THIS ISSUE

Calendar of Events

“BEST IN CLASS” Education Course – Superabrasives Materials, Principles & Applications

SKYTEC BOLT – A new generation of metal bonded diamond wheels for grinding of indexable inserts with electrical discharge conditioning.

IDA Member Companies

Thirteen Years As The Grinding Doc

Progress of Grinding Technology of Monocrystalline Silicon Carbide; for Longer Tool Life and Higher Quality Finished Surfaces

INTERTECH 2019 in New Orleans

In Memoriam: Jack Lunzer

THE LONGEST RUNNING MAGAZINE DEDICATED SOLELY TO THE TECHNOLOGY AND APPLICATION OF SUPERABRASIVES
CBN-AMX

- These crystals were removed from electroplated CBN wheel’s (same manufacturer) after grinding 15,000 Specific Volume Material Removed Vol’ (mm³/mm) of Inconel 718.
- Note the consistent 90 degree fracture mode fracture mode for the AMX which directly relates to the long, consistent grinding cycles (note in the Power vs. Volume chart below).
- Note that the AMX (Pink line) consistently draws lower power and provides a more free cutting crystal.
- Note that the Competitor H crystal, also removed after grinding the same amount of workpiece materials, exhibits a non-uniform crystal breakdown that is clearly exhibited in the Power vs. Volume chart.

POWER VS VOLUME

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FINER POINTS is the longest running publication devoted exclusively to the understanding, selection and application of diamond, cubic boron nitride and related materials. It is edited for recipients who are involved in some way with these “superabrasives”, either as providers of the materials, producers of products containing the materials or users of these products (e.g., grinding wheels, dressing tools, drill bits, saw blades, sawing wires, cutting tools, polishing compounds, CVD film products, etc.).

Photo courtesy of LACH DIAMOND INC. shows Grinding of a PCD compact hogger on a 3Dia-Saw-Grinder for diamond saws. This tooth-by-tooth milling is for sharpening as well as new production on any tooth geometry and even for multiple production processes. Diamond Saw Tools are used for processing Wood and Plastics.

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Welcome to the fall issue of Finer Points. The time for summer vacations has ended as the kids head back to school, hopefully you were able to take some time off, enjoy time with the family and get through that summer read you had on your list. Reading and learning can keep you growing and renew your creative spirit to implement new insight and goals in your life.

We get so mired in the day to day crisis that we sometimes forget to raise our head up to see the people we care about. We come home tired having spent all our energy on the battle at work that we fought all day. Stop, take a breath and keep moving forward. I try to read 10 to 20 books a year, some are easy fun reads and others I have to push myself to get through. The tough ones are often the ones that I find the most interesting after I have finished. A couple of the best books I’ve read so far, this year are “Shoe Dog” by and about Phil Knight the founder of NIKE and “A Man Called Ove” by Fredrik Backman, the ultimate cranky old man.

Share some of your favorite books with family, friends and coworkers. Everyone appreciates a good story. Here are some notable people’s favorite books; Amazon CEO Jeff Bezos said his favorite book was “The Remains of the Day” by Kazuo Ishiguro, a novel about an English butler after the WWII. Former Microsoft CEO Bill Gates’s favorite book is J.D. Salinger’s "The Catcher in the Rye." Oprah Winfrey has said "To Kill a Mockingbird" by Harper Lee is her all-time favorite book. Warren Buffett, the Berkshire Hathaway CEO offered up his favorite: "Business Adventures," by John Brooks.

An ending thought are these excellent quotes from Teddy Roosevelt and Dr. Seuss. "It is not the critic who counts; not the man who points out how the strong man stumbles, or where the doer of deeds could have done them better. The credit belongs to the man who is actually in the arena, whose face is marred by dust and sweat and blood; who strives valiantly; who errs, who comes up short again and again, because there is no effort without error and shortcomings; but who does actually strive to do the deeds; who knows great enthusiasms, the great devotions; who spends himself in a worthy cause; who at best knows in the end the triumph of high achievement, and who at the worst, if he fails, at least fails while daring greatly, so that his place shall never be with those cold and timid souls who neither know victory nor defeat."

- Teddy Roosevelt.

“You have brains in your head. You have feet in your shoes. You can steer yourself any way you choose”

– Dr. Seuss.

Best regards,

Ed Francis, President
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EDUCATION VS TRAINING

A few years back I was part of a company’s training program and in fact our department was called Manufacturing Training Programs. Our mission was to create “training” programs on all the equipment and processes throughout the plant and even to prepare those programs for our overseas plants. Our purpose was to “train” operators on individual operations so they could perform specific functions over and over again as one part of the production process.

In other words we could “train” a person to operate a certain type of lathe or machine to generate one specific shape, one after another. Once that individual could repeat the process over and over again, then we considered them “trained”. However, if we had rethought this and took the time to “educate” an operator on the intricacies and capabilities of any machine under any given situation and on any different material to generate a wide range of parts, then we could say that operator was educated across the entire production line ...

Although Education and Training seem to be interchangeable to most people, there is a clear difference between the two words. The impression that education and training are interchangeable is created by most of the institutions or organizations that substitute training for education. However, there is a vast difference between education and training and those of us who are involved in higher learning have realized this through time and experience.

Education creates a foundation of knowledge about facts, concepts and principles. For instance, at the Industrial Diamond Association of America’s Superabrasive Materials, Principles and Applications course attendees gain the ability to solve problems and make critical decisions “on the job” because they have been educated. Attendees are not just “trained” as most courses promote, but are educated about superabrasive materials and have an in-depth knowledge to understand how and why these tools and abrasives are applied in machining and grinding applications on myriad materials.

On the other hand, training is focused upon gaining a particular skill and is a method that makes a person skilled only in a particular job or task, for instance operating a particular grinder. This is not to say training is not important, it is. The trades would be in bad shape if there wasn’t skilled training, but if education is also introduced then the “trainee” is more well-rounded and a more valuable employee.

