MAY 2006 / VOLUME 58 / NUMBER 5

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Flight–Critical Grinding

Grinding turbine blades challenges manufacturers.

A major challenge of grinding turbine blades is that the workpiece materials, such as nickel-based alloys, tend to be difficult to grind. Further complicating the task is that extreme care must be exercised to prevent parts from suffering thermal damage.

Excessive temperatures cause metallurgical changes in the workpiece material, turning the surface hard and brittle. This is referred to as "white layer."

Not surprisingly, much more effort is put into preventing white layer during turbine blade grinding than, for example, tool grinding. If a drill or a tap contains white layer, the tool is likely to perform poorly or shatter during use. This is annoying, but if an aircraft engine were to fail at 30,000' because of a cracked turbine blade, the repercussions could be catastrophic.

White layer is not visible. Therefore, when a manufacturer begins grinding a blade for the first time, samples must be sent to a laboratory for analysis. This costly, time-consuming process involves cutting, polishing, etching and microscopically examining the samples.

Once a grinding process has achieved acceptable quality, the process is then considered "qualified" and machine settings—speeds, feeds, dressing parameters, etc.—are often locked in and machine operators are not allowed to change them.

But that doesn't preclude white layer from occurring. The vagaries of grinding mean there's always a risk, so workpieces are periodically checked for white layer.

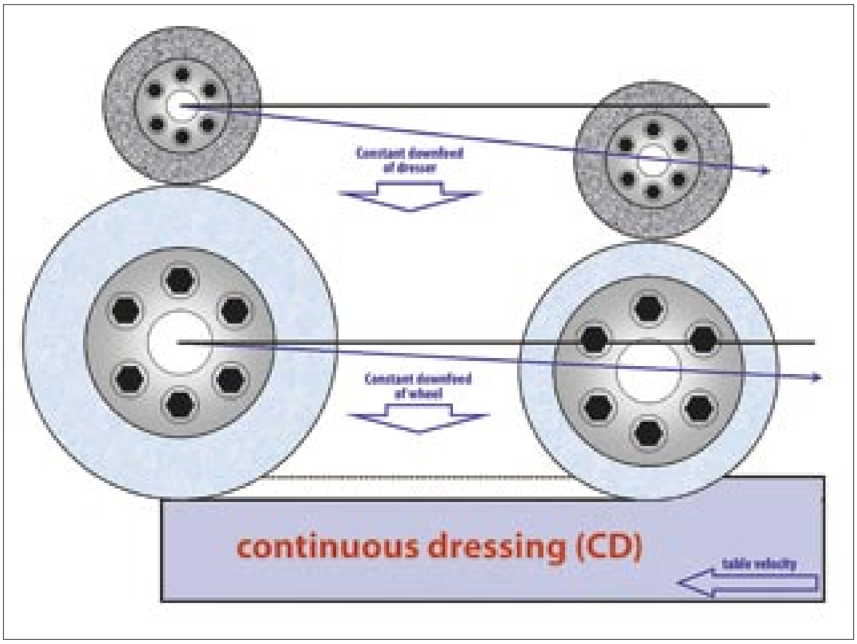

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Figure 1: With continuous dressing, the dresser is in constant contact with the wheel while it is grinding and the wheelhead is continuously feeding down into the workpiece.

Continuous-Dressing Paradox

Creep-feed grinding machines are used to grind the roots and shrouds of turbine blades. With standard CF grinding, the operation is stopped periodically to dress the wheel with a rotary diamond-roll dresser, then grinding resumes. In difficult-to-grind nickel alloys, the wheel dulls quickly, which increases wheel wear, heat generation and the temperature at the wheel/workpiece interface.

This is particularly problematic when grinding long workpieces. By the time the wheel reaches the end of the workpiece, it has become dull and worn. Consequently, excessive heat is generated, and maintaining form is difficult. The continuous-dressing process was developed to counter this.

With continuous dressing, the diamond dresser is in constant contact with the wheel while grinding (Figure 1). In other words, the wheel is being dressed while it's grinding the workpiece, and the wheelhead continuously feeds downward into the workpiece to compensate for the amount dressed off the wheel. The purpose of continuous dressing is to keep the wheel sharp and to maintain form.

