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FORCES AND POWER REQUIRED TO TURN ALUMINUM AND SEVEN ALLOYS

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ABSTRACT

Turning tests on pure Aluminum 1100-H14 and 7 Aluminum alloys were made to develop the formula for the tangential cutting force as a function of the material constant, the feed in inches per revolution, and the depth of cut in inches, when cutting dry, with a solid high speed steel tool ground for turning Aluminum. Equations for each metal have been developed and it is shown that the constants and exponents vary for each metal. Unit net power at the cutter has been computed for several sizes of cut for each metal and the values for a light cut and a medium size cut have been plotted against each of the mechanical properties of the materials. These data show that knowing the Brinell Hardness, the ultimate or yield strength of the metal, or the shear strength, values of the unit net horsepower at the cutter can be computed with considerable accuracy.

FORCES AND POWER REQUIRED TO TURN ALUMINUM AND SEVEN ALLOYS

This paper presents the results of a number of tests dealing with cutting forces, and attempts to correlate them with the mechanical properties of the materials machined. The nominal chemical composition of the wrought aluminum alloys received in two-inch diameter bars is given in Table I. The mechanical properties of the pure aluminum and the seven alloys are given in Table II for each of the metals. In Table II the new temper designations for each alloy and temper are given, together with the old temper designations. The new designations were first published in the company's booklet "ALCOA Aluminum and its Alloys," in 1948.

Cutting tools selected for these tangential force tests were of an 18-4-1 type of high speed steel in the form of solid bars, one-half inch square as illustrated in Figure 1. These were carefully ground to a tool designation of 20° back rake, 40° side rake, 10° end relief, 10° side relief, 10° end cutting edge angle, 15° side cutting edge angle, and a sharp nose. The bars cut to 24-inch lengths were clamped in the jaws of a chuck on the left end and supported on a live center on the right, in a 14-inch American Tool Works Company "Pacemaker" Engine Lathe. The lathe was driven by a 15-hp direct-current motor powered from a Reliance Electric Company's motor generator set to provide field and armature voltage control so that speeds from zero to 3000 rpm in infinite steps were available. This made it possible to machine the surface of any diameter at any desired cutting speed.

In the first series of tests, the tangential forces are measured with a tool dynamometer involving the S-4 Strain Gage and Sanborn Recorder. The force was determined for each of several speeds from 25 fpm up to 1000 fpm for each of the metals. The results shown graphically in Figure 2 indicate that there is no appreciable reduction in tangential cutting force as the speed is increased. The slope of the curves is practically all the same, slightly lower to the right for the higher speeds, with a negative slope of 0.03 as indicated. For these cuts a constant feed of 0.0078 ipr and a depth of cut of 0.080 inch were used. All tests were run dry with the 20, 40, 10, 10, 10, 15, 0-inch tool of high speed steel.

These tangential force tests were continued for a constant speed of 100 feet per minute when the feed was varied for each of four depths of cut, and then the depth was varied for each of four values of feed. These results for the 1100-H14 aluminum are shown in Figure 3. For the pure aluminum bars only, the tangential forces, as a function of feed, give a series of points lying on a curved line (dashed) for each of the four depths

TABLE I

NOMINAL CHEMICAL COMPOSITIONS OF WROUGHT ALUMINUM ALLOYS FOR MACHINING TESTS

	Percent of Alloying Elements--Aluminum and Normal Impurities Constitute Remainder								
Alloy	Copper	Silicon	Manganese	Magnesium	Zinc	Nickel	Chromium	Lead	Bismuth
1100	---	---	---	---	---	---	---	---	---
2011	5.5	---	---	---	---	---	---	0.5	0.5
2014	4.4	0.8	0.8	0.4	---	---	---	---	---
2017	4.0	---	0.5	0.5	---	---	---	---	---
2024	4.5	---	0.6	1.5	---	---	---	---	---
4032	0.9	12.5	---	1.0	---	0.9	---	---	---
6061	0.25	0.6	---	1.0	---	---	0.25	---	---
7075	1.6	---	0.2	2.5	5.6	---	0.3	---	---

TABLE II

MECHANICAL PROPERTIES OF WROUGHT ALUMINUM ALLOYS FOR MACHINING TESTS

Old Alloy New* Temper	Old Alloy Old Temper	New Alloy New Temper	Ultimate Strength psi	Yield Strength psi**	Elongation % in 2 in.	Reduction of Area %	Brinell Hardness No.***	Shearing Strength psi****	Shearing Strength / % Elongation
2S-H14	2S-1/2H	1100-H14	17,900	15,300	35.5	68	32	10,730	320
11S-T3	11S-T3	2011-T3	49,400	38,700	18.5	39	97	31,870	1,790
14S-T6	14S-T	2014-T6	71,800	65,000	13.0	25	139	46,500	3,580
17S-T4	17S-T	2017-T4	63,400	42,900	23.5	38	115	40,670	1,760
24S-T4	24S-T	2024-T4	68,700	49,700	19.0	26	122	41,330	2,170
32S-T6	32S-T	4032-T6	54,500	48,500	8.5	15	115	36,430	4,160
61S-T6	61S-T	6061-T6	43,400	38,800	19.5	51	94	29,300	1,500
75S-T6	75S-T	7075-T6	85,100	76,800	12.5	20	153	51,230	4,160

*Designations since January 1, 1948.

**Set = 0.2%.

***500-kg load on 10-mm ball. Average of tests at center edge and midway between.

****Determined from double-shear test.

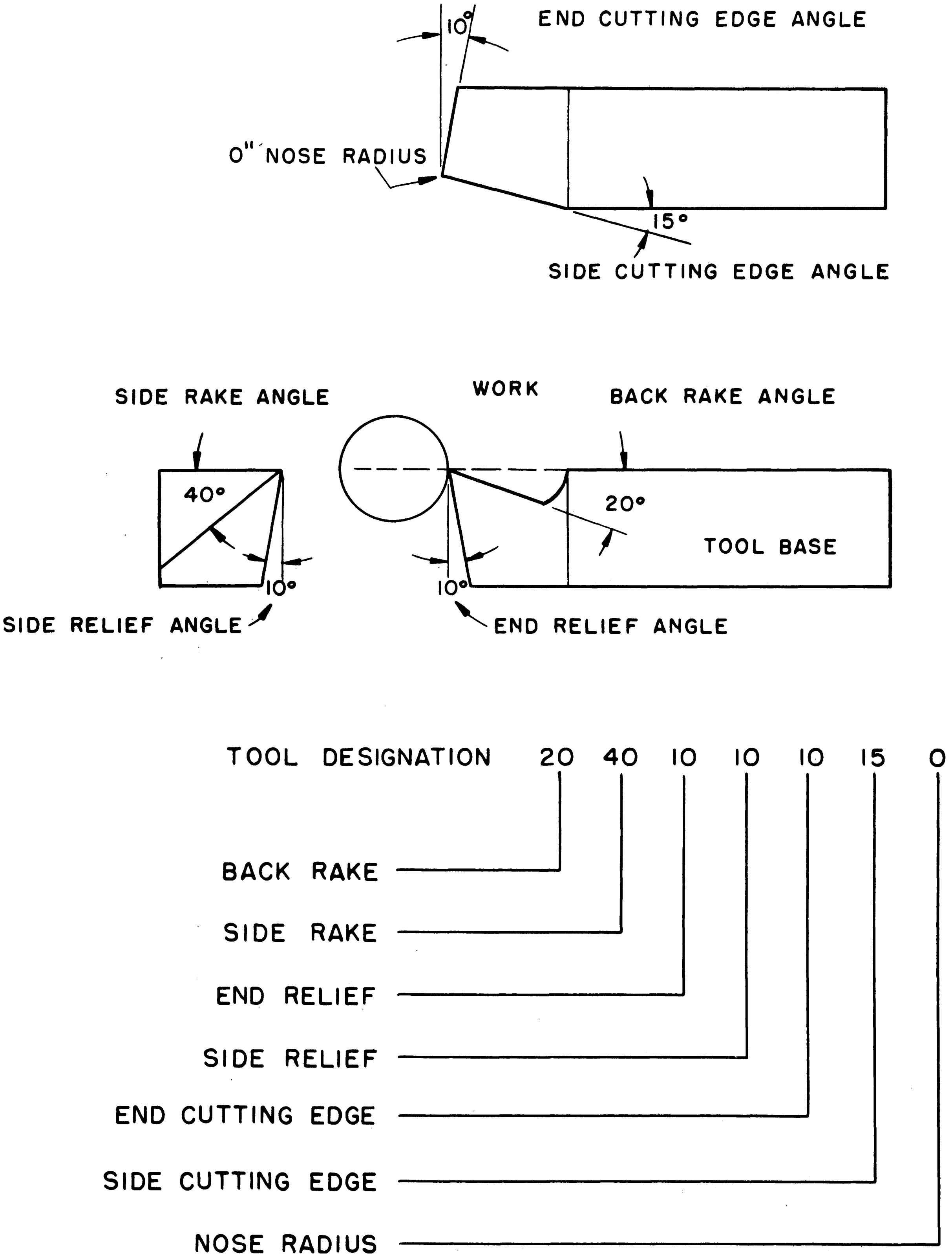

Figure 1. The Nomenclature and Tool Designation for a Typical Solid High Speed Steel Tc
As Ground for Turning Aluminum and Its Alloys.