Throughout all industries we are hearing about losing the skilled workforce. Experts are retiring and the lack of new workers seeking jobs in the trades and manufacturing has become a major problem. Organizations that are promoting entry into the trades and manufacturing are to be commended. There are some professions where skills can be easily learned through practical training rather than through formal education and concepts can be understood through training.

Training is an excellent start and a great way to introduce someone into a workforce where skilled labor is sorely needed. To carry that one step further a highly educated workforce will be able to perform more technical operations such as programming machines and making rational decisions for improving manufacturing operations.

Wise leadership will make the extra effort in educating their workforce realizing that a more educated workforce contributes to the overall performance and profitability of the company. Hopefully we will see these companies represented at the Superabrasive Materials, Principles and Applications Course in November, where training is taken to the higher level of education.
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Here today...

But what about tomorrow? While hundreds of millions of Americans are enjoying the wonders of our national parks each year, the future of the very things they’re coming to see is at risk. For example, although the Mexican black bear population has been slowly recovering at Big Bend National Park, their ongoing survival is threatened. Americans for National Parks is a coalition working to preserve these national treasures, and all the priceless experiences they provide. Find out how you can help at: www.americansfornationalparks.org.
WALL COLMONOY ANNOUNCES FALL SESSION OF MODERN FURNACE BRAZING

Preserving the tradition originated by the late Robert Peaslee, a brazing pioneer who invented the first nickel-based brazing filler metal, Wall Colmonoy offers a fall session of Modern Furnace Brazing School on October 10-12, 2017 at Wall Colmonoy’s Aerobraze Brazing Engineering Center in Cincinnati, Ohio. Engineers, technicians, quality managers, production managers, and others will participate in “hands-on” practical applications while learning about brazing technology from the industry’s leading brazing engineers. For over 60 years, Wall Colmonoy engineers have been gaining practical experience on actual problems in brazing plants around the world. Unlike other classroomonly seminars, Brazing School attendees will tour the facility and see the actual brazing application on the shop floor. They will also have the opportunity to apply different forms of filler metal to supplied samples, have them vacuum brazed and discuss the outcomes. For seminar details and registration information, contact Jim Nicoll, Marketing Associate, at brazingschool@wallcolmonoy.com

BUY AMERICAN AND HIRE AMERICAN* EXECUTIVE ORDER

The president’s executive order instructs federal agencies to examine their purchasing systems to more effectively favor buying American goods. The order follows a campaign promise to use presidential authority to encourage companies to buy American products and hire American workers. The "Buy American" provision of the order will reinforce a stricter adherence to laws that require the federal government to purchase American-made products whenever possible. The "Hire American" part targets government guest-worker programs, particularly the H-1B visa program. The order will crack down on "abuses" in such programs. The executive order won’t make immediate changes to the system but will direct the Labor, Justice, Homeland Security and State departments to undertake a wholesale review of the H-1B visa program and to put forth recommendations that can be achieved administratively or through legislation. That could mean adjusting the wage scale the government uses to assess applicants, giving preference to workers with advanced degrees or taking “a more vigorous stance” in enforcing violations of the program in an effort to root out fraud and abuse.

HARLEY-DAVIDSON’S DECISION TO BUILD PLANT IN THAILAND RAISES EYEBROWS

Harley-Davidson, the iconic motorcycle brand is building a plant in Thailand, the company confirmed as it seeks new buyers in Asia and lower tariffs. The factory – only the third Harley has built outside the United States – highlights the irresistible draw of overseas plants for U.S. manufacturers. "We are expanding our presence in the Asia-Pacific market by building an assembly facility in the Rayong Province in Thailand," said Harley-Davidson spokeswoman Katie Whitmore. She declined to say how much the plant was worth but said it would be up and running in "late 2018." Harley has found it hard to resist the lure of overseas assembly lines - both to be geographically closer to emerging markets and circumvent high tariffs that favor local competitors. It already has assembly plants in Brazil and India that put together bike kits made from parts from its U.S. factories. The Thai plant will do the same. Harley has insisted the Thai plant will not result in American job losses, arguing instead it will enable them to grow their business using American-built parts. "There is no intent to reduce Harley-Davidson U.S. manufacturing due to this expansion," Whitmore said. "Harley-Davidson U.S. manufacturing will continue to supply the U.S. and certain other global markets," she added.
THE INDUSTRIAL DIAMOND ASSOCIATION OF AMERICA (IDA)

Presents

“BEST IN CLASS” Education Course

Superabrasive Materials, Principles & Applications

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● Truing & Dressing Applications
● Grinding Demonstrations and Surface Analysis
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OBJECTIVE

“Superabrasive Materials Principles and Applications” is sponsored by the IDA and designed specifically to educate on the use of industrial diamond, cubic boron nitride (cBN) materials classified as superabrasives. It is Non-commercial, unbiased and representative of accepted principles and practices. Content will include a wide range of products and applications for the automotive, aerospace, medical, electronics, optics and other industries using superabrasives. The attendee will be educated in the primary areas of grinding and machining with peripheral explanation for other uses, such as non-abrasive applications.

WHO SHOULD ATTEND?

This Course will educate End Users processing materials made from difficult to machine and grind materials such as hardened steel, stainless steel, superalloys, titanium, high silicon aluminum, composites, ceramics, bi-metals, metal matrix composites, cermets, glass, and more! It will also educate Machine Tool Builders, Abrasive suppliers, Raw Material Suppliers, Machine Operators, Wheel Makers, Tool Makers, Research Scientists, Academia, Engineers, Sales Personnel or anyone wishing to learn more about superabrasives.

INSTRUCTORS ARE INDUSTRY EXPERTS WITH MANY YEARS COMBINED EXPERIENCE!

