Technology Advances for Continuous Generating Gear Grinding in EV and More

Meeting the challenges of gear grinding with innovative abrasive technology that improves gear efficiency and quality

Spencer Artz, Corporate Application Engineer, Norton | Saint-Gobain Abrasives

Continuous generating cylindrical gear grinding is one of the most demanding grinding applications for automotive and aerospace manufacturers. To improve gear efficiency, gear life, and noise levels, gear profile tolerances and surface finish requirements are becoming more stringent. This is especially true for EV gears, which typically require lower noise characteristics than traditional automotive gears. These new quality requirements must be maintained without sacrificing cycle time, and without inducing grinding burn. One of the biggest factors in achieving these goals is a grinding wheel capable of producing low grinding force and low grinding temperatures while minimizing the wear of the grinding wheel. The toughness and sharpness of the abrasive, porosity and strength of the bond, and interaction between the bond and workpiece are key. A new vitrified wheel matrix has been developed specifically for gear grinding which significantly reduces the friction generated between the bond and the workpiece while maintaining superior form holding at high removal rates. This new bond paired with the newest ceramic abrasive results in an extremely free cutting grinding wheel that exceeds all the requirements necessary to create quiet and long-lasting gears.

An understanding of what is needed for the latest gear designs and how abrasives composition and grinding wheel technology is satisfying the requirements will help define the overall landscape of today's gear grinding solutions.

Gear Requirements for EV

One of the biggest trends in the automotive industry today is the shift from internal combustion engines (ICE) to electric vehicles (EVs). Along with that trend, gear requirements are changing as well. The number of gears is expected to drop quite significantly. With ICE, there's an average of twenty-four gears in a vehicle, and eighteen of those are within the transmission. Whereas with EVs, there's only an average of about eight gears, which is about a third of internal combustion engines.

Furthermore, EV requires different types of gears. For example, electric vehicles operate at higher motor speeds than ICE vehicles, requiring a much finer gear flank finish to reduce friction and improve gear transmission efficiency. Shown in Figure 1 is a typical curve of vehicle speed versus torque, and the shift points that would be normal in an internal combustion engine with a conventional transmission. In an EV, the electric motor would have to operate across this range of speeds, so it is a lot more demanding on the gears.

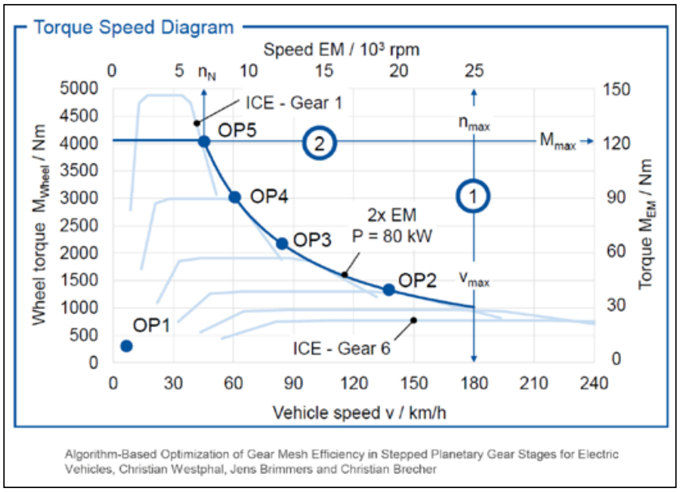


Figure 1

The noise level of gears is another consideration. Gears for EV have a unique challenge because there is no noise from the internal combustion engines. Any noise generated from the gears is not going to be masked, so they have to be considerably quieter. To address this, both sides of the gear flank must have similar performance with tight tolerances on both the acceleration and deceleration sides because of regenerative braking.

Gearbox Designs

There are two main gearbox designs that are currently used in EVs. One is a standard two-speed helical gearbox, and the other is a stepped planetary gearbox, which is much more compact.

Stepped planetary types are especially challenging for continuous generating grinding applications because of the close proximity and interference between the two gears. So, either a much smaller grinding wheel must be applied, or a completely different process has to be used, such as honing.

