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Calculated Grinding

cover focus

By Dr. Jeffrey A. Badger

Parts manufacturers can calculate the optimal parameters when grinding with superabrasive wheels to achieve high material-removal rates and more consistent results.

When choosing grinding parameters, engineers and machine operators often use a trial-and-error approach, tweaking speeds and feeds until they find parameters that "feel right and sound right" and give acceptable results. This technique is unreliable and time consuming as operators have to repeat this exercise each time they grind an unfamiliar part, geometry or material, even when applying the same wheel.

However, there is a method for finding the optimal speeds and feeds for a given grinding operation using what I term "grinding aggressiveness." It has been used successfully in grinding ferrous materials and nickel-base alloys with both Al_2O_3 and CBN wheels and tungsten-carbide materials with diamond wheels. Operators appreciate it as it is simple and down-to-earth. Once they find an aggressiveness number that works for a given wheel and workpiece combination, they can simply choose the speeds and feeds that give the same aggressiveness number, regardless of part size, number of passes and limitations on wheel speed.

In this article, the concept is defined and case studies are presented. Finally, recommendations are given for practical use of aggressiveness, particularly as an output option on a CNC.

The question of optimal wheel speed for a given wheel and workpiece combination comes up frequently when discussing grinding parameters. Machine operators will argue about the best wheel speed for a given job. However, even with a fixed material type, machine type and grinding operation, a range of wheel speeds can be appropriate depending on the DOC, infeeds and even the individual machine operator. For grinding of tungsten carbide with a resin-bonded diamond wheel, common wheel speeds range from 8 m/sec. to 45 m/sec. In most cases, the optimal wheel speed was arrived at through trial and error.

In spite of this range of speeds, if one looks at the aggressiveness of these operations, it can be seen that the range of aggressiveness values is much narrower. For a given wheel, machine operators will usually find a narrow practical range of aggressiveness values, even if using a wide range of wheel speeds.

Concept

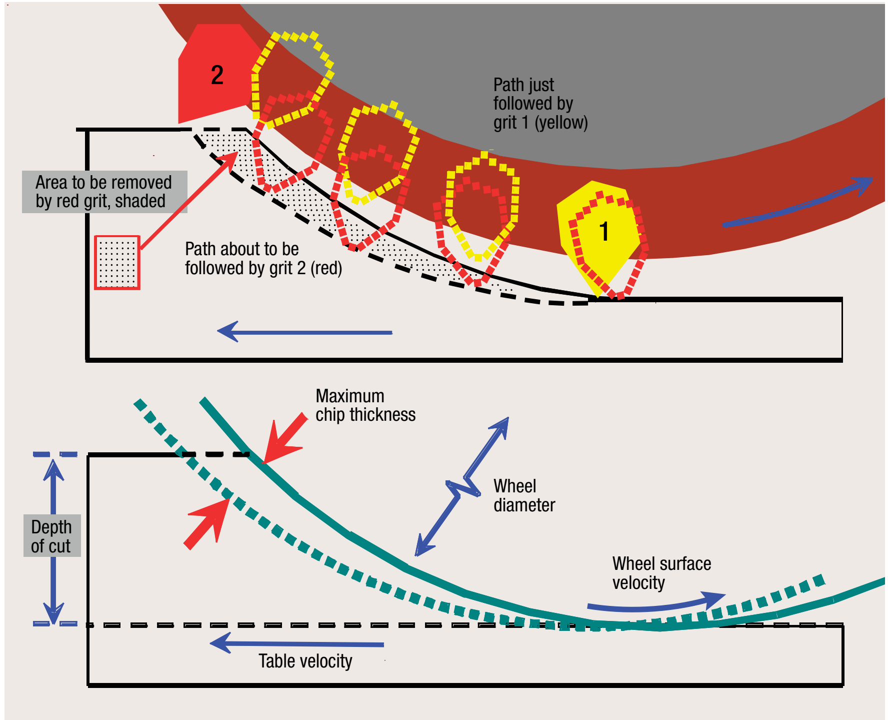
The concept of maximum chip thickness is familiar in grinding, particularly to those involved in R&D. For straight plunge grinding, the maximum chip thickness (h_{cu}) can be calculated using:

