WHITE PAPER

UNDERSTANDING FORCES IN CREEPFEED GRINDING FOR REDUCING COSTS AND IMPROVING CONSISTENCY

WHY CREEPFEED GRINDING?

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One of the major benefits to creepfeed grinding is the combination of quick material removal with the ability to generate a precision ground surface on difficult-to-grind materials. Typically, creepfeed grinding results in a lower undeformed chip thickness relative to surface grinding, thereby improving surface finish on the workpiece and reducing wheel wear. However, this advantage comes with a few drawbacks. Creepfeed grinding applications tend to draw more power and have higher forces. Hence it requires higher power spindles and more robustly engineered machines and fixtures than traditional surface grinding applications.

When developing new creepfeed grinding applications, factoring in the grinding forces can be beneficial to ensuring adequate fixture design, clamping pressures, and part support. They also influence wheel specifications and process conditions. This article will highlight some of the basic forces that can be calculated in creepfeed grinding, and will conclude with an example application.

Forces in Creepfeed Grinding

Consider a simple 2D creepfeed grind as shown in Figure 1. In this application, there are two primary forces which act on the wheel – tangential force and normal force. The normal force (f_n) is the force applied perpendicular to the contact area between the wheel and workpiece, and tangential force (f_t) is the force applied parallel to the contact area between the wheel and the workpiece. The magnitude and direction of the grinding forces drives the design requirements for fixturing, workpiece clamping, and system rigidity. The direction of these forces is a particularly important consideration for processes where the point of tangency between the wheel and workpiece might change during the grinding process, resulting in a change in direction of the grinding forces, for example in 5-axis grinding operations.

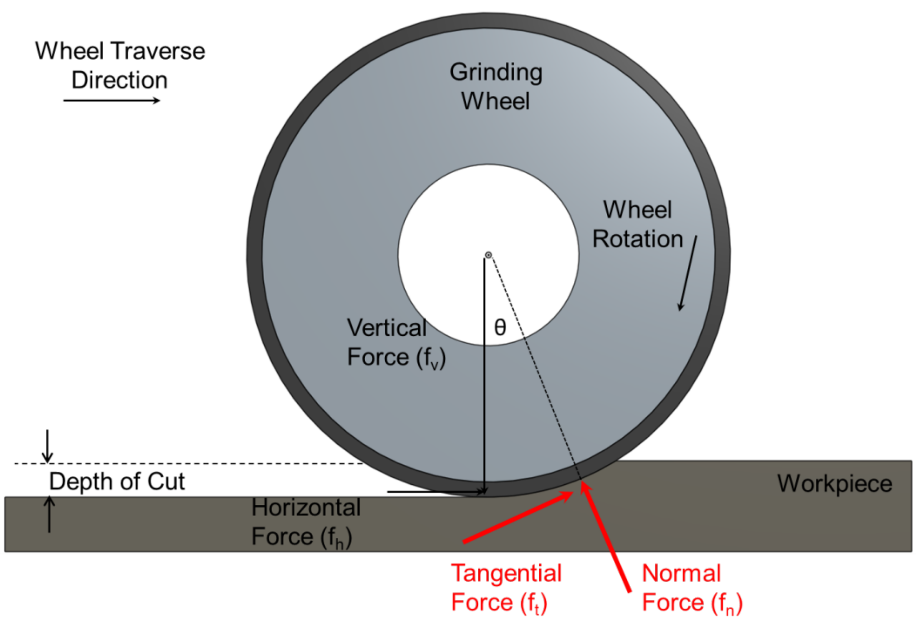

Figure 1: Schematic of simple creepfeed grinding operation

The tangential force is the force required to maintain the wheel speed while it is engaged with the workpiece under the given frictional and cutting forces. It is the sum of the abrasive cutting forces (i.e. forces required to remove material) and frictional forces between the grains, swarf and wheel bond material. Tangential force is influenced by coolant lubricity, grinding wheel sharpness, abrasive grain density, workpiece material properties and wheel profile.

It is possible to calculate the tangential forces (F_t) acting on the wheel in creepfeed grinding in two ways. The first is directly from the grinding spindle power and wheel speed as shown:

$$Power = \frac{F_t * V_s}{33{,}000} \quad \text{or} \quad F_t = \frac{Grinding\ Hp * 33000}{V_s}$$

Where power is in Hp, F_t is in lb_f, V_s is the wheel speed (in sfpm) and 33000 (lb*ft/min/hp) is the conversion factor. At the point of contact, the normal and tangential forces on the wheel are equal and opposite to the forces acting on the workpiece, so these equations can also be used to calculate forces on the workpiece. Once the tangential force is known, the normal force can be estimated by the ratio of the grinding coefficient of friction. The chart in Figure 2 shows the grinding coefficient of friction as a function of hardness for several materials. The majority of high strength superalloys and steels have a grinding coefficient of friction between 0.25 and 0.40.