Aerospace applications also utilize planetary gear sets and other gear types. One example is a high-bypass turbofan engine that requires a speed reduction between the turbines and fan blades, keeping the tips of the fan blades from going supersonic.

Aerospace materials can be difficult to grind, creating some unique challenges. Materials include superalloys such as Inconel's that have very poor grindability and very high heat resistance. Traditionally many aerospace gear grinding applications use profile grinding, but continuous generating grinding can provide a much better pitch accuracy and higher productivity where the gear design allows.

Hard Gear Finishing

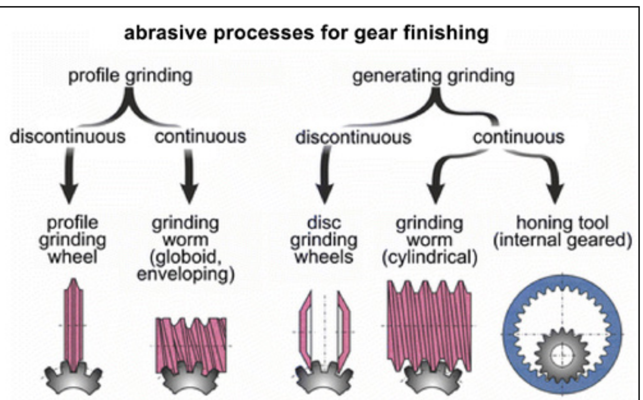
There are several different gear finishing methods, each with its own advantages. For example, when performing *honing*, which produces a profile quality of DIN 4-5 and pitch quality 5-6, excellent noise characteristics are achieved, and tool life is good. When finishing by *hard skiving*, the profile quality falls between DIN 6-7, and the pitch quality is DIN 5-8 with good noise characteristics, but tool life is short. With skiving, the cutters are changed frequently, or some machines resharpen the cutter, which adds cycle time.

When *finish grinding*, the profile quality is like honing. However, when *continuous generating grinding* the pitch quality is much better than other methods, primarily due to the manufacturing process itself. Noise characteristics are also good. The tool life is typically much longer than skiving and slightly longer than honing.

Understanding Continuous Generating Grinding

Many types of gear-grinding processes exist with varying levels of part quality and productivity. Knowing the terminology related to continuous generating gear grinding is helpful, and described as follows:

- When *profile grinding*, the gear tooth profile is formed from a grinding wheel dressed with the same profile as the gear tooth.
- When *generating grinding*, the gear tooth profile is formed using machine motion with a grinding wheel dressed to a gear rack form.
- Within each profile and generating grinding finishing process there are continuous and discontinuous distinctions (see Figure 2).



Karpuschewski, B. (2018). Gear Grinding. In: The International Academy for Production (eds) CIRP Encyclopedia of Production Engineering. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_6425-3

Figure 2

- *Continuous* processes refer to the gear and grinding wheel staying in rotation as the tooth profile is formed.
- Whereas, *discontinuous* means the grinding wheel retracts from the grinding wheel after each gear tooth is formed.

Continuous generating grinding is a unique and extremely demanding grinding process. Profile deviations and surface finish must be kept to an absolute minimum because of gear noise challenges. However, when considering the involute profile of the gear, the arc length and the chip thickness generated from the grinding cycle vary dramatically from the tip to the root. So, one edge will wear faster than the other, creating some difficulties when trying to increase the grinding wheel life. If these grinding wheels fail, it will typically be either due to profile deviation, from grinding burn, or as a result of waviness that is generated on the gear flank.

For grinding processes, it is also important to pay attention to chip length and chip thickness. For example, cylindrical OD grinding processes typically have a small contact area and will generate a chip with a large chip thickness, but short chip length. Creepfeed grinding, however, has a small chip thickness and a long chip length.

The chip thickness is generally a good index of how aggressive a grinding cycle is. The larger the chip thickness value, the more aggressive the grinding operation. Chip length, on the other hand, has a big effect on grinding temperatures, and chips with a long chip length are at risk of becoming embedded in the grinding wheel. With longer chip lengths, higher amounts of grinding wheel porosity are necessary to all the chips to be properly evacuated from the grinding wheel.

