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Power Equations

Turning-test results yield equations designed to maximize productivity.

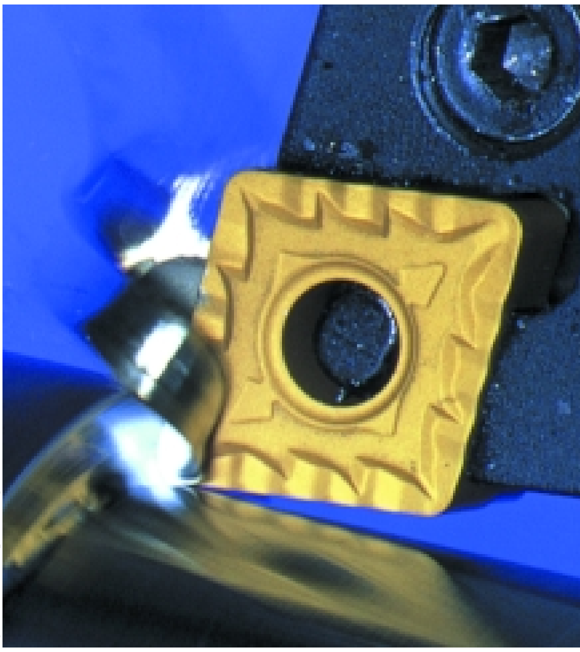
A machinist who knows a machine tool's maximum level of productivity can run the machine at its highest-capable speeds and feeds without stalling it. To help determine the maximum productivity when turning, I developed the methodology and supervised the testing of 20 workpiece materials. Based on these test results, five equations were developed to generate actual numbers that represent the workpiece material for various machining conditions with different cutting parameters.

Traditionally, machining power when turning is estimated through the metal-removal rate multiplied by the power constant of a workpiece material (also known as the "p-factor"). The method is simple, but not accurate. The reason is that the power constant of any workpiece depends on many variables, including the microstructure and hardness of the work material, cutting tool geometry, sharpness of the cutting edge, depth of cut and feed rate. This explains why power-constant values are usually overestimated, sometimes by more than 40 percent. This overestimating results in lost productivity, since the machine isn't operated at its highest speeds and feeds.

The test results I obtained led to the development of more accurate power-constant values than those currently used for most common carbon and alloy steels, stainless and tool steels, cast irons, nickel-base alloys, titanium alloys and aluminum alloys.

These reassessed power-constant values for work materials provide greater accuracy in calculating both the tangential cutting force and required machining power in relationship to DOC and feed rate.

In addition, the test results illustrate that a change in a material's properties, such as its hardness, affects the amount of power required and the cutting parameters.



Kyocera-Ceratip Cutting Tools

Interacting Forces

The interaction of a cutting tool with a rotating workpiece produces cutting forces that combine with tangential, feed and radial forces. These forces can be measured by a three-component turning dynamometer. Of the three cutting force components, the tangential force is the greatest. It generates torque on the workpiece that's rotated by the spindle; the reaction to the tangential force accounts for more than 95 percent of the machining power.

The accuracy of calculating machining power can be increased by considering the tangential cutting force and cutting speed, or by knowing the actual power-constant value of the work material.

The relationship between machining power at the spindle (P_S), tangential force (F_t) and cutting speed (V_c) is expressed as:

$$\textbf{Equation 1: } P_S\ (hp) = \frac{F_t \times V_c}{33{,}000}$$

The relationship between machining power at the spindle (P_S), mrr (Q) and power constant (p) is shown in Equation 2.

$$\textbf{Equation 2: } P_S\ (hp) = Q \times p$$

Since the left sides of the two formulas are equal, their right sides are also equal, as shown in Equation 3.

Equation 3: $\frac{F_t \times V_c}{33,000} = Q \times p$

The mrr (Q) depends on the cutting speed (V_c), DOC (d) and feed rate (f), and is determined by Equation 4.

Equation 4: $Q\ (\text{in.}^3/\text{min.}) = 12 \times V_c \times d \times f$

Substituting (Q) from Equation 4 into Equation 3 and solving Equation 3 with respect to the power constant (p) is shown in Equation 5.

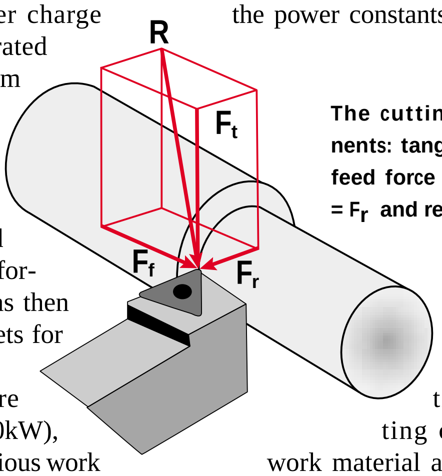
Equation 5: $P\ (\text{hp/in.}^3/\text{min.}) = \frac{F_t}{396,000 \times d \times f}$

Thus, a work material's power constant can be accurately determined by measuring the tangential force at a given DOC and feed rate.