$$h_{cu} = \sqrt{\frac{V_w}{V_s} \times \frac{1}{Cr} \sqrt{\frac{a_d}{d_e}}}$$

where V_w is the table speed, V_s is the wheel speed, C is the grit density (cutting edges per unit area), r is the cutting point shape factor, a_d is the DOC and d_e is the wheel diameter. Maximum chip thickness can also be looked at as the depth of penetration of the grit into the workpiece (Figure 1).

However, this equation is intimidating to all but those working in the academic world on grinding. Also, Cr is difficult to measure and depends on the wheel truing and dressing conditions.

Since Cr will be fixed for a given wheel under consistent dressing conditions, we can simplify the equation and put it in more accessible terms as:



All figures: J. Badger

Figure 1: Path traced out by an individual grit showing maximum penetration depth.

$$\text{Aggressiveness number} = 1{,}000{,}000 \times \frac{\text{Workpiece speed}}{\text{Wheel surface speed}} \times \sqrt{\frac{\text{DOC}}{\text{Wheel diameter}}}$$

The constant in front is used simply to put the value in more graspable terms. Typical aggressiveness values range from 5 to 40. Because the units in the numerator and denominator of each term are the same, the final value is dimensionless, and any units can be used as long as they are consistent. However, if the most common units are attached, the formula becomes the following:

$$\text{Aggressiveness number} = 16.7 \times \frac{\text{Workpiece speed (mm/min.)}}{\text{Wheel surface speed (m/sec.)}} \times \sqrt{\frac{\text{DOC (mm)}}{\text{Wheel diameter (mm)}}}$$

The formula can be expressed in imperial units, too. Aggressiveness values can also be determined for ID and OD grinding (See appendix on page 47).

At low aggressiveness values, the grit does not penetrate deeply into the workpiece. In more ductile materials, this results in excessive rubbing and

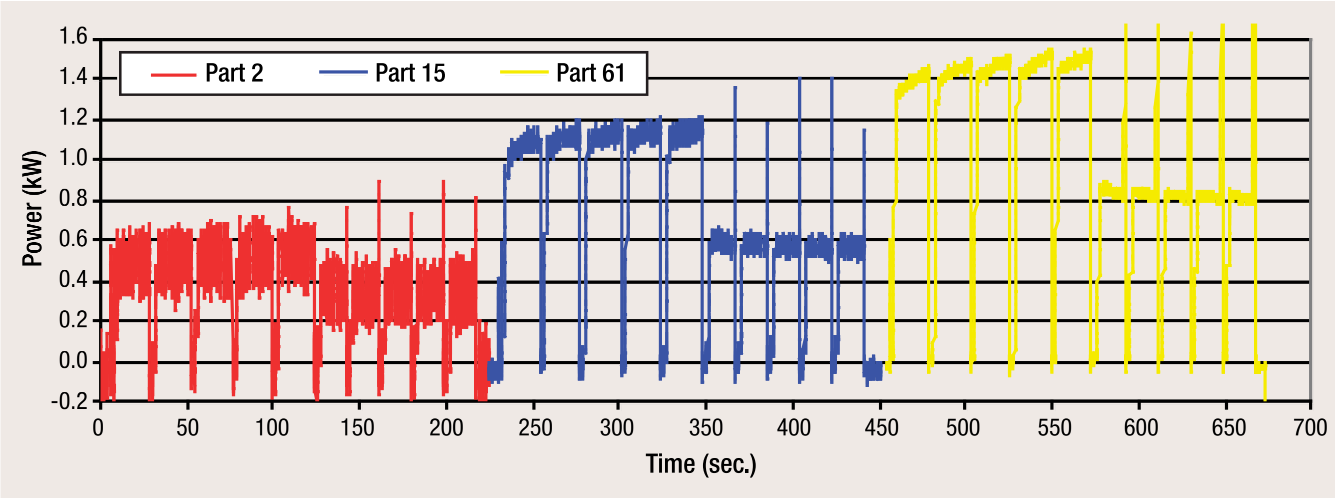


Figure 2: Power profile for flute grinding of tungsten carbide.