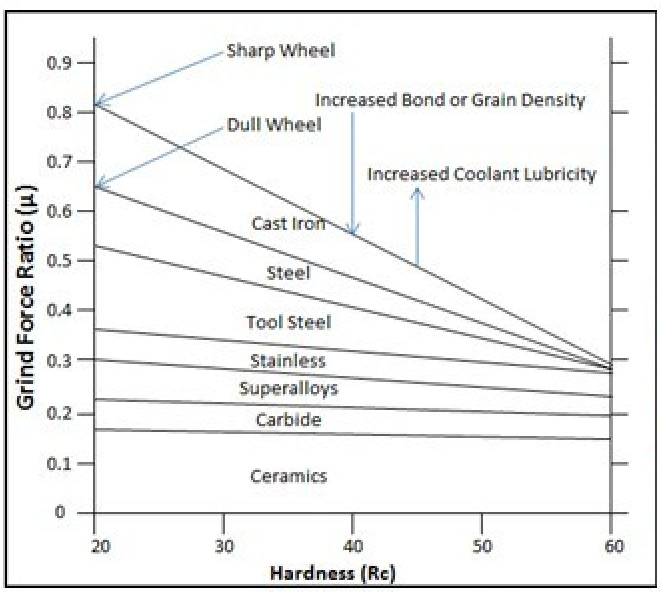

Figure 2: Variation in grinding force ratio (µ) as a function of material type and hardness.

Once μ and F_t are known, the normal force can be estimated through the equation:

$$\mu = \frac{F_t}{F_n}$$

A second method to measure the tangential force is to use a dynamometer and measure the vertical and horizontal forces during the grind. Then, knowing the normal force vector angle (θ - see Figure 1), the normal and tangential forces can be calculated from the following equations:

$$F_n = F_v \cos(\theta) - F_h \sin(\theta)$$

$$F_t = F_v \sin(\theta) + F_h \cos(\theta)$$

$$\text{Where } \theta = \sqrt{\frac{Depth\ of\ Cut}{Wheel\ Diameter}}$$

It is important to note the normal and tangential forces in creepfeed grinding are not the same as the vertical and horizontal forces, respectively. While this can be useful in a laboratory type environment, it is not often practical in production grinding and hence the alternative method to calculate f_n and f_t will likely be used more often.

Measuring Power

In order to accurately calculate F_t, the grinding spindle power must be known. It is strongly recommended that a power monitor be used and connected directly to the spindle drive system. Doing so will ensure the grind power is not influenced by external sources such as coolant pumps or other machine axis movement. Norton | Saint-Gobain utilizes several state-of-the-art power monitoring systems combined with customized LabVIEW software to monitor spindle power in real time during grinding. An example of the system is shown in Figure 3.

Figure 3: Field Instrumentation System used to measure three-phase spindle grinding power

This system utilizes current and voltage inputs from the spindle drive to calculate and plot grinding power in real time. From this graph, idle, peak, and average grinding power along with process time can all be measured and used to determine tangential and normal forces, as well as information such as specific cutting and grinding energies of the process. These values can be utilized to better understand the time dependent behavior of the process and highlight dominant microscopic interactions in the grinding application.