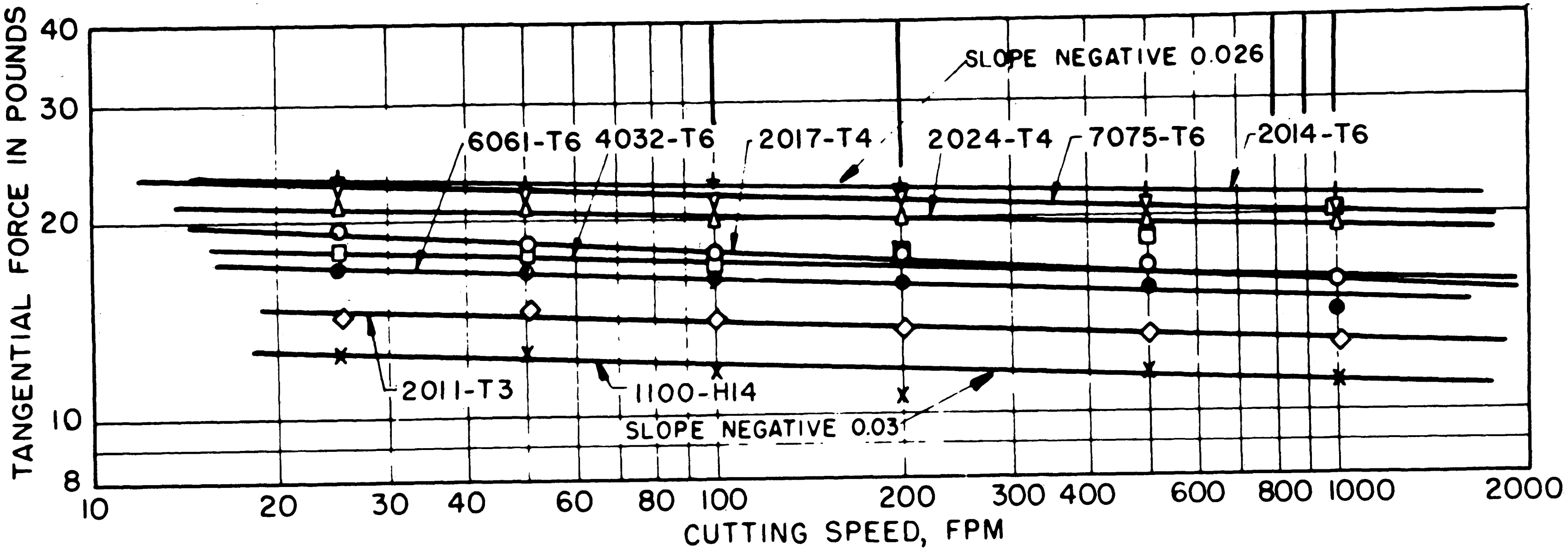

Figure 2. Influence of Cutting Speed on Tangential Forces When Turning Aluminum and Its Alloys, Cutting Dry with a Constant Feed of 0.0078 Inches Per Revolution and Depth of Cut of .080 Inch. The Tool of High-Speed Steel Had a Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius.

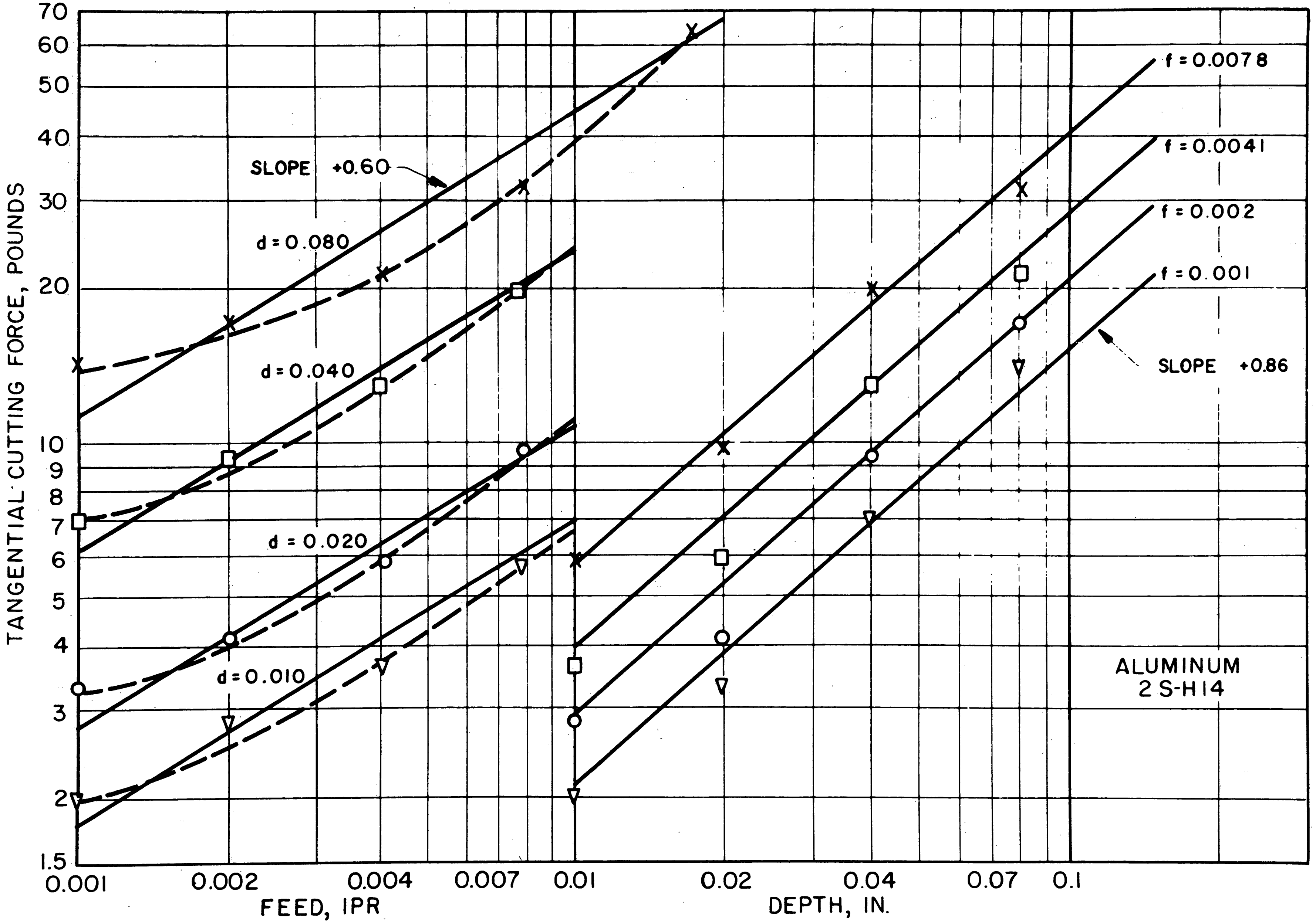

Figure 3. The Tangential Cutting Forces as a Function of the Feed and Depth of Cut When Turning Pure Aluminum 2S-H14, Dry, at a Constant Speed of 100 Feet Per Minute with the Standard Tool.

of cut. Straight solid lines, however, have been drawn to represent these data in order to have a single value of exponent for the feed. The slope of the lines for variable feed for each of the four depths of cut shown at the left in Figure 3 is 0.60. This value represents the exponent of the variable f (feed) in the force equation. Similarly, at the right in Figure 3, the slope of the lines for variable depth for each of the four feeds is 0.86. This indicates the equation $F_T = C \times f^{0.6}\ d^{0.86}$. By substituting the value of tangential force for given values of d and f, the constant is computed to be 5380, to give $F_T = 5380\ f^{0.6}\ d^{0.86}$, as shown for the 1100-H14 aluminum in Table III. Using this equation with the constant given, the tangential force for any other combination of feed and depth may be computed, or the values may be selected directly from the curves given in Figure 3.

Similar tangential force data, as a function of feed and depth when machining the 2024-T4 aluminum alloy at 100 fpm, are given in Figure 4. In this case the slope of the force lines for the variable feed is 0.67, and that for the variable depth lines is 0.96. These values give rise to the formula, $F_T = 17{,}900\ f^{0.67}\ d^{0.96}$, shown for this alloy in Table III. The constant has been computed to be 17,900 using the experimental value of F_T (61 lbs) shown in Table III.

Similar values of tangential cutting force for variable feeds and speeds were obtained for each of the other alloys. A summary of the tangential cutting forces, as a function of feed, for the constant depth of 0.080 inch, for all of the alloys is given in Figure 5. This shows that the 7075-T6 alloy requires about twice the cutting force as the 1100-H14 material. The lines for all the aluminum alloys are straight and nearly parallel (the pure aluminum 1100-H14, excepted). The slope of the variable feed lines for the alloys is represented by an average value of 0.7, which is the exponent of the variable, or $f^{0.7}$. This holds fairly well for all alloys except the 1100-H14 and 2011-T3.