heat generation. In harder work materials, like ceramics, it results in insufficient penetration to cause microfracture and consequently material removal, leading to excessive wheel glazing and heat generation, which result in excessive wheel wear. At high aggressiveness values, the insufficient grit penetration results in large forces on individual grits, causing excessive wheel wear.

This is why a typical curve seen when plotting G-ratio vs. wheel speed or G-ratio vs. feed rate is an inverted U, according to Frank Hughes' book "Diamond Grinding of Metals" and Horst Juchem's article "Diamond Choice for Ceramics Machining." In between these two extremes is the wheel's "sweet spot."

Through trial and error and having a feel for the process, machine operators become skilled at finding this sweet spot. But, given new conditions, say, a smaller part diameter and therefore a smaller DOC, they have to go through this trial-and-error process again.

If the concept of aggressiveness—in lieu of chip thickness—is used, though, operators can: (1) find the parameters that put them in the sweet spot, (2) calculate the aggressiveness number for these parameters and (3) use the number to find the optimal speeds and feeds on all subsequent jobs using this wheel.

Finding the Sweet Spot

During a visit to a carbide tool manufacturer, I noticed that grinding parameters for a recently introduced grinding wheel were obtained in two ways: the parameters on the wheel manufacturer's brochure for the wheel, and the actual parameters being used in production to grind endmills with this wheel. The actual parameters, specifically those for roughing, were found over several months by machine operators through trial and error.

A comparison of these parameters is given in the table on page 47. In (a), a case study for grinding carbide endmills using a wheel speed of 33 m/sec. gives a material-removal rate of 10.0. In (b), the actual grinding parameters found by the machine operator that work well for this particular wheel use a wheel speed much lower than the case study in the brochure (about one half). However, the aggressiveness values of (a) and (b) are nearly identical, in spite of the different wheel speeds. In (c), taken from