With surface grinding and profile gear grinding, the chip length is typically between three and four millimeters. However, continuous generating gear grinding has extremely long chips compared to these processes, making it closer to a creepfeed grinding process. A high porosity wheel is required to accommodate long chips. And a strong wheel is needed because the chip thickness is also fairly high (see Figure 3).

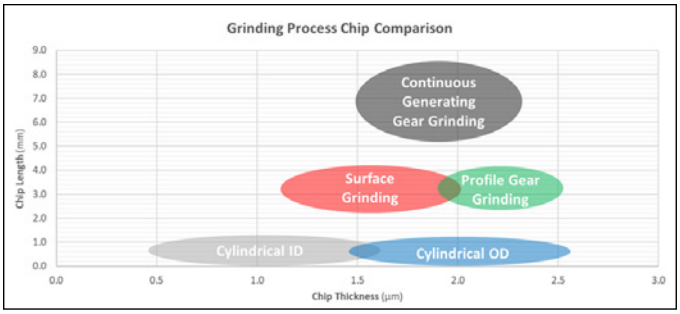


Figure 3

Grinding Wheel Wear Mechanisms

Both the abrasive and the bond are grinding wheel wear mechanisms. Figure 4 shows three abrasives with bond posts connecting them. The first type of abrasive wear is chemical or may have resulted from the flattening or flat spotting of the abrasive grain. When there are very flat abrasive grains, metal capping or loading will adhere to the tips of the grains, which can generate heat. Next is micro-fracturing, which is the preferred wear mode for abrasives. Micro-fracturing generates very small cracks that keep the grinding wheel sharp. The third type of abrasive wear is macro fracturing where the grain actually fractures in half. This accelerates wheel wear, increasing the overall surface finish.

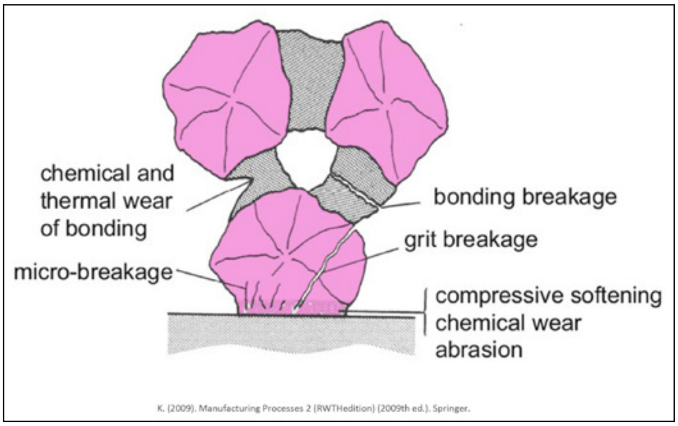


Figure 4

There are also three different primary types of bond wear. First, abrasive pullout is when the abrasive is totally pulled from the bond. In the instance of fracture bond wear, the bond will break. Or there is chemical or thermal wear that occurs from high grinding temperatures.

Essentially, you can enhance grinding wheel performance by either improving the wear resistance or toughness of the grain, or by increasing the strength and wear resistance of the bond. Wheel wear is also impacted by the homogeneity or uniformity of the grain dispersed throughout the grinding wheel. Even distribution of the grinding forces will create even wear, which is important for reducing transmission error and tooth variation.

When quantifying grinding wheel wear, G-ratio is an important index. G-ratio is defined as the ratio between the volume ground from the workpiece and the volume lost from the grinding wheel. So, a higher G-ratio indicates that a grinding wheel can remove more material before it requires dressing to restore the profile. G-ratio becomes even more critical as the grinding wheel gets smaller and reaches the end of its life because wheel wear increases as wheel diameter decreases, Also, the wheel speed is reduced as the wheel gets smaller, but because wear increases from the smaller wheel diameter, wheel volume is decreased.

Figure 5 shows the typical wear that you would see in continuous generating gear grinding. The profile and flank would start to become wavy, resulting in slope errors and form errors.