In Figure 6 is shown the relationship between the tangential cutting force and the depth of cut for a feed of 0.0078 ipr, when the cutting speed was 100 fpm. The slopes of these lines vary from a minimum of 0.86 for the 1100-H14, and 0.80 for the 2011-T3 to roughly 0.95 for the balance of the metals. These values represent the exponent of the variable depth, and are summarized in the equations of Table III, which shows also a general equation of $F_T = C\ f^{0.7}\ d^1$, which is close for all metals except 1100-H14 and 2011-T3. The constants given in Table III should be used for each metal, however, for accurate values as was done done in computing the values in Table IV.

The unit horsepower, u hp_c, that is, the net horsepower at the cutter per cubic inch of metal removed per minute is another means of representing the machinability of the aluminum and its seven alloys. The net horsepower at the cutter is equal to the tangential cutting force, F_T, times the cutting speed, V, divided by 33,000. The unit horsepower at the cutter is equal to this value of hp_c divided by the cubic inches removed per minute. Therefore, u hp_c equals hp_c divided by 12 f d B, or

TABLE III

Aluminum	F_T for Cut 0.0078 f 0.080 d	Values of "C" and Force Equation $F_T = Cf^x \; d^y$
1100-H14	33.1	$F_T = 5380\ f^{.60}\ d^{.86}$
2011-T3	38.5	$F_T = 8000\ f^{.68}\ d^{.80}$
2014-T6	61.5	$F_T = 20380\ f^{.69}\ d^{.97}$
2017-T4	54	$F_T = 18800\ f^{.69}\ d^{.99}$
2024-T4	61	$F_T = 17900\ f^{.67}\ d^{.96}$
4032-T6	54	$F_T = 17850\ f^{.69}\ d^{.97}$
6061-T6	49	$F_T = 13850\ f^{.70}\ d^{.89}$
7075-T6	66	$F_T = 23600\ f^{.68}\ d^{1.02}$
All Alloys(a)		$F_T = c\ f^{.7}\ d$

(a)Approximate general equation for all alloys except 2S and 11S when using "C" for each metal.

Equations for Tangential Cutting Forces, F_T, and Values of "C" Computed for Each Metal using Test Data Indicated.

Tool Shape 20, 40, 10, 10, 10, 15, 0-in. Nose Radius, and Cutting Speed, 100 fpm.

TABLE IV

Metals	Exponents of		Values of F_T and u hp_c for Each Cut							
	f	d	f = .004 d = .010		f = .008 d = .080		f = .012 d = .125		f = .024 d = .125	
			F_T	u hp_c	F_T	u hp_c	F_T	u hp_c	F_T	u hp_c
1100-H14	.60	.86	3.68	.232	33.7	.133	63.4	.108	83.8	.071
2011-T3	.68	.80	4.68	.295	39.3	.155	75.0	.126	119.5	.101
2014-T6	.69	.97	5.15	.325	62.3	.245	127.6	.215	206.0	.173
2017-T4	.69	.99	4.35	.274	54.9	.216	114.6	.193	178	.150
2024-T4	.67	.96	5.31	.335	62.4	.246	126.0	.212	200	.168
4032-T6	.69	.97	4.52	.285	55.3	.218	112.4	.189	180	.152
6061-T6	.70	.89	4.8	.302	49.7	.196	98.3	.166	159	.134
7075-T6	.68	1.02	5.03	.318	66.7	.266	139.6	.235	224	.189

Values of u hp_c for Eight Aluminum Metals for Each of Several Sizes of Cut as Computed from Equations of Table III.

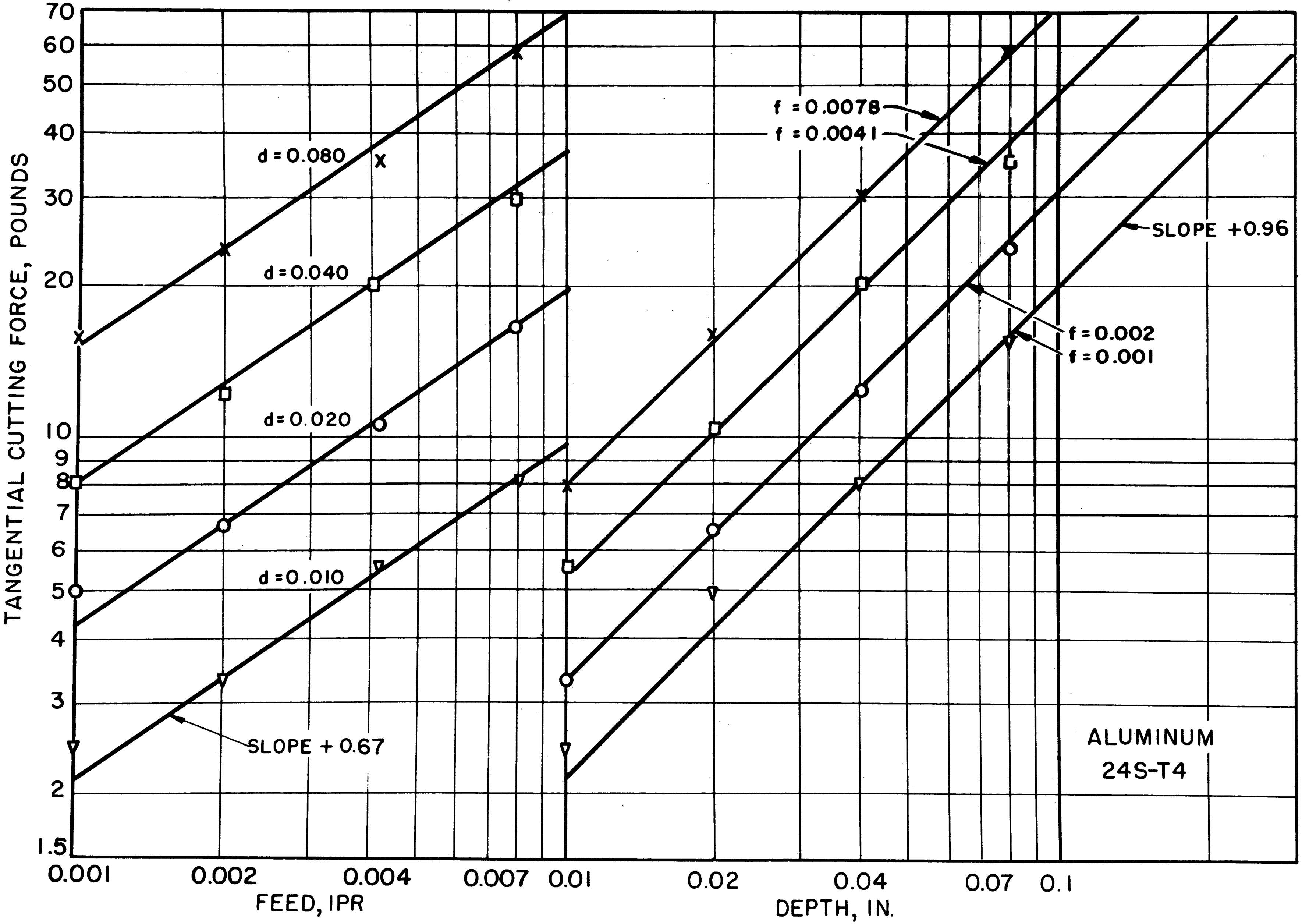

Figure 4. The Tangential Cutting Forces Are Shown as a Function of the Feed and Depth of Cut When Turning the Aluminum Alloy 24S-T4, Dry, at a Constant Speed of 100 Feet Per Minute with the Standard Tool.