A typical scenario in CF grinding of blades is to grind one heavy pass in the continuous-dressing mode to remove the majority of material (typically 0.5"), followed by a finishing pass (0.004") without continuous dressing.

The dilemma blade manufacturers

face is that continuous dressing consumes a lot of the wheel. For example, grinding a 60mm-long workpiece with a table velocity of 60 mm/minute would require 60 seconds of grinding. If a 500mm-dia. wheel were running at 1,000 rpm and were continuous-dressed at an infeed rate of 1.0µm per wheel revolution, wheel consumption per part would be 1mm off the radius or 2mm off the diameter.

The formula is:

$$\text{radial wheel consumption (mm)} = \frac{\text{dresser infeed rate (µm/wheel rev.)} \times \text{wheel rpm} \times \text{workpiece length (mm)}}{\text{table velocity (mm/min.)} \times 1{,}000}$$

If the wheel diameter goes from 500mm to 300mm, that's only 100 parts per wheel. At $150 per set for multiwheel jobs, wheel consumption alone would total $1.50 per part.

Just as important, frequent wheel changes take time. For a 2-minute cycle time, changing the wheel every 100 parts means a wheel change every 3 hours and 20 minutes.

Consequently, blade manufacturers seek ways to decrease wheel consumption. One quick and easy way to do this is to decrease the continuous-dress infeed rate from, say, 1.0µm per wheel revolution to 0.3µm per wheel revolution. This would significantly reduce wheel consumption, but it also would dull the wheel, thereby generating a lot of excess heat.

Figure 2 shows power generation (which converts to heat at the wheel/workpiece interface) vs. the dresser infeed rate while continuous dressing. As in all dressing operations, dressing more aggressively—in this case, at a higher infeed rate—results in a sharper, more open wheel. A lower infeed rate closes the wheel. When dressing at a lower infeed rate, the benefit of continuous dressing—to keep the wheel sharp—is negated and the temperature increases.

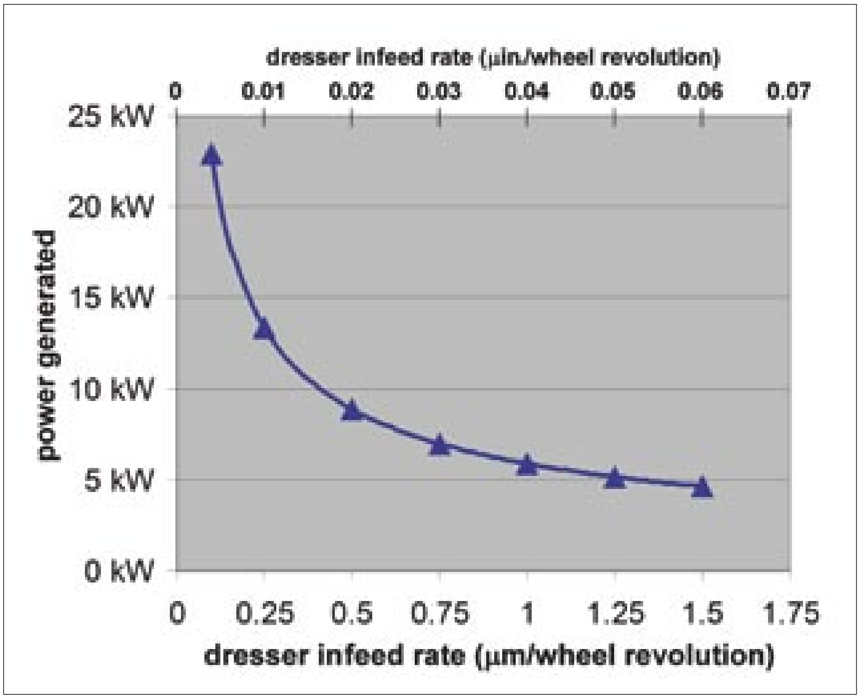

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Figure 2: Power (and heat) generated vs. dresser infeed rate for continuous-dress creep-feed grinding.