Experimental Procedure

For the testing procedure, a Kistler turning dynamometer (Type 9263) measured the tangential, feed and radial forces. The tangential force was used to calculate the power constants of common work materials at various cutting conditions.

Outputs from the dynamometer were connected to the Kistler charge amplifiers, which generated DC signals and sent them to the data-acquisition card installed in a personal computer. Custom software collected the analog force data and converted it to a digital format. The digital data was then transferred to spreadsheets for analysis.



The cutting force components: tangential force = F_t, feed force = F_f, radial force = F_r and resultant force = R.

Dry turning tests were performed on a 40-hp (30kW), slant-bed CNC lathe. Various work materials were machined: carbon, alloy, stainless and tool steels; gray and ductile cast irons; and nickel-base, titanium and aluminum alloys. The indexable inserts applied were CNMG-432 (the most popular style and size), CNMG-543, CNMA-432, CNMA-543 and CNGP-432. The cutting tools represented the most common angles, including:

- Rake (back, side) angles: 5° (negative)
- Cutting edge (end, side) angles: 5° (positive)
- Relief (end, side) angles: 5° (positive)
- Lead angle: 5° (positive)

The indexable-insert styles, geometries, carbide grades and cutting conditions (DOC, feed rate and cutting speed) corresponded with the work materials and their hardnesses.

Turning tests for each work material included nine data points per machining condition: roughing (four data points), medium (one data point repeated three times) and finishing (four data points).

To ensure that each test was performed with a sharp cutting edge, the insert was indexed after an equal length of cut for each workpiece. The length of cut per data point was 1" (25.4mm). The influence of the cutting conditions and hardness of the work materials on cutting forces, power constants and machining power was then studied.

Test Results

Tangential, feed and radial forces were recorded at various machining conditions when turning each of the work materials selected for testing. The tangential force data was used to calculate the power constants and machining power requirements in relationship to cutting conditions, the work material and its hardness. The ratios of tangential force to feed force to radial force were calculated.

As mentioned earlier, the power constant depends on the hardness of the work material, DOC, feed rate and cutting speed. When two materials from the same class but with different hardnesses were tested, the one with the greater hardness had a higher power constant. A higher DOC and feed rate (at a constant cutting speed) decreased the power constant more than an increase in cutting speed.

Conversion Equations

To convert cutting speed from sfm to m/min., multiply the sfm value by 0.3048 and round off to the nearest integer. To convert cutting force from lbf (pound-force) to N (Newton), multiply the lbf value by 4.4482 and round off to the nearest integer, and to convert the p-factor in hp/in.^{3}/min. to kW/cm^3/min., multiply the hp/in.^{3}/min. value by 0.0455.

An increase in cutting speed (at a constant DOC and feed rate) slightly decreased the power constant. This phenomenon can be explained by the fact that the higher the DOC and feed rate, the greater the volume of material removed from the workpiece and, as a result, the cutting process became more efficient. Analysis of the calculated power constants led to the following conclusions:

- The minimum power-constant values are always at high DOCs and high feed rates, which are roughing characteristics. With respect to the volume of material removed from the workpiece, roughing is high-efficiency cutting.
- The maximum power-constant values are always at low DOCs and low feed rates, which are finishing characteristics. With respect to the volume of material removed, finishing is low-efficiency cutting.
- The harder the work material, the higher its power constant.
- Different types of work materials with the same hardness are characterized by different power constants. The power constants of steels are higher than cast irons, and the power constants of nickel-base alloys are higher than alpha-beta titanium alloys (for example, Inconel 718 vs. Ti-6Al-4V).

Due to the length of the 20 test results, only two are presented here: AISI 4140 alloy steel with hardnesses of 200 HB and 250 HB (Tables 1 and 2). These tests were conducted under the following machining conditions:

- Cutting speed range: 500 to 1,000 sfm (152 to 305m/min.)
- DOC range: 0.080" to 0.200"

KEY

Cutting speed: V_c

DOC: d

Feed rate: f

Machine tool efficiency factor: E

Metal-removal rate: Q

Power constant: p

Power at motor: P_m

Power at spindle: P_s

Tangential force: F_t

(2.03mm to 5.08mm)

- Feed rate range: 0.008 to 0.020 ipr (0.20 to 0.51mm/rev.)

Tangential, feed and radial cutting forces were measured and recorded, and the power constants, or p-factor values, were calculated using Equation 5 for each data point.

As the tables show, the p-factor values decrease from finishing to medium machining to roughing. Cutting forces increase when there's an increase in the DOC and feed rate. The tangential cutting force increases in direct proportion to the feed rate, within 8 to 11 percent, at a DOC of 0.080" and within 4 to 7 percent at a DOC of 0.200".