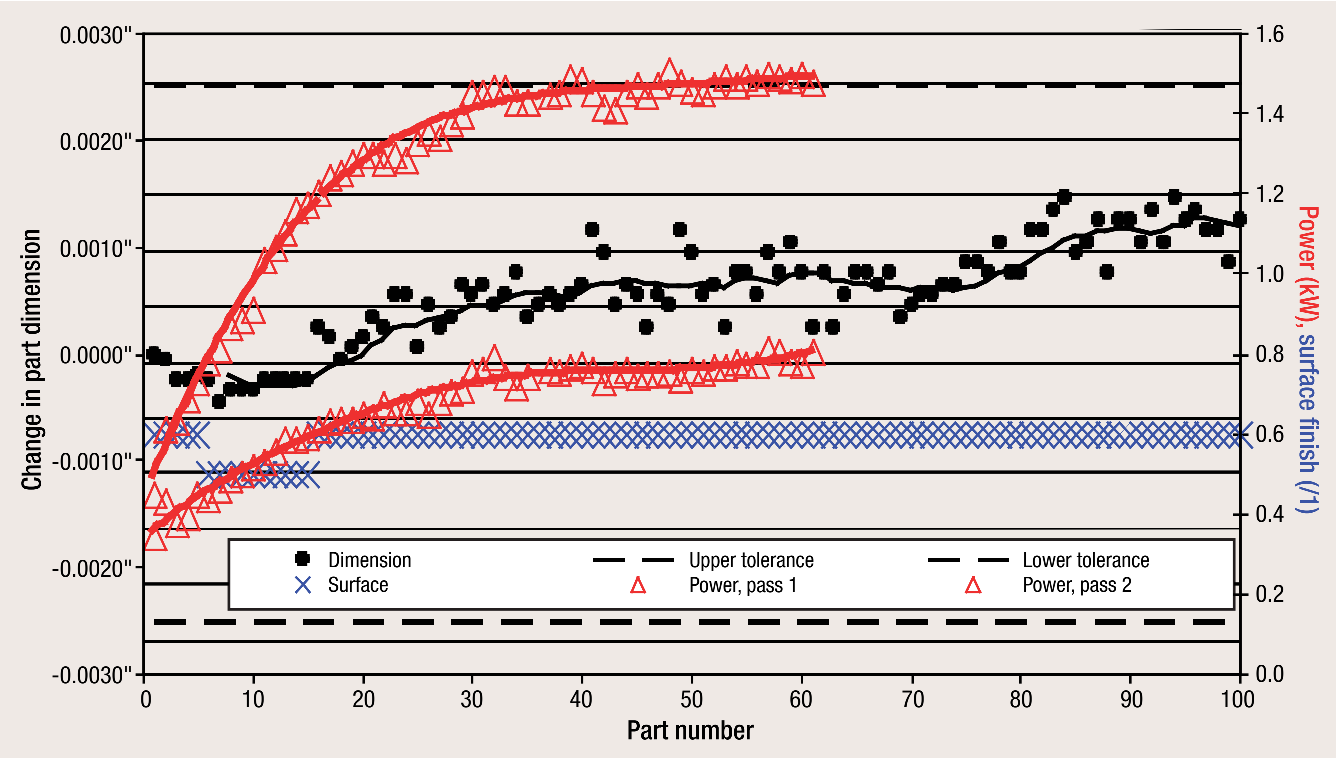


Figure 3: A standard cycle with a wheel speed of 20.3 m/sec. at 100 percent of table speed, with aggressiveness value of 11.4 for roughing and 7.4 for finishing.