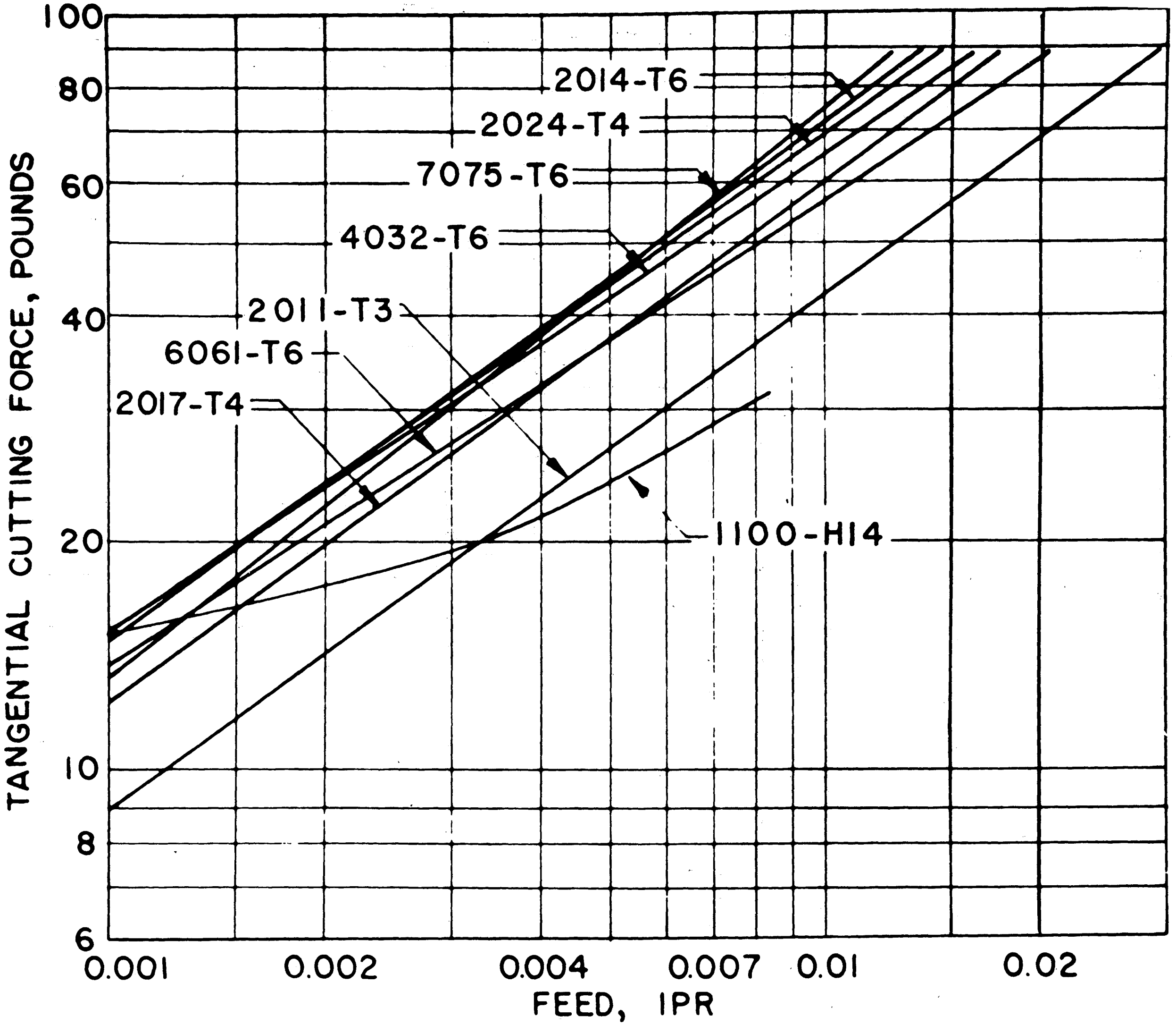

Figure 5. Relation between Tangential Cutting Force, F_T, and the Feed at a Constant Depth of 0.080 Inch When Turning Aluminum and Its Alloys at a Speed of 100 Feet Per Minute, Cutting Dry. The Slopes of the Lines Correspond to the Exponent of "f" in Table III. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used.

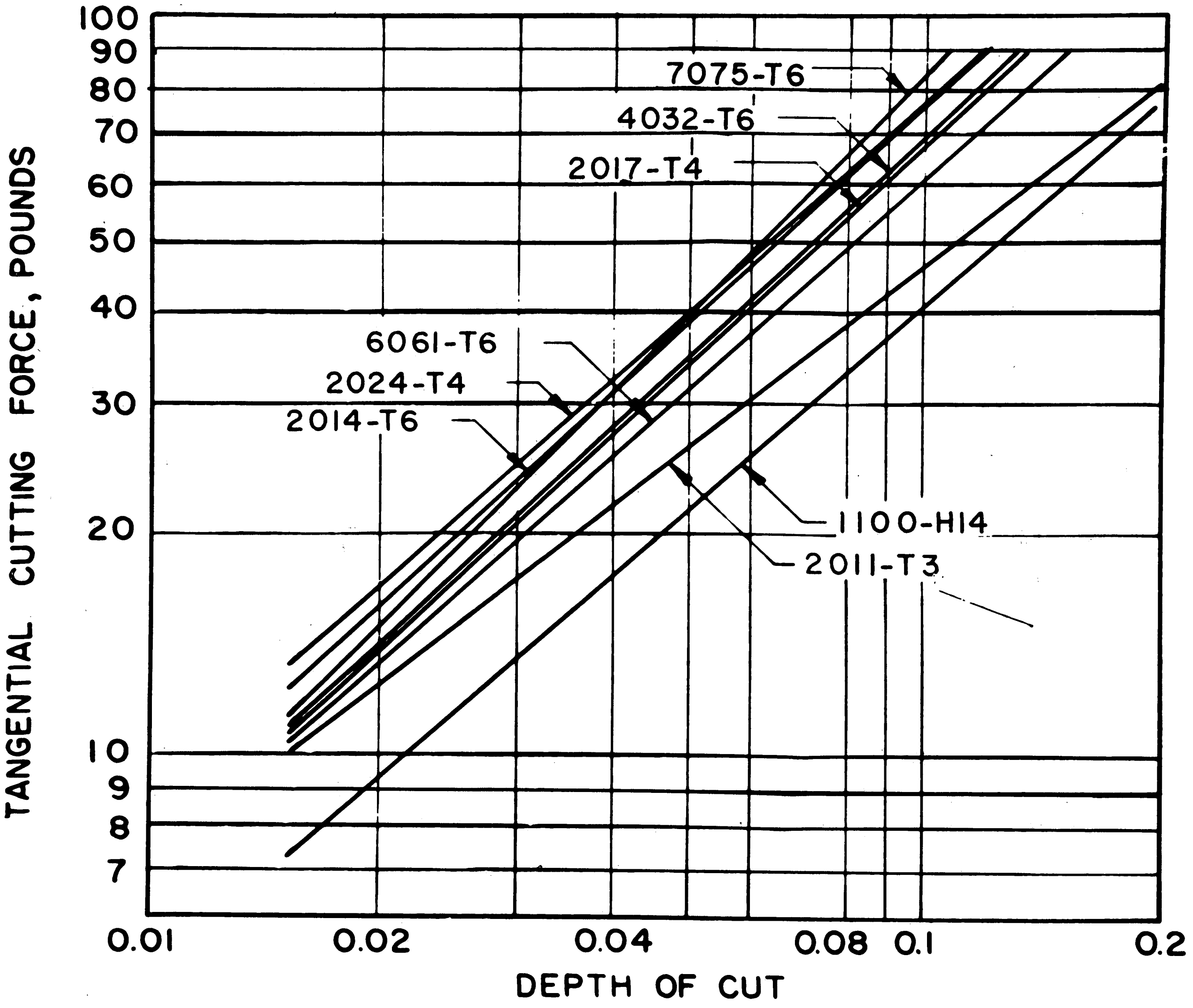

Figure 6. Tangential Cutting Force, F_T, Versus Depth of Cut for a Feed of 0.008 Inch Per Revolution When Turning Aluminum and Its Alloys at a Constant Speed of 100 Feet Per Minute, Cutting Dry. The Slopes of the Lines Correspond to the Exponent of "d" in Table III. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used.

$$u\ hp_c = \frac{F_T\ V}{12\ fdV \times 33{,}000} = \frac{F_T}{396{,}000\ fd}$$

For the 2014-T6 alloy, this becomes $(127.6/396{,}000fd)$. For a feed of 0.012 inch and a depth of 0.125 inch,

$$u\ hp_c = \frac{127.6}{396{,}000 \times .012 \times 0.125} = .215$$

as shown for this cut in Table IV along with similar values for all metals for each of four sizes of cut, from a feed of 0.004 inch up to 0.024 inch. These data show that the unit hp_c is lower for the values of heavier feeds. For example, for the 7075-T6 alloy, the unit hp_c is reduced from 0.318 for the cut of 0.004 x 0.010 to 0.189 for the cut of 0.024 x 0.125 inch. This reduction is due principally to the increase in feed.

Values of u hp_c are shown for each of the metals when taking a cut, dry, at 100 fpm, for each of four sizes of cut in Figure 7. For the heaviest cut, the highest value of u hp_c is for the 7075-T6 alloy. The next highest value is for the 2014-T6 alloy. The values for alloys to 6061 are nearly equal and still lower, but the lowest values are for 1100 and 2011. The greatest spread for the heaviest cut is from 0.071 for 1100-H14 to 0.189 for 7075-T6. The latter is 2.67 times the former. Further, the value of u hp_c for 7075-T6 for the lightest cut is 0.318 and it is 0.189 for the heaviest cut. The former is 1.68 times the latter.

The greatest overall spread for all metals is 0.335 for the 2024-T4 alloy at the lightest cut to 0.71 for the 1100-H14 aluminum at the heaviest cut. This indicates the range or variation in net power at the cutter per cubic inch of metal removed per minute when cutting all aluminum metals at various sizes of cut in industry.