The tangential and feed forces decrease slightly at higher cutting speeds when the DOC and feed rate remain constant (except for the last data point in Table 2). The feed forces are approximately 40 to 60 percent of the tangential forces and the radial forces are approximately 20 to 30 percent of the tangential forces.

Calculated Decisions

A trade-show attendee who wanted to buy a machine tool asked a salesman to recommend a machine for turning 4140 alloy steel with a hardness of 250 HB at the following cutting parameters:

- DOC: 0.200" (5.08mm)
- Feed rate: 0.012 ipr (0.30mm/rev.)
- Cutting speed: 550 sfm (168m/min.)

The salesman recommended a 30-hp CNC lathe. The end user thought that he needed a smaller and less expensive

Cutting speed, sfm	Depth of cut, in.	Feed rate, ipr	Tangential force, lbf	Feed force, lbf	Radial force, lbf	p-factor, hp/in.^{3}/min.
600	0.080	0.008	211.4	119.2	58.1	0.834
1,000	0.080	0.008	209.3	110.1	56.1	0.826
600	0.080	0.012	292.3	136.6	75.2	0.769
1,000	0.080	0.012	282.7	127.0	73.8	0.744
800	0.140	0.015	604.9	287.3	117.9	0.727
800	0.140	0.015	610.5	285.6	119.7	0.734
800	0.140	0.015	606.7	284.0	119.9	0.730
500	0.200	0.010	616.8	348.0	98.5	0.779
900	0.200	0.010	584.9	304.6	96.7	0.739
500	0.200	0.020	1,164.1	546.6	193.9	0.735
900	0.200	0.020	1,091.9	459.3	190.1	0.689

Table 1. 4140 alloy steel, 200 HB

Cutting speed, sfm	Depth of cut, in.	Feed rate, ipr	Tangential force, lbf	Feed force, lbf	Radial force, lbf	p-factor, hp/in.^{3}/min.
600	0.080	0.008	227.5	133.5	63.1	0.898
1,000	0.080	0.008	221.8	127.8	63.4	0.875
600	0.080	0.012	311.4	149.9	80.5	0.819
1,000	0.080	0.012	306.9	149.9	84.9	0.807
800	0.140	0.015	644.6	351.7	145.4	0.775
800	0.140	0.015	654.4	379.1	171.8	0.787
800	0.140	0.015	662.3	405.1	191.8	0.796
500	0.200	0.010	628.6	353.9	103.7	0.794
900	0.200	0.010	615.1	340.1	109.6	0.777
500	0.200	0.020	1,173.0	531.9	195.2	0.741
900	0.200	0.020	1,186.0	599.8	205.9	0.749

Table 2. 4140 alloy steel, 250 HB

machine. The following calculations could have helped him make the best decision.

1. The machining power at the spindle can be calculated with either Equation 1 or 2. If Equation 2 is used, the mrr should be determined first.

2. The mrr can be calculated with Equation 4.

$$Q = 12 \times 550 \times 0.2 \times 0.012 = 15.84 \text{ in.}^3\text{/min. } (259.6\text{cm}^3\text{/min.}).$$

3. The power constant for the given conditions is p = 0.79. (This value is the best suited of the test results—500~0.794—shown in Table 2.)

4. Therefore, the machining power at the spindle is:

$$P_s = 15.84 \times 0.79 = 12.5 \text{ hp (U.S. units), or}$$

$$P_s = 259.6 \times (0.79 \times 0.0455) = 9.3\text{kW (metric units).}$$

5. The machining power at the machine tool's motor is:

$$P_m = \frac{P_s}{E = 0.85} \frac{12.5}{0.85} = 14.7 \text{ hp (10.9kW).}$$

E is the machine tool efficiency factor, which depends on the type of drive. In most cases, when the type of drive is unknown, it's recommended that E = 0.80 to 0.85.

6. If Equation 1 is used to calculate the machining power, the tangential cutting force should be determined first.

7. The tangential cutting force is determined by Equation 5.

$$\begin{aligned} F_t &= 396{,}000 \times d \times f \times p \\ &= 396{,}000 \times 0.2 \times 0.012 \times 0.79 \\ &= 750.8 \text{ lbf (3,340N).} \end{aligned}$$

8. The machining power at the spindle is determined by Equations 2 and 3.

$$\begin{aligned} P_s &= \frac{F_t \times V_c}{33{,}000} \\ &= \frac{750.8 \times 550}{33{,}000} \\ &= 12.5 \text{ hp (9.3kW).} \end{aligned}$$

Counter to the salesman's recommendation, the calculations show that a 15-hp (12kW) lathe is sufficient for the required cutting conditions.

Calculations of the machining power based on the tangential force and cutting speed, as well as the mrr and reassessed power constants, provide higher accuracy than the traditional method based on the mrr and currently used p-factors.

To maximize machine tool productivity, it's essential to have knowledge of machining power requirements in relation to cutting conditions and workpiece properties.

About the Author

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