Monitoring the G-ratio is important for continuous generating gear grinding because these wheels should be running at a constant RPM for the best results. Performance must be maintained from the new grinding wheel diameter to stub.

The G-ratio is also directly affected by how aggressive the grinding cycle is. Chip thickness is a good indicator of aggressiveness. Different factors will affect the aggressiveness of the grinding cycle to varying degrees, some more than others. Factors include wheel speed, the number of wheel starts, feedrate, wheel diameter, and depth-of-cut.

Aggressive grinding cycles typically require tougher abrasives and stronger bonds to maintain wheel form, creating a challenge when trying to keep grinding temperatures low. It is critical to avoid excessive heat generation in gear grinding, as high temperatures can lead to thermal damage of the gear flank. Subsequently, thermal damage can cause tensile residual stress, which will significantly reduce the load-carrying capacity and fatigue life of the gear tooth. To help reduce grinding temperatures, grinding parameters can be adjusted, but these adjustments are usually at the expense of cycle time and overall productivity. Thankfully, new grain and bond technology advancements can reduce grinding temperatures while maintaining productivity.

Abrasive Types, Evolution

There are two commonly used abrasive types in gear grinding—fused and sintered. Fused abrasives tend to break apart into large particles, while sintered abrasives are designed to break down slowly into smaller particles while maintaining sharpness. Superabrasives are also an excellent option, although their usage is still emerging in gear-grinding applications (see Figure 6).