Each one has with “real world” knowledge of superabrasives, applications and characteristics. They have already established manufacturing operations in aerospace, automotive and literally every other production operation around the world. Now, you can learn what superabrasives are, where they are used and the characteristics and properties that affect their performance in manufacturing operations. Do you want to understand wear mechanisms in machining and grinding? What is friability? What is a rake angle? What affects chip formation? What crystal is used in a given application? How does burn and thermal damage affect structural integrity of a part? What is residual stress in metal components such as turbine engine fan blades? Why true & dress a wheel? What are the different coolant types and delivery systems? What is edge prep on a cutting tool and why is it performed? What is the Modulus of Resistance and what abrasive performs best on a particular workpiece material and why? If you currently are using conventional abrasives you will learn the advantages of superabrasives and how they can be applied to increase productivity, reduce scrap and improve the cost effectiveness in manufacturing operations.
Modern indexable inserts consist of hard materials (tungsten carbide, cermet, ceramic, polycrystalline diamond (PCD), polycrystalline cubic boron nitride (PCBN)) and are usually ground after sintering to precise shape and dimensions with diamond grinding wheels. Face grinding of the periphery (clearance surface) of the inserts is a very time consuming step besides grinding the radii and a possible chamfer due to the high stock removal. Resin, metal and vitrified bonded diamond wheels have been used usually over the last decades. Because the wheels are clogging, loading, wearing and losing shape, they have to be dressed conventionally using wheels made of silicon carbide (SiC) or aluminum oxide (Al2O3) for cleaning and restoring a flat surface geometry. This article presents a new generation of metal bonded grinding wheels which are dressed in process using electrical discharge conditioning (EDC). This combined process called “PowerGrind” was developed and introduced by the machine builder Agathon, Switzerland.

There are some basic requirements to grinding wheels dressed by electrical discharge conditioning: Firstly, a highly electrical conductance of the diamond wheel is necessary: Due to high current flow (up to 60 Amperes discharge current, discharge time 1-2µs) during the electrical discharge the body (carrier) of the wheel, the rim and the interface (glue or thin copper layer) between the body and the diamond layer have to be electrical conductive. It was found out, that the resistance between the diamond layer and body should be lower than 20mΩ.

**SKYTEC BOLT – A NEW GENERATION of metal bonded diamond wheels for grinding of indexable inserts with electrical discharge conditioning**

Author – Dr. KARL MAYROHER, R&D Resin and Metal Bonds, TYROLIT, Austria
Presenter – CHRISTOPHER GOLSER, Sr. Application Engineer, RADIAC ABRASIVES, USA
respectively the conductance should be greater than 50S. Usually the rims are glued on aluminum cores which have a sufficient specific electrical conductivity (38*10\(^6\) S/m).

Secondly, the bond must be machinable by EDC in order to dress, sharp and clean the grinding wheel. In consequence metal bond with a low melting temperature is preferred for a controlled wheel wear. Theoretically, a conductive highly metal (e.g. copper) filled resin bond diamond wheel could be conditioned by EDC. But due to the locally high temperature (T > 4000 K) caused by the spark discharges, the resin bond would be decomposed. Also a electrical conductive ceramic bond would work.

Thirdly, there are some requirements due to the grinding process: The grinding parameters (peripheral speed, infeed, stock) and the workpiece and material to be ground have a great influence on evaluating the right grinding wheel specification: The type of diamond, the grit size and size distribution and the concentration (amount of the diamond in the rim, 25 Vol.% = C100) and bond are primarily crucial for the grinding of the inserts. The bond is responsible for the diamond retention. In case of insert grinding the bond should not be too tough because of clogging the wheel with the hard material of the workpiece. Concerning these requirements, grinding wheels with different types of diamond, different grit sizes and concentrations retained in different metal bonds were tested to achieve an optimal grinding result. After then the grinding parameters in conjunction with the PowerGrind Process were optimized. The grinding was performed on an AGATHON 400 Penta CNC machine (Switzerland) equipped with electrical discharge conditioning in process (PowerGrind). The grinding oil was a low viscosity dielectricum (=non electrical conductive fluid) enabling electrical discharge machining, lubricating and cooling. In this paper the surface topographies of a spark eroded and conventionally dressed metal bonded diamond wheel are compared (figure 1, 2). Further, the influence of the metal bond (figure 3, 4), the influence of EDC (figure 5, 6, 7), and the grit size (fig.8,9) on grinding forces are discussed.

Additionally some productivity enhancements are presented. Finally a conclusion is drawn. Figure 1 shows the surface topography of a metal bonded D28 grinding wheel dressed conventionally with a ceramic bonded 400 mesh Aluminum oxide dressing wheel: The surface appearance is chopped, edgy and shows many ruptures. The diamonds show signs of mechanical damage. The metal bond is plastically deformed. Figure 1 SEM (scanning electron microscopy) of the surface topography of a metal bonded D28 grinding wheel after dressing with a 400 mesh Aluminum oxide; 500-fold magnification

Figure 2 shows the surface topography of the metal bonded D28 grinding wheel after electrical discharge conditioning. The resulting topography seems more open, skeleton like and with predominantly round shapes. The diamonds are not mechanically damaged. Some of the diamonds are covered with molten bond material. The surface of the diamonds seems higher than in Figure 1 for the conventional case although the identical grinding wheel was used.

Figure 3 shows the forces during grinding of two V-shaped tungsten carbide inserts with a pure copper bonded D28
diamond wheel. The four ground face sides correspond to the peaks of the four normal forces and respectively to the four signals of the tangential forces. As can be seen the wheel was slipping because the tangential force became negative. Due to the high normal forces of 380N and temporarily negative tangential forces, the pure copper bonded diamond wheel was overloaded. After face grinding the two radii were ground corresponding to the negative peaks of the normal forces. The normal forces were for kinematic reason negative because the grinding wheel was moving back from the insert.

Figure 4 depicts the grinding forces when a optimized bronze bonded D28 wheel was grinding two V-shaped tungsten carbide inserts. There was no slipping of the wheel observed and the maximum normal forces were much lower (280N) in comparison to the copper bonded wheel. So the bond of the diamond has a huge impact on grindability!

