Cubitron II: Precision-Shaped Grain (PSG) Turns the Concept of Gear Grinding Upside Down

New abrasive grains developed by 3M are redefining the process of gear grinding.

By Walter Graf
TO DATE, GRINDING, ACCORDING TO THE GERMAN DIN STANDARD 8580, IS “MACHINING WITH GEOMETRICALLY UNDEFINED CUTTING EDGES” WHILE OTHER MACHINING PROCESSES SUCH AS TURNING AND MILLING ARE CLASSIFIED AS PROCESSES WITH “GEOMETRICALLY DEFINED CUTTING EDGES.”

New abrasive grains, developed by 3M and called Precision-Shaped Grain, stands this definition on its head. For the first time, grinding wheels made with PSG, called Cubitron™ II, can claim to be made up of “geometrically defined cutting edges” as every grain is exactly the same engineered shape. Hence, it might be more appropriate to talk about “micro-milling” rather than grinding. This is borne out by looking at the resulting “flowing” chips—an akin to chips seen in milling operations, just finer. These free-flowing chips no longer clog up the grinding wheel and, therefore, the grinding wheel remains free-cutting and dressing becomes necessary only due to loss of form, rather than loss of cutting ability. In repeated tests, this has shown to drastically reduce the risk of burning and to give consistent and predictable results. Furthermore, tests and subsequent long-term trials under production conditions have shown that grinding time can be cut in many cases by at least 50% in comparison to grinding wheels made of standard ceramic abrasives.

Based on more than 100 carefully monitored and documented gear grinding trials, this article will demonstrate how Cubitron II grinding wheels work both in continuous generating grinding of car and truck gears, and in form grinding of large diameter gears (e.g. wind generators). Furthermore, the paper will discuss chip formation, filmed with high resolution slow motion; and the benefits of the free flowing chips in terms of resulting consistent surface finish, superior form holding, and extended dressing cycles.

Since the introduction of ceramic abrasives some 20 years ago, the conventional vitrified bonded grinding wheel has undoubtedly undergone technical improvements, but only in small steps. In this author’s opinion, advances in gear grinding technology in the last ten years can be more attributed to improvements in machine tool technology than the grinding wheels themselves. In fact, in some instances, such as spiral bevel grinding, it can be argued that grinding wheels have held back advances made in machine tool technology.

Grinding wheels called Cubitron II, made of 3M Precision-Shaped Grain (PSG) (see Figure 1), will change this situation and are challenging machine technology. In fact, some machine tool builders have already adapted to the potential inherent in these new grains by adding spindle power and by adopting their software grinding model.

Grinding, according to the German DIN Standard 8580, is “machining with geometrically undefined cutting edges.” Other machining processes such as turning and milling are classified as processes with “geometrically defined cutting edges.”

With any abrasives, the grinding process is a combination of plowing and cutting during the chip formation stage. Plowing carries much of the responsibility of the high-energy consumption inherent in conventional grinding. The

![Figure 1: Precision shaped grain (PSG)](image1)

![Figure 2: Stages of material deformation during the formation of chips](image2)

![Figure 3: Less material deformation and lateral build-up](image3)
chip formation of conventional grinding takes place in three stages as illustrated in Figure 2. In Stage I, elastic deformation occurs as the grain attempts to penetrate the workpiece material which flows back to some extent, this is then followed in Stage II as plastic deformation (plowing) and finally, in Stage III, a chip is formed. As the heat generated in grinding is carried away by the chips, it is of paramount importance that the chips are formed as early as possible, and that Stages I and II are as short as possible to avoid heat build-up, and as a consequence, thermal damage to the workpiece. 

Precision-shaped grains, however, move much quicker into the chip formation Stage III, see Figure 3. This in turn, reduces the risk of thermal damage to the workpiece. While it is difficult to witness the chip formation with direct observation, the resulting chip shapes lead to this conclusion. However, in the actual presentation, a film sequence was shown, filmed with 400 frames per second, of a dry grinding process in which chip formation was illustrated. 

Comparing grinding forces between PSG and conventional ceramic grains at the same cutting parameters have confirmed this. Long flowing chips have an inherent advantage in that they do not load up the grinding wheel (Figure 4). One of the positive surprises of working with PSG has been that the grinding wheel stays very clean over its full working life. This has been observed in all gear applications under full multi-shift production conditions. Wheel loading may also be responsible for visual surface blemishes such as scratches that can be observed in processes run with conventional ceramic abrasives.