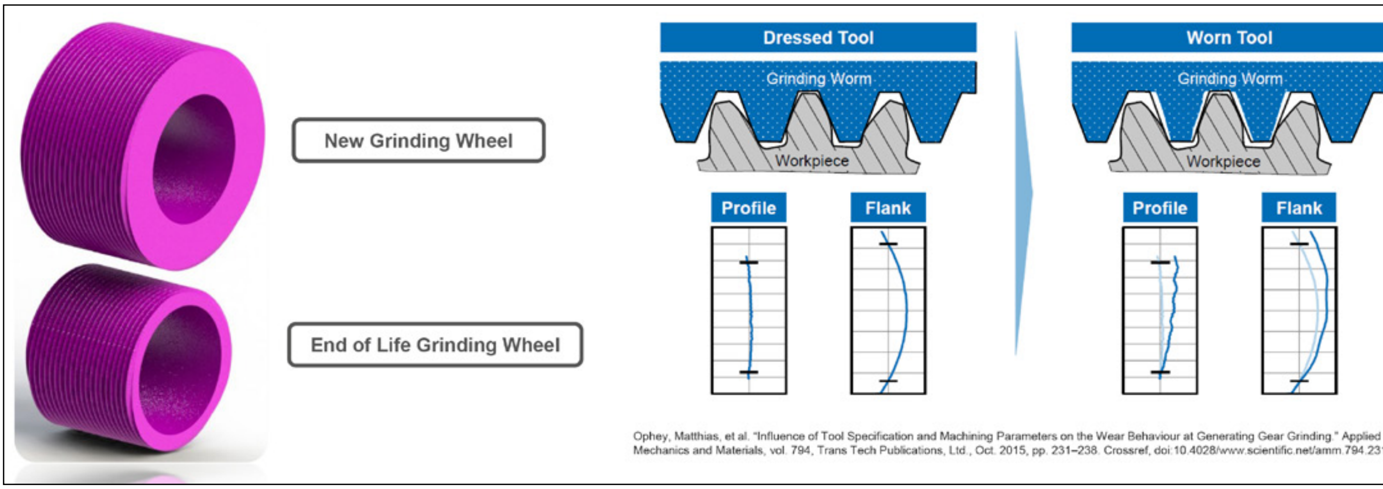


Figure 5

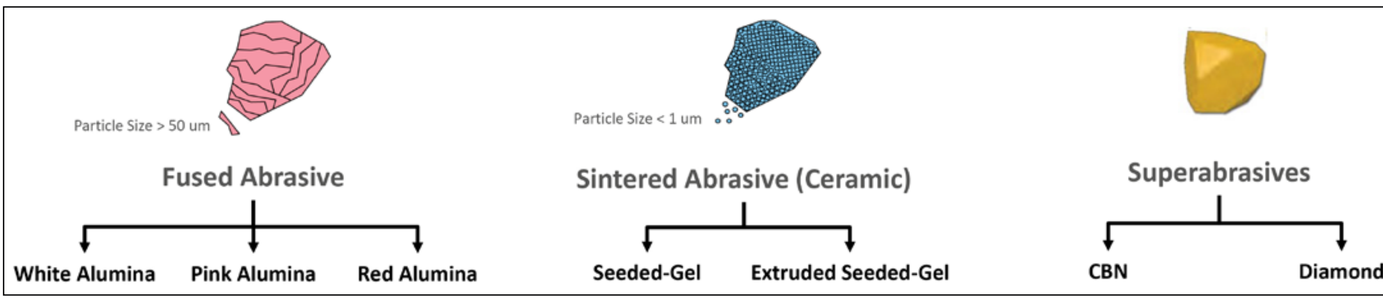


Figure 6

Abrasive grain comes in several forms. Aluminum oxide is one example that will change in appearance, toughness, and hardness based on the manufacturing process. Brown or natural aluminum oxide is typically brown and has a high toughness but lower hardness due to its impurities. White or pure aluminum oxide is typically white and is very sharp and reliable. By adding chromium oxide or titanium oxide, the properties of the abrasive can be modified. Adding ~0.2 percent chromium oxide results in pink aluminum oxide, and adding ~2 percent chromium oxide creates red/ ruby aluminum oxide. In gear grinding applications, pink and red aluminum oxides are the most used (see Figure 7).

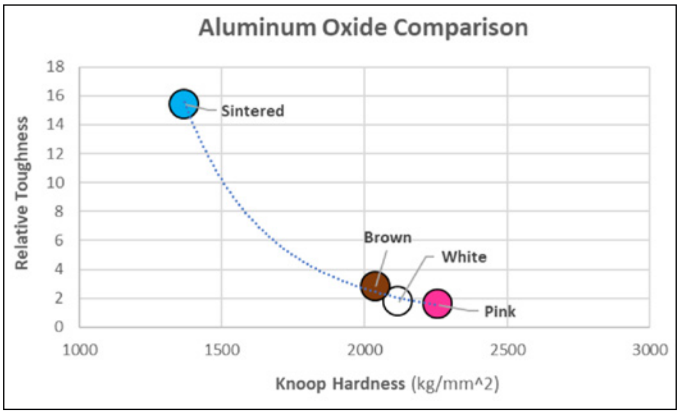


Figure 7

Seeded-gel ceramic abrasives are another form. Norton revolutionized the grinding industry in 1986 when it introduced "SG", the first of its kind, and Norton has been continually enhancing this seeded-gel ceramic technology ever since. SG is a small microstructure that creates a very tough abrasive, enabling controlled grain breakdown at high material removal rates. Seeded-gel abrasives typically have ~1:1 aspect ratio and provide a good balance of performance and quality. Norton Quantum, also known as NQ, was released in 2007 adding fracture point inducers to increase grain friability, resulting in reduced grinding forces when compared to its SG predecessor.

In 2021, Norton introduced its newest seeded-gel ceramic abrasive, Quantum Prime also known as NQN. Norton Quantum Prime has a smaller grain size, reducing wheel wear and producing finer surface finishes. This newest seeded-gel abrasive technology is well suited for gear grinding due to its ability to maintain sharpness while consistently breaking down (see Figure 8).

Norton released the first extruded seeded-gel abrasives in 1999 called "TG". Due to its geometry, extruded ceramics facilitate higher material removal rates and higher G-ratios than traditional seeded-gel ceramics. Typically, extruded ceramic abrasives are used in larger, cylindrical gears that require high material removal rates, or for grinding gears from solid. Norton "TQ" is the second-generation TG grain that uses NQ chemistry to produce smaller fracture plans. The smaller microstructure results in longer wheel life and lower grinding power.