Figure 5 and 6 demonstrate the impact of the in process dressing with EDC on grinding forces. Figure 5 depicts the grinding forces when 10 pieces V-shaped tungsten carbide inserts were ground without EDC. As can be seen, the normal forces grew from insert to insert starting at 300 Newton and reaching 380 Newton after 12 inserts. The tangential force were constantly at 100 Newton. Then the grinding was repeated under identical conditions with the exception that EDC was on. The normal forces kept constantly at 300 Newton (figure 6).

The friction coefficient $\mu$ is the ratio of the tangential force ($F_t$) and the normal force ($F_N$) and a measure of the grindability: $\mu = F_t / F_N$. Figure 7 shows the friction coefficient calculated from the force data yielded in figure 5 and 6 over 10 inserts. When the grinding wheel was electrical discharge dressed in process (EDC ON), then the friction coefficients are always significantly higher than without EDC (EDC OFF).

Figure 8 shows the normal forces (blue) and tangential forces (red) when C-shaped tungsten carbide inserts were ground with a metal bonded D12 grinding wheel. When the grit size of the diamond was doubled to D25 (fig.9), the maximum normal forces decreased significantly form 280 to 210 Newtons.

The results of table 1 and table 2 show examples of the very high potential of grinding inserts with metal bonded grinding wheels dressed in process with electrical discharge conditioning. In table 1 a productivity comparison is drawn between a resin bonded D46 wheel, dressed conventionally, and a metal bonded D28 wheel, dressed with spark eroding. The indexable insert was a
ultra fine grade tungsten carbide with a side length of some centimeters. Despite the one third lower grit size of the metal bonded wheel, the cycle time wass more than a half lower (108 seconds) because the infeed was more than doubled. Additionally, the edge chipping of the inserts was reduced significantly to 12µm.

The second application example is a rhombus shaped indexable insert made of solid pCBN with a side length of about 2 centimeters. Again, EDC enables a much higher productivity. The cycle time in this example can be reduced by 60%, again using a finer diamond grit.

The new metal bonded high concentrated fine grit diamond wheel can be easily and optimal dressed in process with electrical discharge conditioning. In consequence the grinding wheel is during grinding always flat, clean and sharp. Due to lower grinding forces the infeed speed can be tremendously increased by declining cycle times. Using smaller grit sizes (D12) and higher concentration enables reduced edge chipping of the inserts.

Table 2: Productivity Comparison Solid pCBN

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>EDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Time (seconds)</td>
<td>300</td>
<td>115</td>
</tr>
<tr>
<td>Material Removal Rate [mm³/min]</td>
<td>14</td>
<td>36,5</td>
</tr>
<tr>
<td>Grinding Wheel Grit Size</td>
<td>D46</td>
<td>D25</td>
</tr>
</tbody>
</table>

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**Lands Superabrasives Co.**  
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**Lieber & Solow Co.**  
www.lieberandsolow.com

**Megadiamond Inc.**  
www.megadiamond.com

**Morgan Advanced Materials and Technology**  
www.morganplc.com

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www.mwiloueloquence.com

**National Research Co.**  
www.nationalresearchcompany.com

**Niabraze Corp.**  
www.niabraze.com

**Noritake Co Inc.**  
www.noritake.com

**Pinnacle Abrasives**  
www.pinnacleab.com

**Precision Eforming**  
www.precisioneforming.com

**Protech Diamond Tool Inc.**  
www.protecdiamondtoolsinc.com

**Radiac Abrasives Inc.**  
A Tyrolit Company  
www.radiac.com

**Rollomatic, Inc.**  
www.rollomatic.ch/en/contact/usa

**Sandvik Hyperion**  
www.hyperion.sandvik.com

**Saint-Gobain Surface Conditioning Group**  
(Saint-Gobain Ceramic Materials)  
www.innovativeorganics.com

**Scio Diamond Technology**  
www.sciodiamond.com

**Spec Tool**  
www.spec-tool.com

**Standard Die & Fabricating Inc.**  
www.standarddie.com

**Sumitomo Electric Carbide Inc.**  
Materials Group  
www.sumicarbide.com/diamondgroup

**Superabrasives Inc.**  
www.superabrasives.com

**Syntech Abrasives Inc.**  
www.syntechabrasives.com

**Tomei Corp. of America**  
www.tomeidiamond.com

**Ulbrich Stainless Steels & Special Metals, Inc.**  
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TECHNOLOGY BEGINS HERE

The world seeks better technology. Amid many aspects that define better technology, tools are among the most influential ones. As much as tools are important, there are challenges in building a suitable tool for machining superhard materials. Let ILJIN’s PCD and PCBN, with assured quality by advanced quality control system, be your breakthrough for finding the right solution. When you create a new technology, ILJIN will always be by your side.
I did a Bachelor’s at the University of Texas at Austin, a Master’s from Penn State, and a Ph.D. from Trinity College in Dublin, Ireland, all in mechanical engineering. The research focus of my Ph.D. was grinding. I then worked several short contracts for companies in England and Sweden that were suffering from “grinding burn,” followed by two years at a steel company in Sweden doing research on the “grindability” of different steel grades. During that time I started writing a question/answer column on grinding for the trade magazine Cutting Tool Engineering. I needed a catchy name. I figured that if Dr. Phil could give advice on psychology and Dr. Deepak Chopra could give advice on spiritual enlightenment, I could give advice on grinding. I called myself “The Grinding Doc”. The name stuck.

In 2004 I went on the road as The Grinding Doc, independent grinding expert. I advised companies on grinding research, did grinding troubleshooting, particularly for burn, developed a three-day grinding education course, and developed “The Grindometer” power meter for evaluating grinding cycles. When I started, most of my experience was grinding tool steel, but I gradually branched out into other industries on carbide tooling, aerospace, gears, bearings, crankshafts, camshafts, rolls and even gemstones. I read all the books and academic literature I could find. I spent my days on the shop floor measuring power, wheel wear and surface finish and evenings processing the results ... I learned a lot.