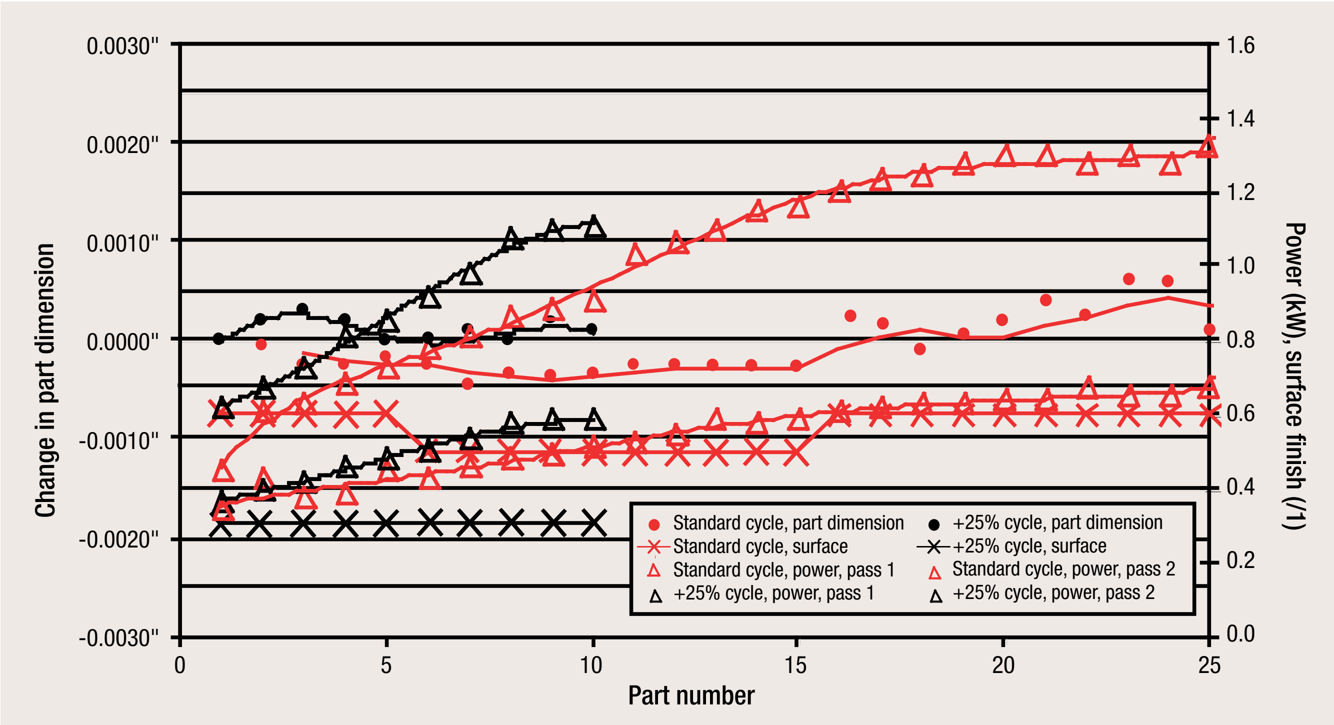


Figure 4: A standard cycle (red) and new cycle (black) with the same wheel speed, 20.3 m/sec., but with table speed increased by 25 percent. The original aggressiveness values were 11.4 (roughing) and 7.4 (finishing). The new values are 14.3 for roughing and 9.3 for finishing.

an actual grinding operation with this wheel but on a different machine, there is also a very different wheel speed compared to (a). However, the aggressiveness number is close to that given in the case study by the wheel manufacturer.

This data indicates that the sweet spot of a given wheel is not at a certain wheel speed but rather at a certain aggressiveness value and that any wheel speed can be used as long as the other parameters are chosen to give this optimal aggressiveness.

Being Aggressive

Tests were performed by flute-grinding 4-flute, solid-carbide endmills with a resin-bonded diamond wheel on a Rollomatic machine. Two passes per flute were taken with a wheel speed of 20.3 m/sec. for both passes and removal rates of 4.1 and 1.3 mm^3/mm/sec. and aggressiveness values of 11.4 and 7.4 for the first and second passes, respectively. Spindle power was measured with the Grindometer, a tool for analyzing and optimizing grinding processes. Also, core growth was measured, and surface finish in terms of microchipping at the cutting edge and roughness on the rake face was determined by eye and given a ranking between 0 and 1. One hundred parts were ground. Spindle power for parts 2, 15 and 61 are shown in Figure 2 on page 43.

The maximum power on the roughing

Table: Grinding parameters and aggressiveness values for a single wheel specification when roughing.

	DOC (mm)	Table speed (mm/min.)	Wheel speed (m/sec.)	Wheel diameter (mm)	Material-removal rate (mm^3/mm/sec.)	Aggressiveness
(a) Brochure on wheel from wheel manufacturer; Case study: grinding of medium-diameter carbide endmill.	2	300	33	150	10.0	17.5
(b) Parameters found by machine operator; Process 1: small-diameter carbide endmill.	2.5	150	18.5	50	6.3	17.4
(c) Parameters found by machine operator; Process 2: large-diameter carbide endmill.	2.9	115	16.5	120	5.6	18.1

Appendix: Calculations for Imperial Units, OD Grinding and ID Grinding

For imperial units, the aggressiveness number is calculated via:

$$\text{Aggressiveness number} = 83{,}000 \times \frac{\text{Workpiece speed (in./min.)}}{\text{Wheel surface speed (sfm)}} \times \sqrt{\frac{\text{DOC (in.)}}{\text{Wheel diameter (in.)}}}$$

For ID and OD grinding, the concept of aggressiveness is valid as long as the equivalent diameter is used, which is calculated via:

$$\text{Equivalent diameter for OD grinding} = \frac{\text{Workpiece diameter} \times \text{wheel diameter}}{\text{Workpiece diameter} + \text{wheel diameter}}$$

$$\text{Equivalent diameter for ID grinding} = \frac{\text{Workpiece diameter} \times \text{wheel diameter}}{\text{Workpiece diameter} - \text{wheel diameter}}$$

pass and finishing pass was determined. Power, change-in-core dimension and surface finish are given in Figure 3. It is evident that after dressing, power increases as the wheel "closes down," grits become blunt and the cutting-point density increases. The part dimension actually dropped (possibly due to wheel self-dressing that caused lower normal forces or heat generation that caused thermal expansion during grinding), and then gradually increased. After 100 parts, the part dimension was still within tolerance. Surface finish remained steady throughout, at a ranking of around 0.6.