It is important to note that in gear grinding, ceramic wheels are not typically 100 percent ceramic, instead they are blended with various aluminum oxides to make the grinding wheels more economical. In continuous generating gear grinding, ceramic concentration is typically in the range of 10–50 percent with 10–30 percent being the most common. The concentration of ceramic and the selection of the secondary abrasive play a big role in the grinding wheel performance. Higher ceramic grain content improves profile retention and extends grinding wheel life at the expense of increased dresser wear.

Bonds

The purpose of a grinding wheel's bond is multifaceted. Bonds enable the abrasive to retain sharpness and enough porosity for coolant and grinding chips. They also release worn abrasive, and reduce bond and workpiece interaction as much as possible. Typically gear grinding wheels tend to use a porous structure and relatively soft bonds to keep grinding temperatures low. The disadvantage is this also increases wheel wear.

A new bond technology from Norton for gear grinding reduces grinding temperatures and forces. The novel bond technology allows the bond itself to grind and remove workpiece material rather than rub against the workpiece, generating heat. An abrasive phase is grown into the bond during the manufacturing process which enhances grinding wheel performance (see Figure 9).

New Grinding Wheel Technologies

As gear designs are influenced by EV and other industries that demand lower, finer finishes, grinding wheels alone are unable to achieve the surface requirements. By using a dual polishing grinding wheel, the roughing and finishing process is performed with the grinding portion of the wheel, while an additional polishing step is performed with the wheel's polishing portion. The resulting polishing creates a much lower surface finish than previously attainable with just a grinding capability. And significantly lower flank roughness values result in reduced micro-pitting of the gear flank as well as improved transmission efficiency (see Figure 10).