The grinding world is a small place so my work took me around the globe. I spent months on the road – a week at a company in Spain, three weeks at three different companies in Sweden, a week at a company in Slovenia, two weeks between jobs processing the results on my laptop at the beach in Croatia, then a three-day course in England followed by trips China, Korea and Australia. During one period, I lived out of a suitcase for 18 months, without a home. I was learning so much, so I kept going.

Thirteen years later I’ve visited hundreds of companies in over 30 countries and spent countless hours on the shop floor battling burn, chatter, long cycle-times and general grinding headaches. Here’s what I’ve learned so far that may help others to improve grinding operations.

1. Master the fundamentals.

Grinding is like golf. You can have the most expensive club in the world, but if you have a bad swing, you’ll be a bad golfer. Many grinders think they just have to get the right wheel and that burn problem will go away. It won’t. When I was fresh out of my Ph.D., I also was guilty of the “find the perfect wheel” mentality. What I learned – the hard way – was that if you’ve got a good understanding of grinding, dressing and cooling fundamentals and set up the process correctly, just about any wheel will do. Nowadays when I go to a company with burn problems, they call me a few weeks before and say, “Dr. Badger, what test wheels would you like us to order?” They’re surprised when I say, “None. We’ll get rid of the burn with the wheel
you have." They reply, “But you don’t even know which wheel we have.” And I say, “I don’t, but I’m sure it’s fine.” We spend three days on things like wheel wear, chip-formation, removal rates, aggressiveness, dressing overlap ratios and speed ratios, coolant pressures and velocities, RPM ratios and a host of other fundamental concepts. We then spend about 10 minutes on wheel choice. That’s not to say a better wheel won’t help you. But the place to start is with the fundamentals.

2. Don’t tell people how to grind – give them the tools and knowledge about grinding and turn them loose.

Early in my career, I’d get on a machine and change the parameters to produce a super, no-burn, chatter-free process with a short-cycle-time. The customer would say, “Yes, that works great. Thank you. We’ll run it.” And they would, for a few weeks. But when I’d return a year later I’d notice that they were running with the original parameters. Why? Because they didn’t have “ownership” of the technology, and when something changed (the dressing diamond flat became larger, the part size changed), they went back to what they knew. Now I spend three days educating them on the fundamentals of grinding and turn them loose to come up with their own ideas. When I return a year later, I’m amazed at what they’ve accomplished – not just on one machine, but on all their machines

3. Do your homework.

Every time I get into a new type of grinding – be it material type, grinding geometry, dressing type – I spend a few days digging through the literature and find out what others have already done. Some of these articles go back to the 1950s. But they allow me to get my head around the grinding operation much more quickly.

4. It’s ok to say, “I don’t know.”

Early in my career, I felt the need to act as if I knew everything about grinding. As I became more confident in my knowledge, I found it easier to say, “I don’t know.” Nowadays, I say it all the time – without flinching. In fact, I enjoy it when there’s something I don’t know. I have access to all the books and literature and am friendly with most of the other experts. If I come across something tricky, I’ll spend the weekend digging into the literature and making phone calls to find the answer.

5. Respect machine operators, they are the true heroes of the industry.

Most machine operators have no training in grinding. We give them a machine and a blueprint and say, “Here, make this happen.” They have to produce a part within specific tolerances and surface finish without burn and chatter, all with a short cycle time, using a machining process on which they’ve had no formal training. It blows my mind that they are able to pull it off. It’s an art form as much as a technical skill.


I spent my Ph.D. years hearing things like “minimum chip-formation energy based on a nonlinear, multivariable stochastic distribution of asperity heights” and thought: “Do people in the real production world really talk like this?” I quickly learned that the answer is a resounding NO! There are two grinding worlds: the academic world and the real world. When I started working in the real world, I discovered that just about everything I learned in the academic world had no practical application. It was like I was starting all over again. Having said that, I later learned to appreciate how understanding the subject from the bottom up – which I
FINER POINTS  Superabrasive Grinding & Education

6. Acquiring knowledge from others.

I developed my academic understanding of grinding from reading over 400 papers and books, and from spending many hours in the lab. I learned a lot of the fundamentals of the subject, but I still had gaps in my understanding. These gaps were filled in by talking to people in the industry, and from developing an understanding of the root causes of the problems I encountered. It was an ongoing learning process.

5. Some basic lessons.

I did a Ph.D. in grinding and for over 20 years I’ve done nothing but grinding, in a variety of industries and applications. I’ve read hundreds of academic articles and every book ever written on the subject. I’ve spent years camped out on grinding machines. Yet every day I’m overwhelmed by what I don’t know and so I press on ...

---

7. Company culture matters.

Within an hour of setting foot into a company, I get a vibe. And that vibe almost always ends up being right. What’s the general mood of the company? Are the operators going to be cooperative or are they going to resist? Optimistic or defeated? I’ve been to companies where operators and engineers have a healthy skepticism, but are also open-minded and enthusiastic about learning. I’ve been to companies where the management and shop-floor are at war with each other. I’ve been to Company A, and then two weeks later to Company B. Both companies are making the same product with more or less the same machines, wheels and coolants. Months later I hear back from Company A and they’re very satisfied. With what they learned, they’re cutting cycle times, reducing wheel costs and dealing with grinding problems in a scientific way. They’re scheduling a follow-up visit. I then call Company B and am told nothing has changed. Why? It seems to be company culture and attitude.


I did a Ph.D. in grinding and for over 20 years I’ve done nothing but grinding, in a variety of industries and applications. I’ve read hundreds of academic articles and every book ever written on the subject. I’ve spent years camped out on grinding machines. Yet every day I’m overwhelmed by what I don’t know and so I press on ...

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Introduction:
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◆ Stable performance, high precision and control accuracy.
◆ Easy operation and maintenance, quality service.