The next step was to increase the table speed by 25 percent on the roughing pass and the finishing pass (Figure 4 on page 45).

Power increased by 39 percent when roughing and by only a small amount when finishing. Surface finish deteriorated to an unacceptable level (from 0.6 to 0.3). Consequently, only 10 parts were ground, not enough to determine trends in core growth.

This poor surface finish was attributed to the higher aggressiveness (exactly 25 percent higher). Therefore, it was decided to go back to the original aggressiveness value. However, as the goal was to increase productivity, the table speed was kept at the 25 percent-higher level and the wheel speed was also increased 25 percent (from 20.3 m/sec. to 25.4 m/sec.) to give the same aggressiveness value, with a 25 percent higher mrr (Figure 5 on page 50).

Here, power went up again in both passes. Surface finish improved back to its original value—better in some cases. Not enough parts were ground to determine core breakdown.

With the success of this method, it was decided to increase table speed and wheel speed by 50 percent. Although not shown here, the results were promising. Power increased by 270 percent, not 50 percent. Not enough parts were ground to see core growth trends, but after 10 parts, nothing catastrophic was evident. Most remarkably, surface finish improved, to a consistent value of 0.7.

Finally, a long, overnight run was done with table speed and wheel speed increased by 25 percent. Several hundred parts were ground. Core growth was measured and was identical to that of the standard parameters. Surface finish was the same as the original, and power—although higher—did not cause any adverse effects.

These results indicate that once an effective set of grinding parameters has been found, an increase in mrr is more likely to be successful if the aggressiveness value is taken into consideration and kept constant.

Implementation

I have been using aggressiveness values for years and teaching the method in my 3-day grinding course. Engineers and machine operators have said they find the method extremely useful. A spreadsheet/computer program, the

Lower cost grits increasing CBN wheel applications

ALTHOUGH PARTICULARLY effective for grinding ferrous materials, CBN wheels are generally not considered to be an economical option, but that's changing as the price of low-end CBN grits from low labor-cost countries, such as China, is making the cost of CBN wheels more attractive, according to Tom Corcoran, president of abrasive wholesaler American Superabrasives Corp., Shrewsbury, N.J.

He added that his company purchases CBN grits for as low as 20 cents per carat; high-quality grits cost about $2 per carat. "Where wheel manufacturers used to sell a wheel for $1,000, they can sell it for $400 now," Corcoran said. "Before, some guys would never entertain the thought of a $1,000 wheel, but at $400 they might switch from aluminum oxide."

Corcoran pointed out that a CBN wheel made with lower-quality grits is not going to produce as many parts as one made from higher-quality grits. "A CBN wheel is 80 percent as good from low-cost competitors," he said. In addition, depending on the application, an Al_2O_3 wheel may still be the better choice. "It's not like CBN wheels are going to replace them all."

The end users purchasing lower-cost CBN wheels are generally not switching from premium CBN wheels because if a lower-cost wheel causes any increase in cycle time, the cost per part increases. Nonetheless, purchasing agents may not realize that. "PAs think they're saving money. They go, 'Hey, I can save 20 percent on each wheel,' but on the final analysis, they don't," Corcoran said.

The cost of low-end CBN grits may have bottomed out, though. "I believe we're at the lowest we're ever going to see prices of CBN grit right now," Corcoran said. "The trend is all raw materials are going up."

—Alan Richter

Grinder's Toolbox, has been created to calculate aggressiveness values from the speeds and feeds of plunge grinding and cylindrical grinding. Operators find the speeds and feeds that work well for a given wheel and then use that aggressiveness value when determining speeds and feeds in other grinding jobs using the same wheel.