Figure 10

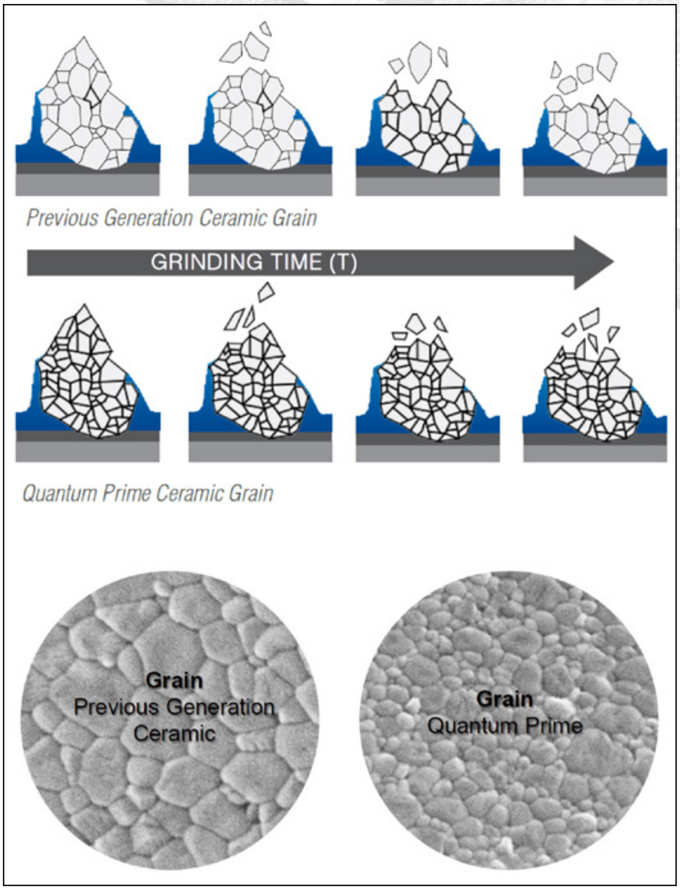


Figure 8

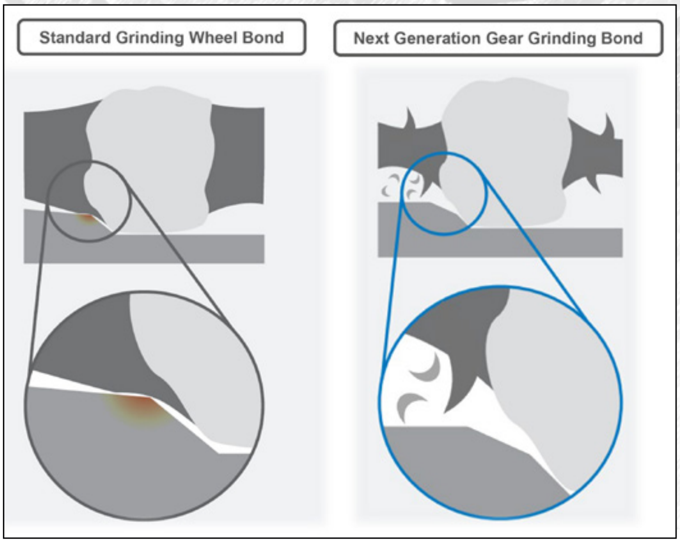
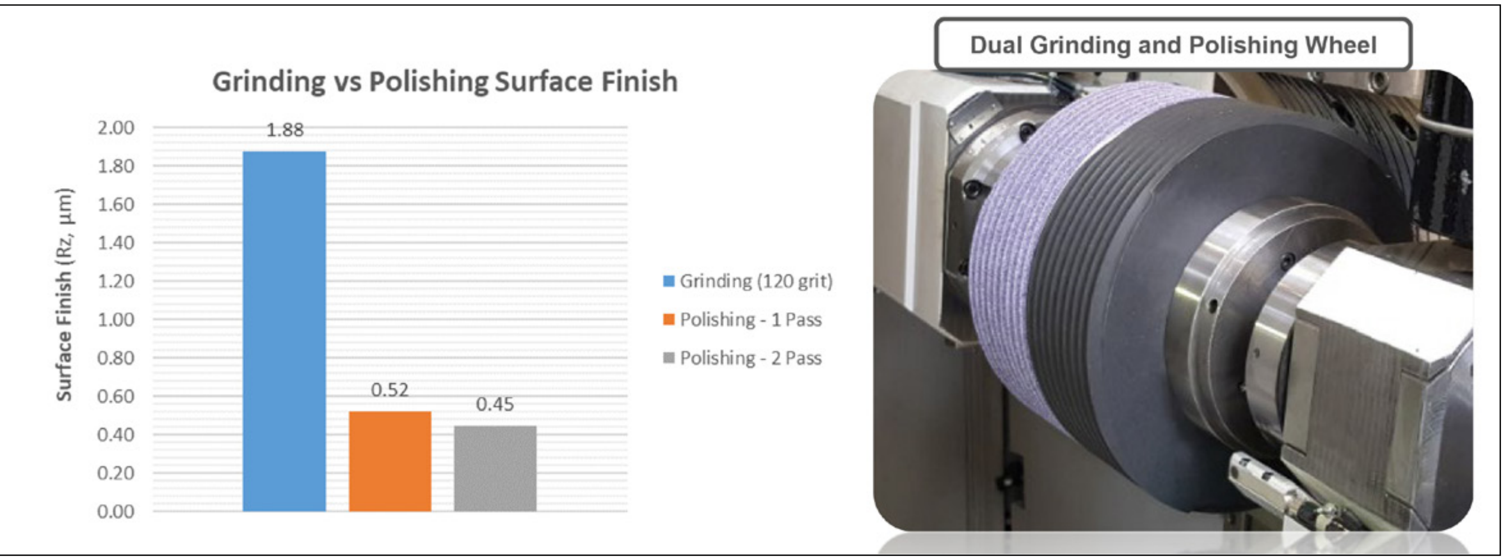