Grinding machine operators sometimes try to overcome the problem of high temperatures by decreasing table velocity. This reduces the temperature in the grinding zone, because the material-removal rate is lower. However, the reduced table velocity means a longer time to traverse the workpiece and, consequently, a longer continuous-dressing time. The result is even higher wheel consumption.

In turn, some operators decrease the dresser infeed rate even more, exacerbating an already bad problem. They become victims of the continuous-dress paradox.

To solve this dilemma, in-process dressing was developed (Figure 3). With IPD, dressing performed during grinding is done in increments. The wheel is dressed periodically throughout the grinding traverse, and the wheelhead is moved downward during each dress to compensate. Therefore, grinders can use more aggressive dresser infeed rates without consuming unacceptable amounts of wheel.

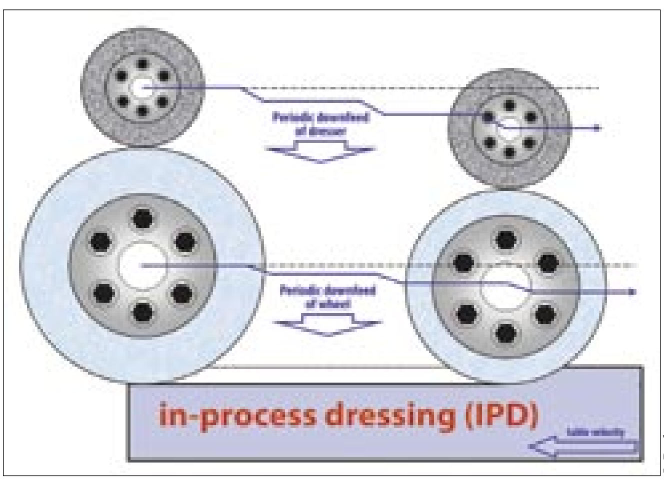

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Figure 3: During in-process dressing, the wheel is dressed periodically throughout the grinding traverse, and the wheelhead is moved downward during each dress to compensate.

Unfortunately, many continuous-dress grinding machines are not capable of running in the IPD mode, even though the concept is similar to continuous dressing. That leaves the operator with a choice: Keep wheel consumption low but risk burning the workpiece or minimize heat generation but consume a lot of wheel.

However, savvy grinders can have it both ways by choosing their grinding and dressing parameters wisely and by making some passes without continuous dressing.

Choosing Parameters

The case of a wheel maker and one of his customers demonstrates the effects of finding the optimal parameters for low heat generation and low wheel consumption. The wheel manufacturer had designed a new wheel for

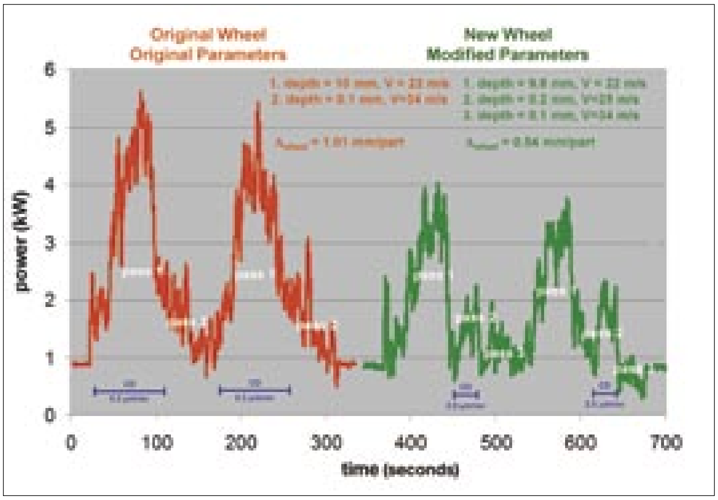


Figure 4: Power generation vs. time for two grinding processes: original parameters and modified parameters. By modifying parameters, wheel consumption and power generation were both decreased significantly. CD = continuous dressing; V = wheel speed.

the customer, and, for it to run optimally, he knew that the existing grinding parameters would need to be changed.