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Progresses of Grinding Technology of Monocrystalline Silicon Carbide; for Longer Tool Life and Higher Quality Finished Surfaces

In order to accelerate the mass production of SiC power semiconductor devices, which possess a higher performance than Si based power semiconductor devices, lowering the machining cost and obtaining higher-quality finished surfaces in the wafer thinning process are crucial. This paper will introduce the latest progresses of grinding technologies of SiC wafers, which can significantly reduce the machining cost and improve the quality of finished surfaces.

1. Introduction Power Semiconductor Devices and SiC

Due to the growing concern of energy depletion, power semiconductor devices that enable more efficient use of electricity in many fields such as automobiles, trains, and power grids, are gathering more attention and projected to be increasingly prevalent. Currently, the most commonly used material for power semiconductor devices is silicon (Si). However, the performances of Si-based power semiconductor devices have almost reached the limitation of the physical property of Si, and it is said that it cannot meet the forthcoming requirements for power semiconductor devices, e.g., higher operating temperature and voltage resistance. Silicon carbide (SiC), on the other hand, possesses superior physical properties and is considered as a more promising material for next-generation power semiconductor devices. By employing SiC, power semiconductor devices can work in the said severe conditions and reduce the losses of electricity thanks to its high switching performance.

Obstacles in Commercial Use of SiC Power Semiconductor Devices

In spite of said merits of SiC-based power semiconductor devices, SiC is a hard-to-cut material and its wafer fabrication is extremely difficult. Figure 1 shows the SiC wafer fabrication process. Slicing of ingots, thinning by lapping, and Chemical Mechanical Polishing (CMP) are the major processes. Among them, the thinning process by lapping is one of the most costly and time-consuming processes mainly due to following two reasons:

1. Low lapping rate
Because of the hardness of SiC, the lapping rate usually remains a few microns per hour. Therefore, wafer thinning by 100µm, which is the typical removal amount, takes 24 to 48 hours per wafer.

2. Surface roughness and flatness
In order to reduce machining time of CMP, making flat and...
smooth wafers in the lapping process, which is the front-end of CMP, is crucial. However, by its nature of lapping, edges of wafers are primarily machined, causing deterioration of flatness. The reality is that more time is needed in the lapping process to obtain flat wafers. Furthermore, this deterioration in flatness becomes more evident in wafers with larger diameter. Also, scratches are often left on wafers on account of aggregation of ultrafine abrasive grains in the slurry. To remove those scratches, more CMP time is needed. Therefore, an alternative thinning method which can greatly reduce process time and cost is desired.

Grinding - A Better Choice for Machining of SiC Wafers

A.L.M.T. has been working on the development of fixed abrasive grinding wheels for SiC for years in the aim of high-efficiency, low cost, and high-quality finished surfaces in SiC wafer thinning. The proposed wafer thinning consists of 2 steps, i.e., rough grinding and finish grinding. It was proven in the previous study that wafer thinning by fixed abrasive grinding is much faster than the conventional lapping process without deterioration of the flatness of wafers; 240 µm wafer thinning of 3” SiC was done in less than 0.2 hours while Total Thickness Variation (TTV) of the wafer was maintained within 1µm. These achievements paved the way for high productivity in SiC wafer fabrication.

Nevertheless, there are still many challenges to be tackled in this process, and A.L.M.T. has been constantly developing new grinding technologies. In this paper, progresses of grinding technologies of SiC wafers that is expected to accelerate the commercial use of SiC power semiconductor devices are going to be introduced. The next section focuses on the reduction of wear of rough grinding wheels, which will reduce the machining cost of SiC wafers. In the following section, how smoother surface can be obtained by grinding will be discussed. This will also contribute to the reduction of total cost of SiC wafer fabrication. The last section summarizes this study.

2. Reduction of Wheel Wear in Rough Grinding for Cost Reduction

BACKGROUND – One of the major obstacles in SiC wafer fabrication is the considerable machining cost. Since almost 90% of the material removal is done in rough grinding, reducing wheel wear in rough grinding greatly contributes to the lower machining cost. Moreover, the diameter of SiC wafers most commonly used is currently in transition from 4” to 6”. In general, wafer thinning suffers larger grinding force and wheel wear as the diameter of wafers increases. In light of this fact, grinding wheels which can machine 6” SiC wafers cheaply are demanded. Hence, understanding on the machinability of 6” SiC wafers is essential.

In this section rough grinding of both 4” and 6” SiC wafers is performed to demonstrate their machinability. Then, through tests of two newly developed grinding wheels, how wheel wear can be reduced will be discussed.

Method

The schematic of the grinding of monocrystalline SiC wafer is shown in Figure 2. The specifications of the grinding wheels and the conditions of the tests are shown in Table 1. Three grinding wheels, i.e., a conventional grinding wheel which is capable of grinding SiC wafers, and two newly developed wheels, are examined. Among the two newly developed wheels, one has enhanced retention of abrasive grains by optimizing the compounding ratio of diamond superabrasive and vitrified bond, namely ‘high-retention’. The other one, namely ‘micro-fracture’, is intended to fracture the surface of the grinding wheel more minutely than the conventional wheel. For the convenience of following discussions, each combination of wafer diameter and wheel is abbreviated as shown in Table 2.