Influence of Various Mechanical Properties of the Aluminum Metals on Unit Net Horsepower

To show the influence of the mechanical properties of the various metals studied in this paper on the unit net horsepower at the cutter, u hp_c, Figures 8 to 13 have been prepared. In each case the value of the unit net horsepower is given as the ordinate and the mechanical property as abscissa. These figures are intended to show the relationships only in general terms. For example, in Figure 8 the unit net horsepower is shown as a function of the Brinell hardness of the various metals for both a light cut and a medium cut. The values of power are taken from the highest curve and the third from the highest curve of Figure 7, or from Table IV. For the heavy cut, which has a feed of 0.012 in. per revolution and a depth of cut of 0.125 in., the relationship is

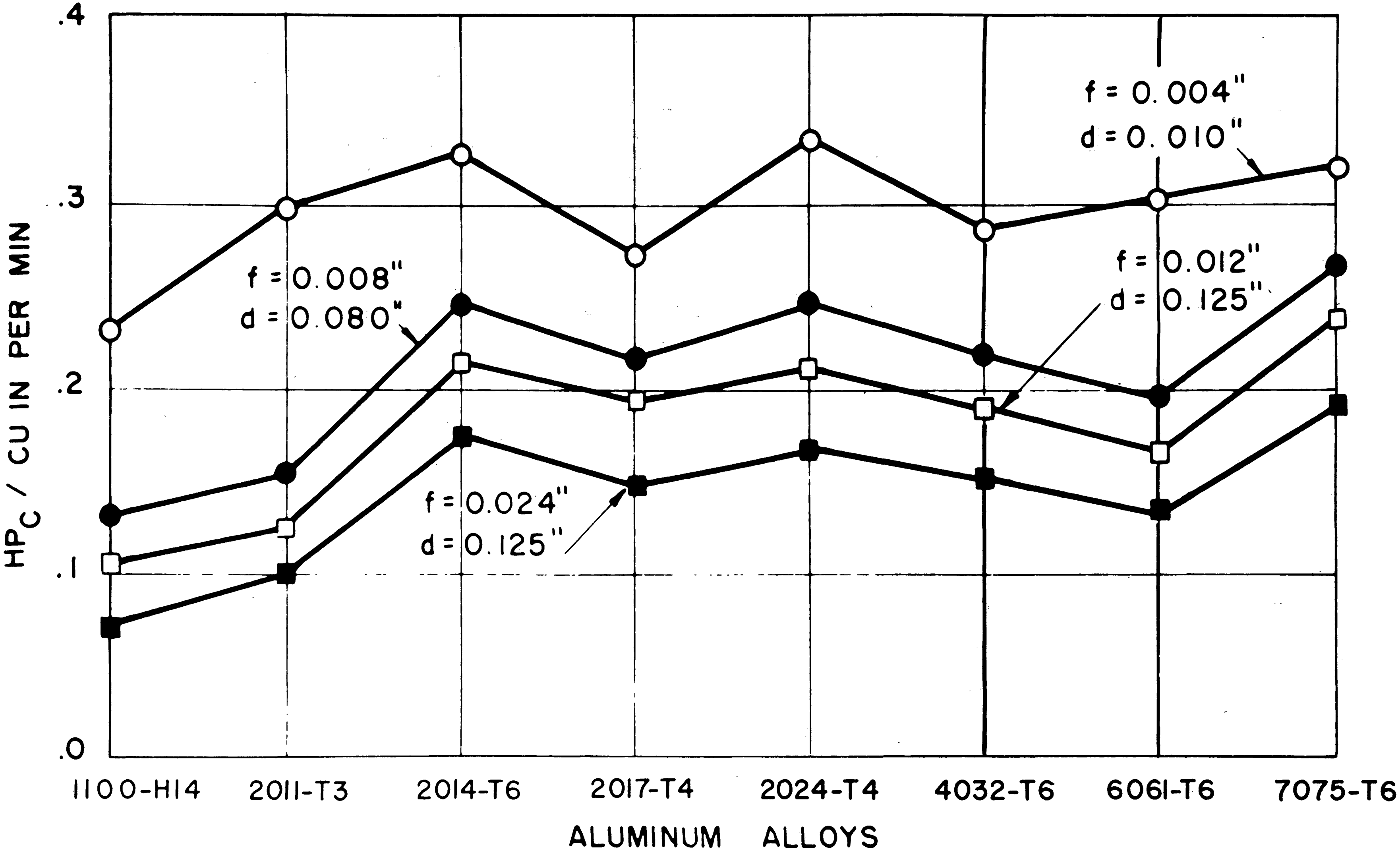

Figure 7. Variation in Unit Horsepower (Horsepower Per Cubic Inch Per Minute) Requirements for Aluminum and Its Alloys When Turning Dry at 100 Feet Per Minute, for Each of Four Cuts Shown. A High Speed Steel Tool with a Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used.

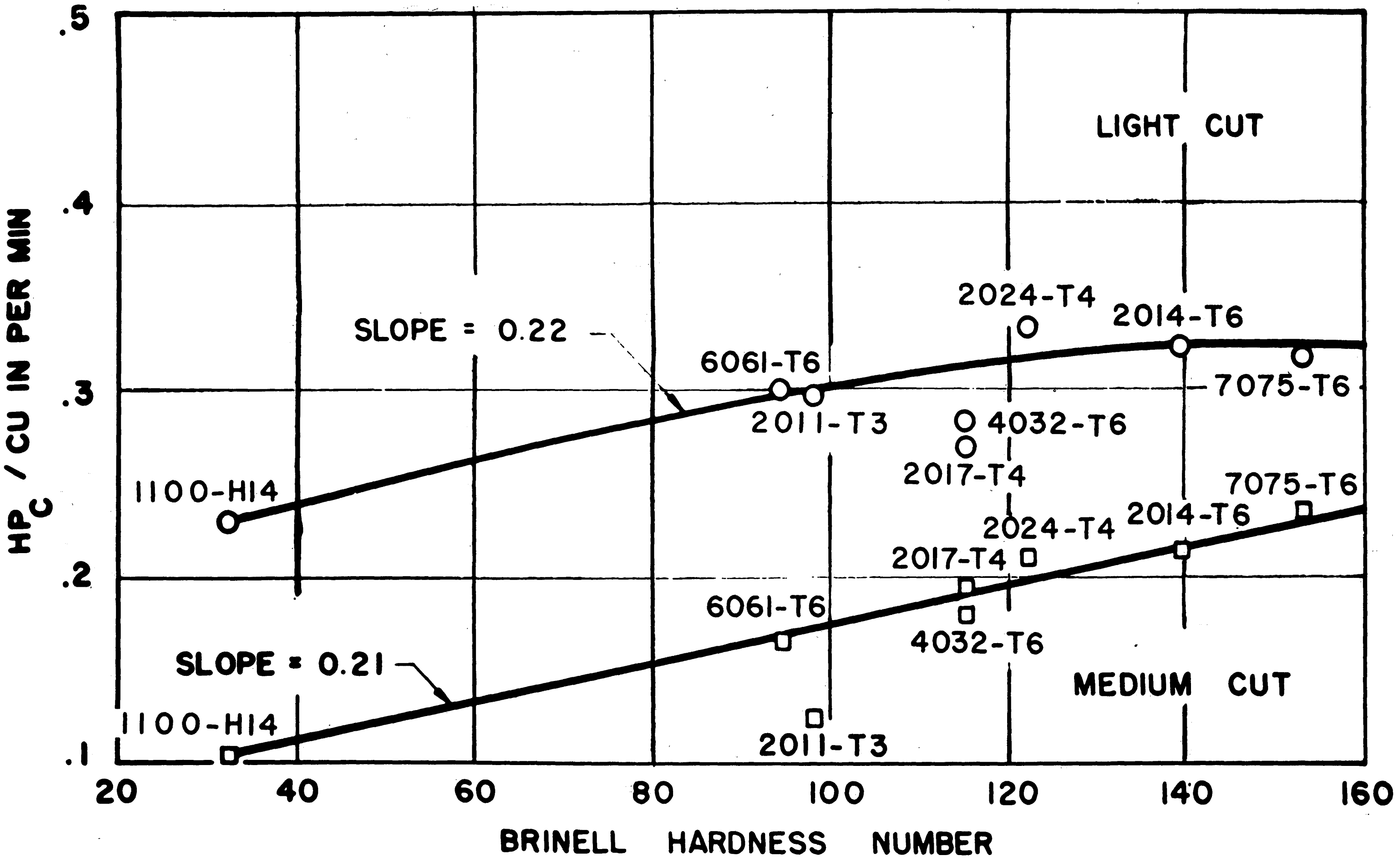

Figure 8. Influence of Brinell Hardness Number on Horsepower Per Cubic Inch Per Minute When Making a Light Cut of f = 0.004 Inch and d = 0.010 Inch, and a Medium Cut of f = 0.012 Inch and d = 0.125 Inch on Aluminum and Its Alloys at 100 Feet Per Minute, Cutting Dry. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used. (u hp = 0.00105 Bhn + 0.069 for the 0.012 x 0.125-In. Cut).