Figure 9



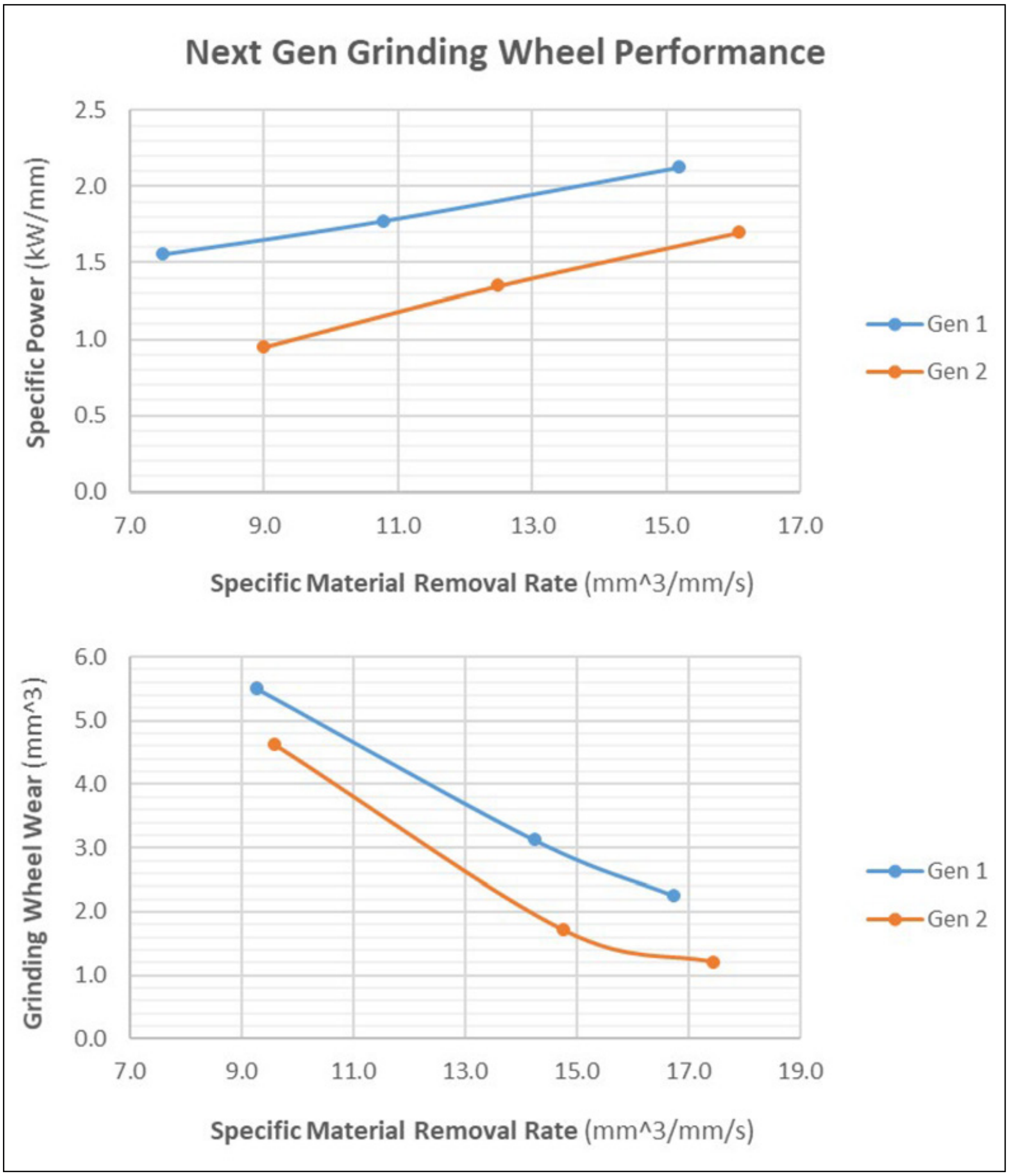


Figure 11

Also, the use of a hard resin instead of a typical rubber bond reduces the amount of polishing wheel deformation during the polishing cycle and improves the form accuracy of the gear tooth.

Benefits Proven in Tests

Field testing has shown that the newest generation gear grinding wheel bond system provides a lower specific power at all material removal rates, indicating that the abrasive phase grown into the bond is reducing friction between the bond and workpiece. Grinding wheel wear is also lower, likely due to the reduction in grinding forces and temperature (see Figure 11).

The profile retention was also improved with the new bond technology. When comparing the generation 1 wheels with the generation 2 gear grinding wheels, Ffα was reduced ~25 percent on average. This improvement results in lower process Cpk, and makes it possible to extend the dressing interval of the wheel.

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