It would be easy to implement this method into a CNC program, outputting the aggressiveness value for the input parameters. Another option would be to allow the machine operator to input the desired aggressiveness and other parameters and have the program calculate either the wheel speed or feed rate that gives this aggressiveness value.

The concept of aggressiveness is useful in determining optimal grinding parameters for a given superabrasive wheel. After the sweet spot is found for one set of grinding conditions, the aggressiveness number can be calculated for this wheel and then applied to all grinding operations using that wheel, regardless of wheel speed. Most importantly, it is graspable and easily applied by those doing the grinding, the people working in real production. **CTE**

About the Author: *Dr. Jeffrey A. Badger is an independent grinding consultant. Much of his work involves helping companies that grind tungsten carbide to improve their operations. Contact him at badgerjeffrey@hotmail.com. This article was adapted from Badger's paper for Intertech 2008, which was held May 5-7 in Orlando, Fla., and was sponsored by the Industrial Diamond Association of America*

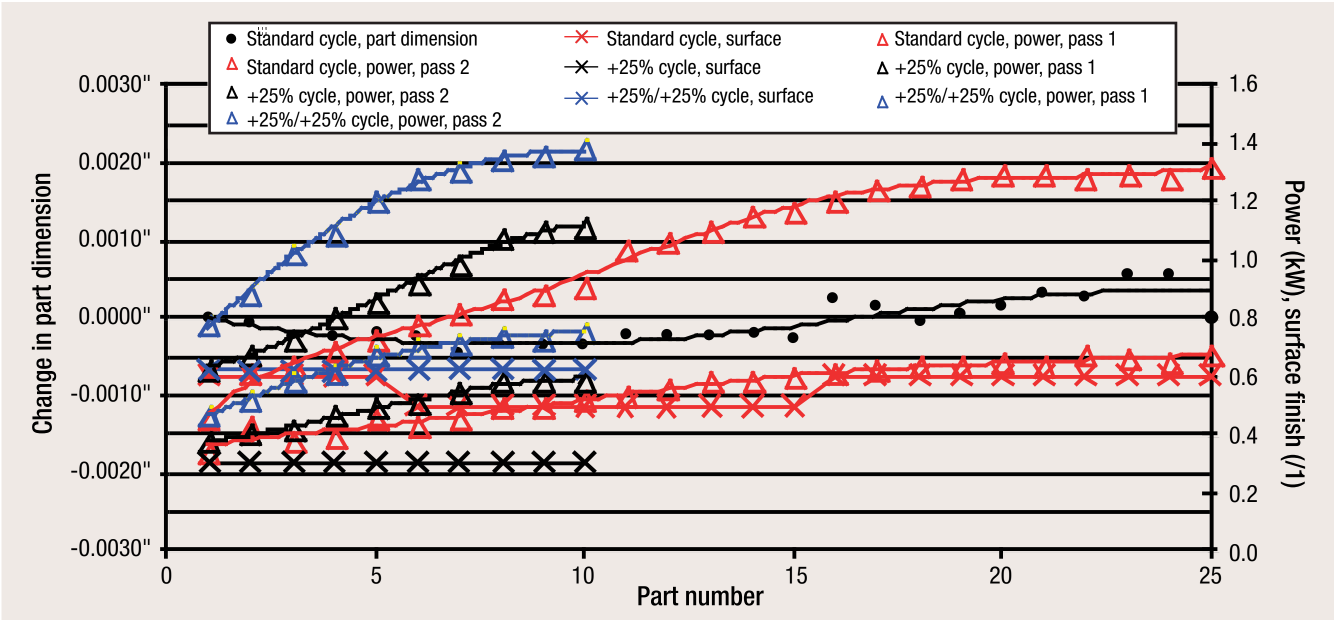


Figure 5: A cycle with both table speed and wheel speed (yellow) increased by 25 percent still gives the same original aggressiveness values.