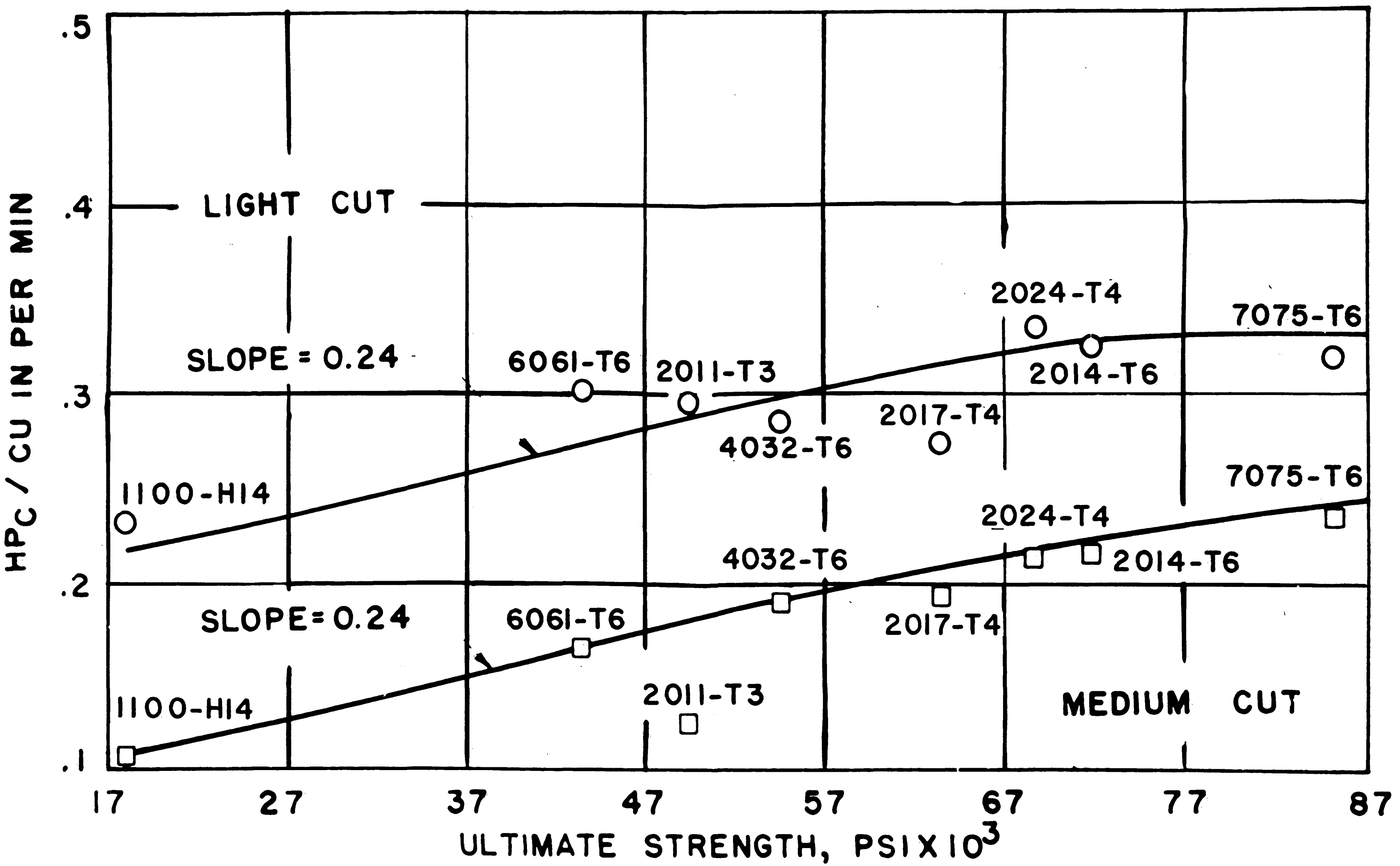

Figure 9. Influence of Ultimate Strength on Unit Horsepower When Making a Light Cut of $f = 0.004$ Inch and $d = 0.010$ Inch, and a Medium Cut of $f = 0.012$ Inch and $d = 0.125$ Inch on Aluminum and Its Alloys at 100 Feet Per Minute, Cutting Dry. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used. ($u\ hp_c = 0.00000205\ US + 0.071$ for the 0.012 x 0.125-In. Cut).

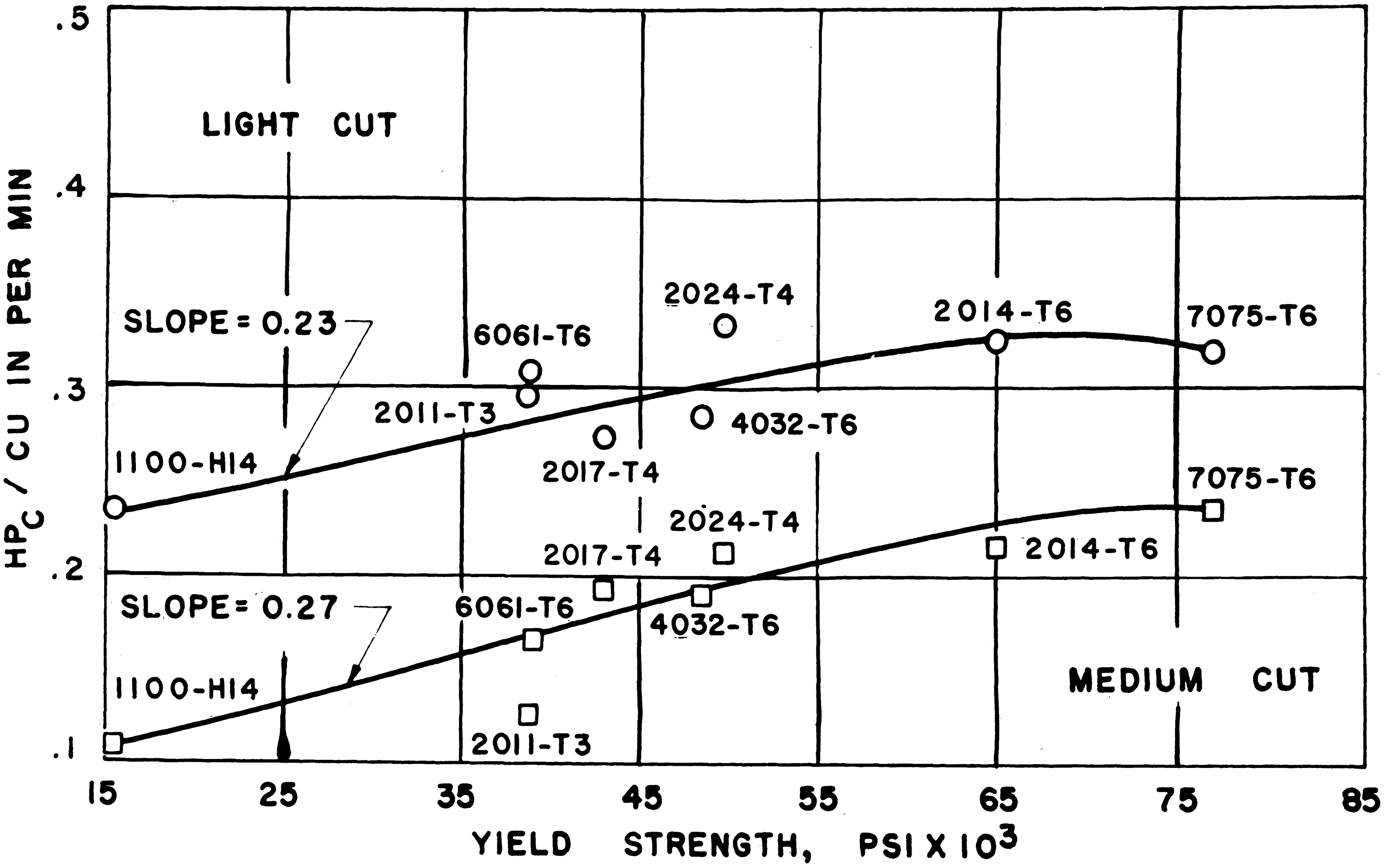

Figure 10. Influence of Yield Strength on Unit Horsepower When Making a Light Cut of f = 0.004 Inch and d = 0.010 Inch, and a Medium Cut of f = 0.012 Inch and d = 0.125 Inch on Aluminum and Its Alloys at 100 Feet Per Minute, Cutting Dry. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used. (u hp$_c$ = 0.000002065 YS + 0.0764 for the 0.012 x 0.125-In. Cut).