When first looking at the wheel structure of a Cubitron II wheel, almost without exception, application engineers have stated that they can recognize that the cutting ability might be superior, but at the same time expressed concern that the resulting surface finish may be much coarser than with current conventional abrasives (Figure 5). However, both in gear grinding with single rib or with threaded wheels, the surface finishes were not inferior to conventional ceramic abrasives. On the contrary, this was particularly visible when looking at larger modules (> 10) that offered a large surface to observe where the resulting surface finishes were free of shading or “cloudiness.” Typically, both in generating grinding with threaded wheels and in profile grinding with single rib wheels, the surface finish was around Ra 0.3 μm across a full range of modules. In generating grinding with threaded wheels, results < Ra 0.3 μm have been achieved, however, with lower material removal rates.

HOW TO USE CUBITRON II WHEELS

As the cutting behavior of PSG grain is very different from standard ceramic grains, machining parameters have to be adapted both in terms of dressing and feeds and speeds. First, we look at single rib wheels, generally used for the grinding of large diameter gears.

The following parameters define the grinding process and shall be described in detail:

- Surface speed, \( v_c \), m/s
- Feed-rate, \( v_f \), mm/min
- Speed ratio (wheel – workpiece), \( q_s \)
- Dressing: overlap ratio, \( u_d \)
- Specific material removal rate, \( Q'_w \), mm³/mm/sec
- Specific chip volume, \( V'_w \), mm³/mm
SURFACE SPEED
In grinding with single rib wheels, the surface speed, $v_c$, is not an indicator of efficiency as this is determined by the depth of cut, $a_e$, and the feed-rate, $v_w$. A lower surface speed of around 30 m/s has proven to be the most efficient for using Cubitron II wheels in single rib profile grinding. While this may appear low, the wheel still does not break down. On the contrary, as a low surface speed increases the chip thickness, the wheel seems to work better as the pressure on the precision--shaped grains increases and fosters self-sharpening.

FEED-RATES, $v_w$
The feed-rate should be chosen as high as the machine tool allows. Looking at the historical development of the feed-rates of profile grinders, less than 10 years ago all seem to hover around a maximum of 4000 mm/min. Today, however, 12,000 mm/min and more have become the standard. The higher the chosen feed-rate is, the more aggressive the wheel behaves, and the lower the speed ratio, $q_s$, becomes. Gear grinding, unfortunately, hovers around a speed ratio, $q_s$, of 500, the most critical range is illustrated in Figure 6.

By increasing the feed-rate, $v_w$, the high speed ratio inherent in gear grinding will come down towards $q_s$ 120, a much safer range for avoiding thermal damage. Incidentally, the high speed ratio range of gear grinding, both for single rib profile grinding and of continuous generating grinding, predicates that only oil can be used as a grinding fluid.

DRESSING OVERLAP RATIOS, UD
The overlap ratio, $u_d$, describes how many revolutions a grinding wheel must make before the effective width, $b_d$, of the dressing tool has move laterally by its own width. The effective width is, of course, a function of the dressing depth $a_d$ and the radius on the dressing roll. While not going into more detail here, the higher the $u_d$ is, the slower is the dressing feed-rate, $v_d$, across the grinding wheel. In the past, it was common wisdom that the $u_d$ must always be greater than 1 to avoid cutting a thread into the grinding wheel. This, however, no longer holds true as recent experienced has shown that for PSG, an $u_d$ of 1, in synchronous mode, is ideal for rough grinding. In finish grinding, however, the $u_d$ ranges between 4 and 6, with the dressing roll and the grinding working in asynchronous mode.

More aggressive abrasive grains generally tend to be more aggressive on the diamond rolls, and the question is legitimate whether PSG will wear out diamond rolls.
quicker than standard ceramic abrasives. As PSG is made of a similar ceramic material, and only differs in shape, one could logically assume that the wear on diamond tool would be similar. This, in fact, was born out by comparative trials of an equal high number of dressing passes at equal depth. Simply stated, the wear can be considered the same at the same number of cycles. However, as PSG requires fewer dressing cycles, the economy is in favor of using PSG. This will be shown when addressing \( V\text{'}w \), the specific chip volume.