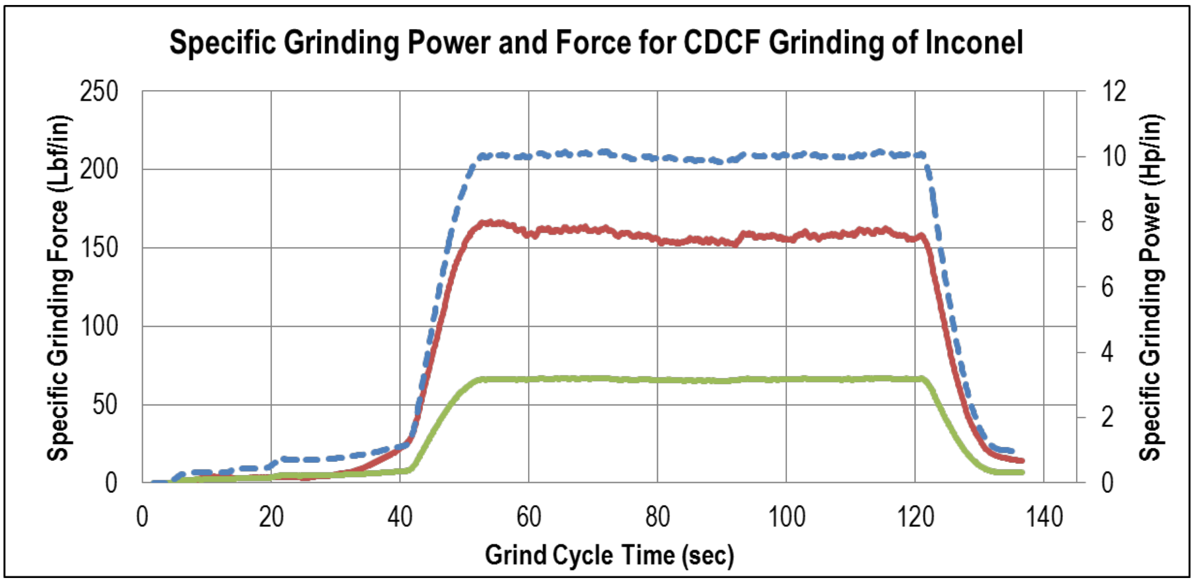

Figure 4: An example of power, normal force and tangential force in creepfeed grinding of Inconel

Recent internal testing of premium ceramic grain creep feed wheels on Inconel 718 at the Norton Higgins Grinding & Technology Center (Northborough, MA USA) showed average specific grinding power to be roughly 10-18 Hp/in of contact width. From internal testing (results shown in Figure 4), it can be seen that the approximate grinding coefficient of friction is 0.38, and the specific grinding power is just over 10 Hp/in. When developing new creepfeed grinding applications, it is common to estimate the spindle power requirements in the range of 12-18 Hp/in to initially develop the process. These values can also be used to estimate grinding forces on new fixture and part designs for new applications. Utilizing specially developed creepfeed bond technologies, such as the Norton Vitrium3 bond, has been shown to lower the grinding power, which can manifest in higher Q' at a given power limit and/or lower grinding forces.

Using Forces for Fixture Design

Typically, on complex parts in a 5-axis machine, such as aerospace turbine components, ensuring adequate support for the workpiece can be challenging due to stiffness issues in the part, clearance issues with the wheel, fixture and coolant nozzle lines, and the complexity of the part shapes. In addition, many turbine engine components have six-point nest datums which require a combination of work supports and clamps to grind a transfer datum for use in the next operation. On simpler 3-axis creepfeed machines, the fixture design can be more traditional, such as using a heavy duty milling vise, sacrificial soft jaws, or step jaws depending on the application and forces expected. It is a good practice once fixtures and parts are installed, to confirm system deflection with a dial indicator and force gauge to ensure adequate clamping and fixture support for the operation.

An Example: Calculating Grinding Forces & Interpreting the Results

- 3-axis creepfeed grinder grinding a 0.75" wide slot in a 1" x 1" square solid bar
- Grinding Inconel 718 alloy (30 HRC)
- 5000 surface feet per minute (sfpm)
- 0.750" wide contact area between wheel face and workpiece
- Assuming 15 Hp/in estimated grind power

$$Estimated\ Required\ Grinding\ Power = 15\frac{Hp}{in} * 0.750\ in = 11.25\ Hp$$

$$F_t = \frac{Power * 33000}{V_s} = \frac{11.25\ Hp * \frac{33000\frac{ft.lb}{min}}{hp}}{5000\ sfpm} = 74.3\ lb_f$$

From the chart in Figure 2, the grinding coefficient of friction for a super alloy at a hardness of 30 RHC is roughly 0.28, so

$$F_n = \frac{F_t}{\mu} = \frac{(74.3\ lbf)}{0.28} = 265.2\ lb_f$$

In this example, knowing or predicting the tangential and normal forces are 74.25 and 265.2 lbf (respectively) can ensure that adequate fixtures are setup to sufficiently support the workpiece. This calculation also allows one to calculate spindle power requirements for a given application with a known contact width, wheel speed, and motor efficiency.

Also, in this example, if the workpiece were clamped such that a one-inch length was cantilevered off the edge of a vice, the 265 lbf normal force could deflect the part by 0.00015" (depending on material heat treatment). This highlights the importance of ensuring the workpiece fixture is sufficiently rigid and supportive. In addition, the grinding forces will scale linearly with contact width, so a 3" wide part of the same parameters above will have a 296 lb tangential force and a 1060 lb normal force. This is important to consider when selecting fixture options and specifying machine table characteristics.

Conclusion

Understanding the importance of grinding forces in creepfeed applications can result in a process that is both lower cost and more consistent when grinding difficult-to-grind materials. Utilizing Norton | Saint-Gobain premium ceramic abrasives with specialized creepfeed porous bond systems, including the Vitrium3 system developed for creepfeed grinding, one can grind with a lower specific grinding energy (or energy required to remove material). This benefit will manifest as a reduction in grinding spindle power, which consequentially lowers the overall grinding force, allows less stringent requirements for fixture and equipment design, and permits higher stock removal at a given grinding power.

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