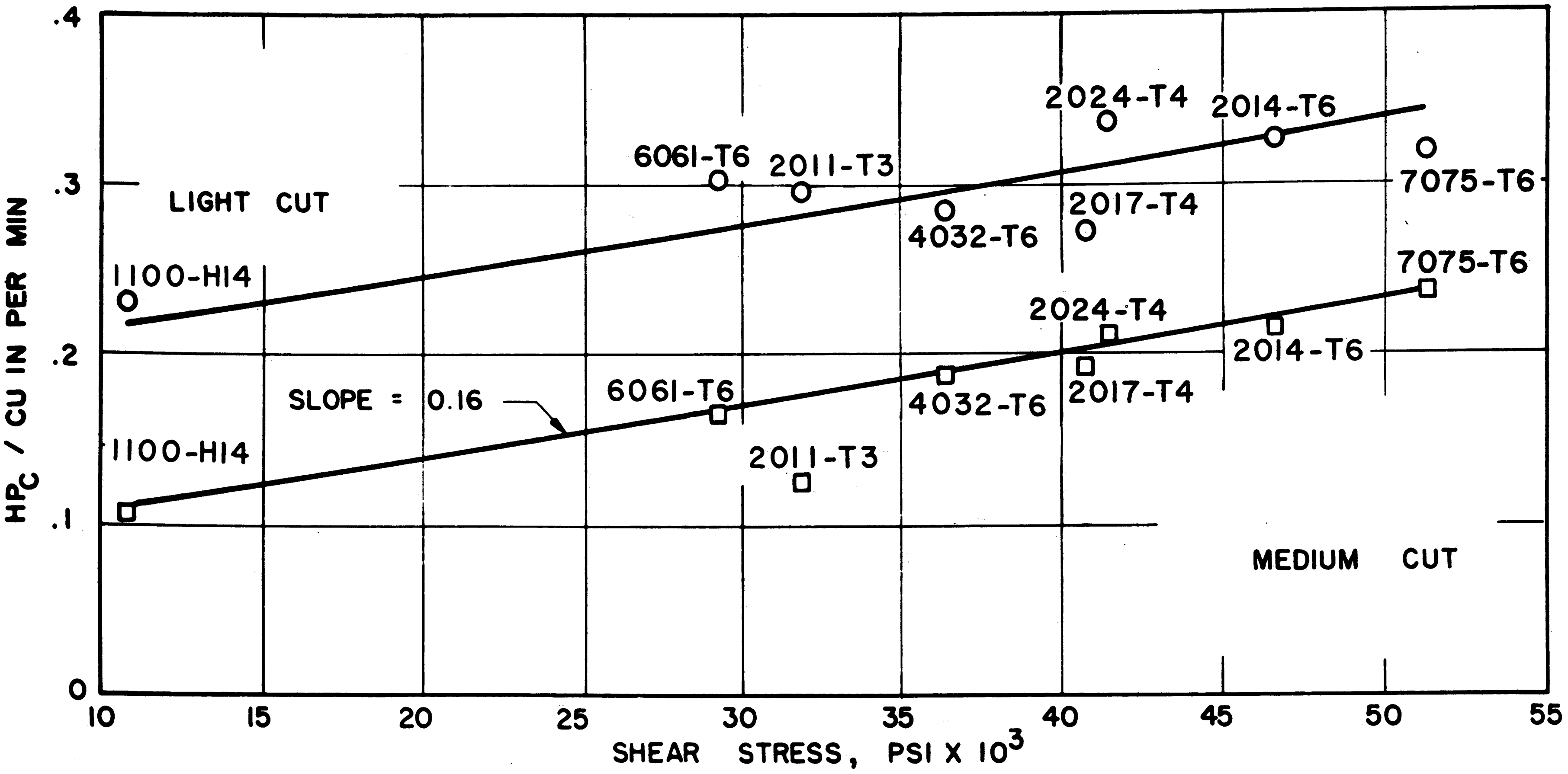

Figure 11. Shear Stress in Pounds Per Square Inch Versus Unit Horsepower for Aluminum and Its Alloys for a Light Cut of f = 0.004 Inch and d = 0.010 Inch and a Medium Turning Cut of f = 0.012 Inch and d = 0.125 Inch, at 100 Feet Per Minute, Cutting Dry. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used. (u hp_c = 0.00000314 SS + 0.0743 for the 0.012 x 0.125-in. Cut).

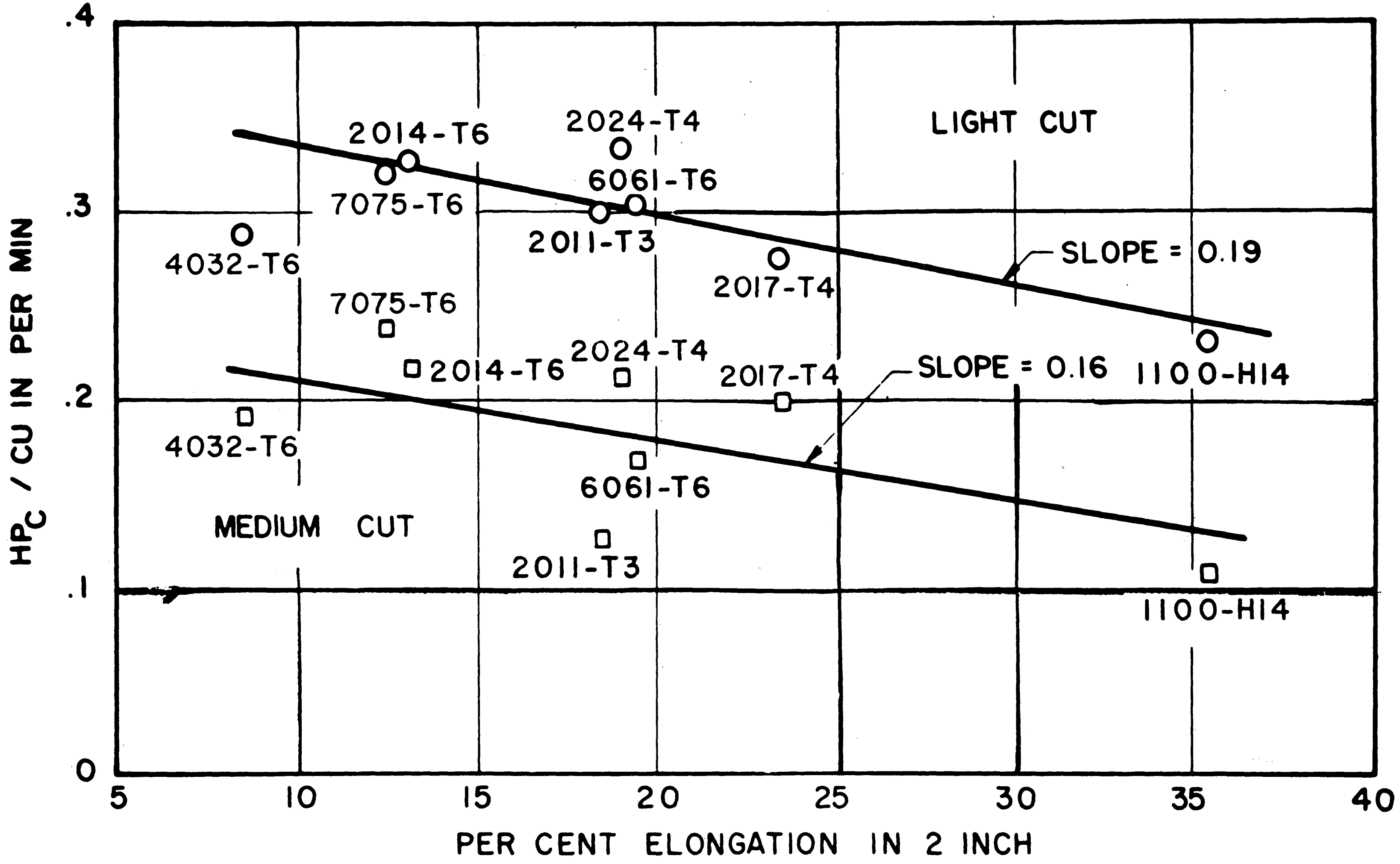

Figure 12. Horsepower Per Cubic Inch Per Minute Versus Percent Elongation When Turning Aluminum and Its Alloys at a Light Cut of f = 0.004 Inch and d = 0.010 Inch, and a Medium Cut of f = 0.012 Inch and d = 0.125 Inch at 100 Feet Per Minute, Cutting Dry. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used.