The wheel maker attached power-monitoring equipment to the grinding machine's spindle motor to measure power. This provided a clear picture of what was happening during the grinding process, particularly in terms of heat generation. Any increase in power above idle (to overcome wheel-bearing friction and coolant acceleration) was converted to heat in the grinding zone. The power signal illustrated this.

Each side of the root form was ground in two passes. During the first pass, the wheel was continuously dressed at an infeed rate of 0.2µm per wheel revolution. This is extremely low and leads to excessive heat generation. It was obvious that the machine operator had reduced it to this level in an effort to decrease wheel consumption, which was a painful 1.01mm per part off the radius.

The finishing pass was run without dressing. White layer was a problem, as was visible oxidation burn on the surface. This was not surprising, considering the timid dresser infeed rate.

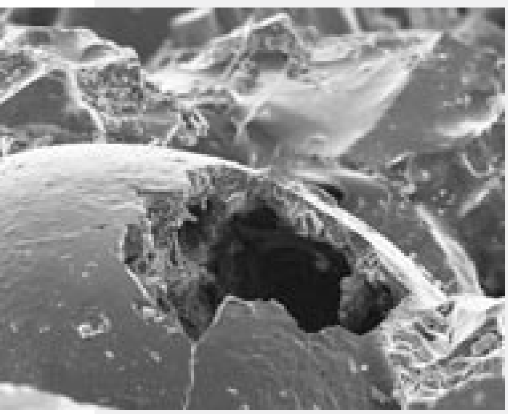
The wheel maker and his customer had a strategy session at which they established two goals: to have the wheel stay sharper and lower the rate at which it was consumed.

They accomplished their objectives by specifying three grinding passes instead of two. The first, long pass was made without continuous dressing, to reduce wheel consumption. For the second pass, the wheel was continuously dressed at an aggressive infeed rate of 2.0µm per wheel revolution. A small DOC and high table velocity were specified for this pass, meaning that the continuous-dressing portion of the cycle was short. These changes served to sharpen the wheel at the high infeed rate, but only for a short period, reducing wheel consumption. The finishing pass—the second pass in the two-pass cycle or the third pass in the three-pass cycle—was not changed.

The results in Figure 4 show that much less heat was generated in the first pass (the wheel was still sharp from the aggressive dress on the previous part). The cycle time was about the same, and wheel consumption was reduced from 1.01mm to 0.54mm per part. Also, white layer was virtually eliminated and all signs of visible oxidation disappeared. △

The porosity factor

Grinding wheel manufacturers devote a lot of time to developing highly porous wheels. They do this because porous wheels help remove heat from the grinding zone better than closed wheels by carrying more coolant to the grinding zone. This is one reason why water-based coolants are still used in blade grinding. Water cools better than oil.



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A broken bubble-alumina pore in a 30-grit ceramic Al_2O_3 wheel.

Heat causes "white layer," which is a metallurgical change that occurs in the workpiece material. Catastrophic consequences can result if turbine blades have white layer.

Ensuring that an adequate amount of coolant reaches the grinding zone is critical when grinding these blades. That is why blade makers use high-pressure, high-volume coolant systems and wheels with a high degree of porosity.

Induced-porosity wheels are manufactured by adding filler material to the wheel, which is burned off during the firing process, leaving pores.

Naphthalene is a common filler material. However, factory workers sometimes complain about the health hazards associated with naphthalene. This has led many companies to stop using it.

An alternative is bubble alumina, which is made up of many small, hollow spheres that don't burn off during firing. In principle, the eggshell-like hollow spheres are broken open during dressing, creating extra porosity.

In practice, it doesn't work as well as porosity created through burned-off filler material. Also, it doesn't produce the contiguous porosity present in burned-off filler material. Contiguous porosity means that the pores in the wheel are not independent. Instead, they form an interconnected network of pores that promotes the "pumping effect."

With the pumping effect, the porosity in the wheel near the grinding zone becomes saturated with coolant, and centrifugal forces push the coolant to the perimeter of the wheel and into the hot spot in the grinding zone.

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