In the test, normal grinding force and wear ratio are evaluated. Wear ratio and grinding ratio are defined as:

\[
\text{wear ratio} = \frac{\text{(the wheel wear in thickness)}}{\text{(the removal of wafer in thickness)}}
\]

![Figure 2: Schematic of Machining Process by Rotary Type Grinder](image)

Table 1: Conditions of Tests (rough grinding)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Surface Grinding Machine (rotary type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel Size</td>
<td>Φ300-3W</td>
</tr>
<tr>
<td>Wheel Specifications</td>
<td></td>
</tr>
<tr>
<td>Diamond Size</td>
<td>2000</td>
</tr>
<tr>
<td>Diamond Size (µm)</td>
<td>9</td>
</tr>
<tr>
<td>Concentration</td>
<td>160</td>
</tr>
<tr>
<td>Bond</td>
<td>Vitrified</td>
</tr>
<tr>
<td>Workpiece</td>
<td>4 &amp; 6 Inch Monocrystalline SiC (Si-face)</td>
</tr>
<tr>
<td>Pre-Ground Surface</td>
<td>Polished</td>
</tr>
<tr>
<td>Wheel Speed (m/min)</td>
<td>1320</td>
</tr>
<tr>
<td>In-Feed Rate (µm/min)</td>
<td>24</td>
</tr>
<tr>
<td>Removal Stock (µm)</td>
<td>30, 60</td>
</tr>
<tr>
<td>Table Speed (min⁻¹)</td>
<td>400</td>
</tr>
<tr>
<td>Spark Out (sec)</td>
<td>5</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
</tr>
</tbody>
</table>

![Figure 1: Comparison of Process Time](image)
Therefore, a smaller wear ratio indicates that the grinding wheel has a longer tool life.

**Results and Discussion**

<table>
<thead>
<tr>
<th>Table 2: Grinding Systems and Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer Diameter</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>4”</td>
</tr>
<tr>
<td>6”</td>
</tr>
<tr>
<td>6”</td>
</tr>
<tr>
<td>6”</td>
</tr>
</tbody>
</table>

First, 4”-conv and 6”-conv were tested. The results are shown in Table 2. In the table, data are shown as relative value with the average of 4”-conv being 1. The normal grinding force of 6”-conv increased by 2.4 times compared to those of 4”-conv. This is directly attributed to the 1.5 times larger area of contact between the wafer and the grinding wheel than that of the grinding of the 4”. Because of this larger area of contact, the force exerted to each abrasive grain disperses making the depth of each cutting abrasive smaller. As a consequence, the grinding process becomes more like rubbing. Similarly, the 2.6 times larger wear of 6”-conv can be also explained by the depth of each cutting abrasive. Because the process is more like rubbing, each abrasive grain attrits and comes off by a self-dressing effect without cutting the workpieces. Lastly, while the normal grinding force of 4”-conv is almost constant (not shown here), that of 6”-conv increased monotonically at first and decreased suddenly at workpiece no.7 as shown in Figure 3. This sharp fall of normal grinding force indicates a large fracture of wheel surface. It is considered that the retention of abrasive grains is not optimal. From those results, the lower machinability of 6” SiC wafers is simply understood.

<table>
<thead>
<tr>
<th>Table 3: Performances of Each Grinding Wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>4”-conv</td>
</tr>
<tr>
<td>6”-conv</td>
</tr>
<tr>
<td>6”-retention</td>
</tr>
<tr>
<td>6”-micro</td>
</tr>
</tbody>
</table>

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- Diamond on Silicon
- Diamond on GaN
- Diamond on Silicon Carbide
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New Orleans has many visitor attractions, from the world-renowned French Quarter; to St. Charles Avenue, (home of Tulane and Loyola Universities, the historic Pontchartrain Hotel, and many 19th-century mansions); to Magazine Street, with its boutique stores and antique shops. According to current travel guides, New Orleans is one of the top ten most-visited cities in the United States. A recent poll of “America’s Favorite Cities” ranked New Orleans first in ten categories, the most first-place rankings of the 30 cities included. According to the poll, New Orleans is the best U.S. city as a destination and for stylish boutique hotels, cocktail hours, singles/bar scenes, live music/concerts and bands, antique and vintage shops, cafes/coffee bars, neighborhood restaurants, and people watching. The city also ranked second for friendliness, hotels/inns, and ethnic food. The French Quarter (known locally as “the Quarter” or Vieux Carré), which was the colonial-era city and is bounded by the Mississippi River, Rampart Street, Canal Street, and Esplanade Avenue, contains many popular hotels, bars, and nightclubs. Notable tourist attractions in the Quarter include Bourbon Street, Jackson Square, St. Louis Cathedral, the French Market (including Café du Monde, famous for café au lait and beignets), and Preservation Hall. Also in the French Quarter is the old New Orleans Mint, a former branch of the United States Mint which now operates as a museum, and The Historic New Orleans Collection, a museum and research center housing art and artifacts relating to the history of New Orleans and the Gulf South. To tour the port, one can ride the Natchez, an authentic steamboat with a calliope, which cruises the Mississippi the length of the city twice daily. Unlike most other places in the United States, the city’s historic cemeteries and their distinct above-ground tombs are attractions in themselves, the oldest and most famous of which, Saint Louis Cemetery, greatly resembles Père Lachaise Cemetery in Paris. The city and area boosts numerous museums and attractions of major interest and historical value. New Orleans ranked No. 7 on Newsmax magazine’s list of the "Top 25 Most Uniquely American Cities and Towns," a piece written by current CBS News travel editor Peter Greenberg. In determining his ranking, Greenberg cited the city’s rebuilding effort post-Katrina as well as its mission to become eco-friendly. The New Orleans area is home to numerous celebrations, the most popular of which is Carnival, often referred to as Mardi Gras. Carnival officially begins on the Feast of the Epiphany, also known as the “Twelfth Night”. Mardi Gras (French for “Fat Tuesday”), the final and grandest day of festivities, is the last Tuesday before the Catholic liturgical season of Lent, which commences on Ash Wednesday. The largest of the city’s many music festivals is the New Orleans Jazz & Heritage Festival. Commonly referred to simply as ‘Jazz Fest’, it is one of the largest music festivals in the nation, featuring crowds of people from all over the world, coming to experience music, food, arts, and crafts.
In order to reduce both normal grinding force and wear, grinding of 6” SiC wafers by two newly developed grinding wheels is examined. The results are shown in Table 2 and Figure 3. First, the high-retention wheel, which is intended to reduce the wear by retaining the abrasive grains more solidly, ended up in divergence of normal grinding force and crack of machined wafers. It is considered that the retention of abrasives was too strong for attired abrasive grains to come off, leading to an excessive number of effective cutting edges. On the other hand, the micro-fracture wheel, which is designed to fracture the surface of the wheel more minutely, succeeded in reducing the normal grinding force to 75% with respect to 6”-conv. Additionally, the normal grinding force of the 6”-micro fluctuates little upon increase of number of ground workpieces, which is desirable for mass production. Also the wear of 6”-micro was reduced to 30% of 6”-conv. It is noteworthy that 6”-micro has even smaller wear than 4”-conv. These results indicate that maintaining sharp edges of abrasive grains on the surface of grinding wheel by prompting minute fractures is effective to extend the tool life and reduce grinding force in 6” SiC wafer grinding.