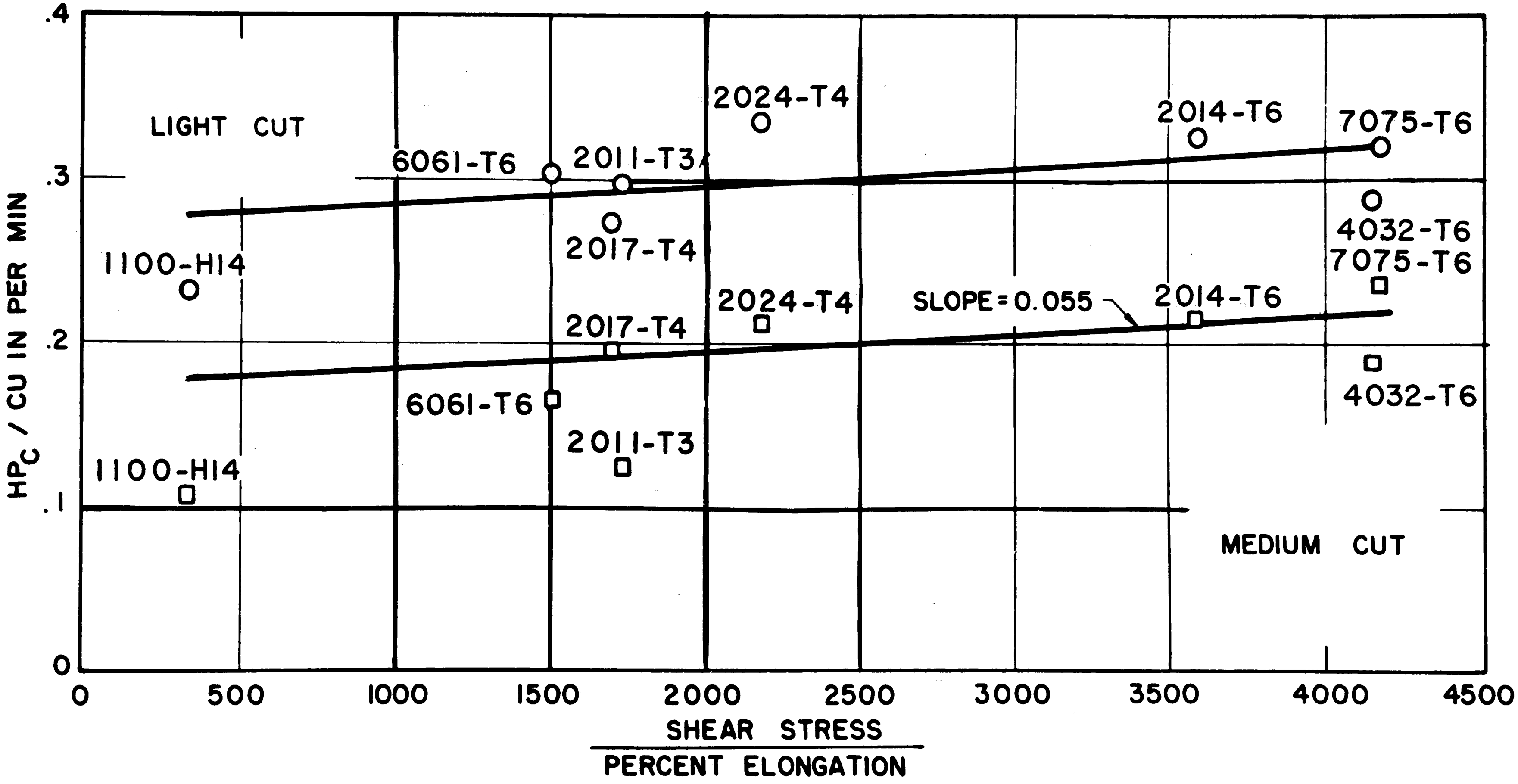

Figure 13. The Influence of the Ratio of Shear Stress to Percent Elongation on Horsepower Per Cubic Inch for Turning Aluminum and Its Alloys with a Light Cut of f = 0.004 Inch and d = 0.010 Inch, and a Medium Cut of f = 0.012 Inch and d = 0.125 Inch at 100 Feet Per Minute, Cutting Dry. A Tool Shape of 20, 40, 10, 10, 10, 15, 0-Inch Nose Radius Was Used.

almost a straight line. The unit power is increased from 0.108 to 0.235 (118 percent) as the Brinell is increased from 32 to 153 (378 percent). For the light cut, however, in which f = 0.004 in. and d = 0.010 in. a general relationship is indicated, although the values of power for the 4032-T6 and 2017-T4 are well below the indicated line while the value for 2017-T4 is slightly above. A line through the points for 2017-T4, 2014-T6 and 7075-T6 alone would show a negative slope.

The ultimate strength and its relation to the unit net horsepower at the cutter for each of the metals is shown for the light cut and medium-sized cut in Figure 9. The lines are drawn merely to represent the relationship of the values to a normal expectancy. Practically all points for the medium-sized cut lie on, or close to, the line. The ultimate strength for 2011-T3 is considerably below the line and out of order. The point for 2017-T4 is also slightly below the line, although it is in relatively close agreement to the expectation. For the 118 percent increase in unit power, there is an increase from 17,900 psi for 1100-H14 to 85,100 psi for 7075-T6, or 376 percent. A greater deviation from the indicated line is shown for the values for the light cut, however. The point for 6061-T6 is slightly above the indicated line and the point for 2017-T4 is somewhat below the line. In fact, a line drawn through the points for 6061, 2011, 4032, and 2017 would be quite different from that indicated for the light cut and have a negative slope indicating a reverse ratio.

Corresponding values of yield strength for the light and medium cuts, as a function of the unit power at the cutter, are shown in Figure 10. The point for the free cutting alloy, 2011-T3, is considerably below the line for the medium-sized cut. Also, the points for 2017-T4 and 4024-T4 are slightly above the indicated line. Otherwise, there appears to be a fairly direct relationship between the yield strength and the unit horsepower for the medium cut. The values for the light cut, as represented by the upper line in Figure 10, show a greater dispersion from the indicated line. The two low points are for 2017-T4 and 4032-T6, while the points for 6061-T6 and 2024-T4 are well above the indicated line.

In Figure 11 is shown the relationship of unit power to the shear stress as determined from a double-shear test. Except for the low value of power for 2011-T3, a single straight line seems to represent the straight-line relationship very well for all the metals for the medium cut. For the light cut several of the points are well off the indicated line indicating a less definite relationship between shear stress and unit power.

The percent elongation is shown as a function of unit net power in Figure 12. In this case, except for the value for 4032-T6, the points lie on an indicated straight line fairly satisfactorily for the light cut. A greater dispersion of the points from the indicated straight line for the medium cut is shown.

The shear stress divided by percent elongation is the mechanical property represented in Figure 13 as a function of unit net power. The points for 1100-H14, 2011-T3 and 4032-T6 are well below the indicated line for the medium cut. The point for 7075-T6 is high. For the light cut, the points for 1100-H14, 2017-T4 and 4032-T6 are all well below the indicated line whereas 2024-T4 is well above the line. There does, however, appear to be a trend for higher unit net power for higher values of shear stress over percent elongation for both cuts.

Conclusions

When turning dry these several aluminum alloys with the high speed steel tool shape indicated as 20, 40, 10, 10, 10, 15, 0, the following general conclusions have been reached:

1) All metals give cutting force values corresponding to exponential equations involving feed and depth, such as $F_T = Cf^x d^y$. However, each metal has its own peculiar exponents, x and y. In cutting most steels for example, the exponents of feed and depth are alike, and only the constant will vary. The aluminum alloys seem to be peculiarly individual in this respect.

2) In turning all eight aluminum metals at speeds from 25 fpm to 1000 fpm, the cutting force remains practically constant for each metal. In other words, at high speeds there appears to be no marked variance in the cutting forces for the different metals.

3) The unit horsepower--that is, the horsepower at the cutter per cubic inch of metal removed per minute--varies almost directly with the Brinell hardness number of the metals for medium-sized cuts. The free-cutting alloy, 2011-T3, is well below the normal line, however. As the unit power is increased 118 percent, the Brinell is increased 378 percent. The equation for this line, so power may be computed from Brinell hardness, is $u\ hp_c = 0.00105\ Bhn + 0.069$. Example: to determine the unit net horsepower at the cutter, $u\ hp_c$, if the Brinell hardness (Bhn) is known to be 94 (for the 6061-T6, Table II) $u\ hp_c = 0.00105\ Bhn + 0.069$. (This is the equation of a straight line, of the form $y = mx + b$.) Then $u\ hp_c = 0.00105 \times 94 + 0.069 = 0.09975 + 0.069 = 0.16875$ which corresponds to 0.166 for this medium cut, Table IV. For a light cut there is a greater fluctuation of points; the direct relationship holds for only five of the eight metals.

4) The ultimate strength of all metals, except 2011-T3, gives almost a straight-line relationship with the unit power for the medium-sized cut. For the increase of 118 percent in unit power, there is an increase of 378 percent in ultimate strength. The equation for this line is $u\ hp_c = 0.00000205\ US + 0.071$, so unit power can be computed from ultimate strength (US). The power for the 2011-T3 is low for its strength. For the light cuts the relationship is more erratic for the several metals.

5) The yield strength (YS) increases almost directly as the unit net power, except for the 2011-T3 alloy which has relatively low power and 2017-T4 and 2024-T4 which have relatively high values, for the medium-sized cuts. For the 118 percent increase in power, the yield strength is increased in power, the yield strength is increased 400 percent. Values of $u\ hp_c = 0.000002065\ YS + 0.0764$. Again, the relationship for the light cut between unit power and yield strength is more erratic.

6) The shear stress (SS), as determined from the double shear test, gives a very good straight-line relationship between unit power and stress, the low values for 2011-T3 being one exception, for the medium cut. For the 118 percent increase in power, the shearing strength is increased 378 percent. For the medium cut 0.012-in. feed and 0.125-in. depth with the tool shown in Figure 1, $u\ hp_c = 0.00000314\ SS + 0.0743$. For the light cut this relationship is less consistent.

7) The percent elongation does not give a satisfactory linear relationship to the unit net power for the medium-sized cut for the various metals, but a better relationship is shown for the light cut except for the value of 32S-T6, which is low.

8) The shear stress divided by the percent elongation does not give an overall satisfactory linear relationship with the unit net power at the cutter for either the light or medium cuts.

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