The purpose of dressing is to sharpen worn and blunt grains (Figure 7). While often understood as a cutting process, it has to be viewed as
a type of hammering process whereby the diamond will fracture the surface of abrasive grains and sharpen them in the process. Both standard ceramics and PSG have chemically integrated fracture point, or lines respectively, in their grain structure. For standard ceramics this means that minute particles break out to generate a serrated surface. PSG grains, in turn have integrated fracture lines that result in a sharp point to maintain their aggressiveness.

**SPECIFIC MATERIAL REMOVAL RATE, Q'_w**

This value refers to a grinding wheels cutting capacity in terms of volume material removed (in mm³) per mm grinding wheel width per second, expressed as mm³/mm/sec. Q’ is an excellent benchmark to determine the performance level of a specific grinding wheel, and allows direct comparison with different wheel specifications. The applied formula of Q’w is shown in Equation 1.

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Q'_w = \frac{a_e \cdot v_w}{60}
\]

However, the depth of cut, ae, is taken as the vertical infeed into the tooth gap, and the result would only be true for the root of the tooth gap. Along the involute curve, the Q’w values vary considerably. However, as everyone applies the same formula, there is practical use in it. Typical industry values of Q’w hover around 10 mm³/mm/sec.
Cubitron II wheels, however, have consistently proven themselves at Q’w values as high as 30 mm³/mm/sec. This translates into considerable savings, allowing grinding times to be reduced by up to 50%, and often even more.

SPECIFIC CHIP VOLUME, V’w

The specific chip volume V’w refers to the volume removed until redressing is initiated. It is given in mm³/mm (volume removed in mm³ per mm wheel width) and mostly suggested by the machine tool software. In other words, the specific chip volume is an economic metric. The higher the value of V’w, the longer the wheel life will be. In this area, Cubitron II wheels have outperformed standard ceramic wheels by a factor of two to three. This translates into substantial cost savings, allowing grinding times to be reduced by up to 50%, and often even more.

CASE HISTORIES

To illustrate the performance of Cubitron II wheels with the precision-shaped grains, five case histories have been chosen to show the extensive range of application, (Figures 9 through 13). This encompasses the grinding of small and large module, grinding from solid or finish grinding. The first four cases show the application of single rib wheels for profile grinding. The last application shows a sample of continuous generating grinding with a threaded wheel.

The use of Cubitron II wheels is of course not restricted to gear grinding with single rib wheels. Threaded wheels made with PSG have shown the same performance increases as witnessed with single rib wheels. Instead of measuring using Q’w, the performance in often measured in Qmax, which measures the total material removed per second.

To date, the performance limits in Qmax using standard ceramic abrasives was approximately 400 mm³/sec. The Cubitron II case history given in Figure 14 shows a Qmax value of in excess of 800 mm³/sec. As the wheel also allowed to take out several roughing passes, the grinding time was reduced from 45 to 9 minutes. While this may seem an extreme example, it shows the full potential of this new precision-shaped grain.

CONCLUSION

In summary, Cubitron II wheels will set a new performance level both in term of material removal rates, grinding times, extended life of diamond dressing tools, and substantially reduced risks of thermal damage. By adapting machine tool technology to the PSG grains full potential, grinding processes will reach new limits, hitherto thought impossible.

ABOUT THE AUTHOR:

Walter Graf completed his tool making apprenticeship in 1974. He worked for 10 years in tool and mold making workshops. Following this, he continued his studies in Australia and the UK and was awarded a Bachelor of Science Degree (Honors). Some 21 years ago he began as a product manager for superabrasives at Winterthur Schleiftechnik AG, Switzerland. Three years later he became their sales manager and prior to the purchase of Winterthur by 3M in 2011, he held the position of chief marketing officer for the entire Winterthur Group. At the time of presenting this paper at the AGMA conference in September 2013, Walter Graf worked for 3M’s Abrasive Systems Division as senior technical consultant and trainer. He has remained in the gear industry and since January 2014 works for Reishauer gear grinding machines as their marketing manager.

For more information about the Cubitron II, visit www.3M.com/PrecisionGSMay.