CUTTING TI-75A TUNGSTEN HI-SPEED BLADES
56 strokes per minute
98 strokes per minute
140 strokes per minute
feed rate 0.001" per stroke
16
15
14
13
12
11
10
9
8
7
6
0
0
8
16
24
32
number of square inches of cross section cut


GRAPH NO.4
B - MOLYBDENUM BLADE
B' - TUNGSTEN BLADE
MATERIAL : 130B
CONDITION : SCALE ON SURFACE
56 STROKES / MINUTE
FULL FEED PRESSURE
COOLANT : SOLUBLE OIL AND
WATER 20:1
B
B'
AVERAGE FEED RATE 0.001" / STROKE
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
8
16
24
32
40
48
56
NUMBER OF SQUARE INCHES OF CROSS SECTION CUT


GRAPH NO. 3
C-A- MOLYBDENUM BLADE
C'-A'- TUNGSTEN BLADE
MATERIAL: 130 B
CONDITION: NO SCALE ON SURFACE
56 STROKES / MINUTE
FULL FEED PRESSURE
COOLANT: SOLUBLE OIL AND
WATER 20:1
A
A'
C
C'
AVERAGE FEED RATE 0.001"/ STROKE
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
8
16
24
32
40
48
56
NUMBER OF SQUARE INCHES OF CROSS SECTION CUT


GRAPH NO. 2
A-B MOLYBDENUM BLADES
A'-B' TUNGSTEN BLADES
MATERIAL : 150 A
CONDITION : NO SCALE ON SURFACE
56 STROKES / MINUTE
FULL FEED PRESSURE
COOLANT : SOLUBLE OIL AND WATER 20:1
A
B
A'
B'
B'
A'
AVERAGE FEED RATE 0.001" / STROKE
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
8
16
24
32
40
48
56
NUMBER OF SQUARE INCHES OF CROSS SECTION CUT


GRAPH NO. 1
A-MOLYBDENUM BLADE
B-TUNGSTEN BLADE
MATERIAL : 75 A
CONDITION: SCALE ON SURFACE
56 STROKES / MIN.
FULL FEED PRESSURE
COOLANT: SOLUBLE OIL AND
WATER 20:1
A
B
AVERAGE FEED RATE 0.001" / STROKE
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
8
16
24
32
40
48
56
NUMBER OF SQUARE INCHES OF CROSS SECTION CUT