Summary

In this section, the machinabilities of 4” and 6” SiC wafers were examined. By the conventional wheel, the wear of 6” SiC wafers increased by 2.4 times, showing low machinability of 6” SiC. However, it was understood that the wheel wear and grinding force can be reduced to a great extent by optimizing the fracture scale of the grinding wheel. In this study, the wear was reduced to one third, indicating the machining cost can also be reduced to one third. This will significantly reduce the machining cost of SiC wafers. Also, further improvements in efficiency can also be expected by optimizing the ability.

3. Newly Developed Wheel for Finish Grinding

BACKGROUND - In the last section, the developments of rough grinding wheel are reviewed from the view point of cost reduction through the extension of tool life. However, obtaining a smooth and flat finished surface can also contribute to the reduction of total machining cost. Thus, demands on finish grinding are also increasing. In this section, progresses of finish grinding are going to be introduced.

So far, only surface roughness and flatness of finished SiC wafers are entirely focused. This is because a smoother surface is more advantageous to reduce the time of CMP, in which Ra=0.1 µm is typically required. Similarly, because wafers need to be evenly polished in CMP, flat wafers are preferred. Thus, smooth and flat wafers help the reduction of CMP time, and consequently reduce the total machining time and cost. Roughness and flatness of wafers are still important evaluation indices.

On the other hand, recent studies suggest a possibility that defects, including strains on wafer surface introduced in the machining process, are often not removed completely even after CMP. This may deteriorate the quality of the epitaxial layer, which lowers the performances of SiC devices. However, whichever machining process is causing those defects is not understood well.

In this section, the latest finish grinding technologies are introduced. Finish grinding with different diameters of ultrafine diamond superabrasives is performed first. Next, the strain of each wafer, as well as measurements done before e.g., surface roughness and flatness, are evaluated. By comparing them to those of lapped wafers, finish grinding is characterized. Finally, how the yield rate of SiC wafer fabrication can be increased is proposed.

Method

In the following, D50 denotes the median diameter of diamond superabrasive. The grinding conditions are shown in table 4. In this section, 3” SiC wafers are used as workpieces. Diamond abrasives (D50 = 0.5, 0.3 and 0.1 µm) are employed in grinding wheels. These grinding wheels employ a special dispersing technique to avoid the aggregation of ultrafine diamond abrasives. Two wafers for comparison provided by cooperative groups are also evaluated; one was lapped by 0.1µm diamond powder and the other was polished by 0.5µm diamond powder. In the test, cooperative groups are also evaluated; one was lapped by 0.1µm diamond powder and the other was polished by 0.5µm diamond powder. In the test, surface roughness, Transmission Electron Microscopy (TEM) images, and strain of wafer surfaces are evaluated. The surface roughness and strain of the wafer surface are measured by optical surface profiler and Electron Back Scattering Diffraction (EBSD), respectively. Note that those measurements are not done to all samples due to limited resources.

Table 4: Conditions of Tests (finish grinding)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Surface Grinding Machine (rotary type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel Specifications</td>
<td>Wheel Size: 6”300-3W</td>
</tr>
<tr>
<td></td>
<td>Diamond Size (µm)</td>
</tr>
<tr>
<td></td>
<td>Bond</td>
</tr>
<tr>
<td></td>
<td>Vitrified</td>
</tr>
<tr>
<td>Workpiece</td>
<td>3 Inch Monocrystalline SiC (Siface)</td>
</tr>
<tr>
<td>Pre-Ground Surface</td>
<td>#2000 or #8000</td>
</tr>
<tr>
<td>Wheel Speed (m/min)</td>
<td>1225</td>
</tr>
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<td>In-Feed Rate (µm/min)</td>
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</tr>
<tr>
<td>Removal Stock (µm)</td>
<td>10</td>
</tr>
<tr>
<td>Table Speed (min⁻¹)</td>
<td>400</td>
</tr>
<tr>
<td>Spark Out (sec)</td>
<td>5</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
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</table>

Results and Discussions

The results are shown in Table 5. First grinding of SiC wafers (pre-ground #2000) was possible for D50=0.5 and 0.3 µm wheels. In contrast, that of D50=0.1µm wheel was obtained via #8000 (D50=0.5µm) surface. All machining processes with removal stock of 10 µm took only a few minutes, and much higher efficiency than lapping was also confirmed in finish grinding. TTV of all ground wafers were within 1 µm.

Comparing the surface roughness between grinding and lapping, 3 dimensional roughness (Sa) of the lapped
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<th>Frequency</th>
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<th>4X</th>
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</thead>
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<td>$3800</td>
<td>$3270</td>
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<tr>
<td>Full-page, 7-1/2&quot;W x 10&quot;H, Black/2nd Color</td>
<td>$3270</td>
<td>$2750</td>
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<td>$2820</td>
<td>$2560</td>
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<tr>
<td>Half-page, 5&quot;W x 7-1/2&quot;H, Four Color</td>
<td>$2230</td>
<td>$1960</td>
</tr>
<tr>
<td>Half-page, 7-1/2&quot;W x 5&quot;H, Four Color</td>
<td>$2230</td>
<td>$1960</td>
</tr>
<tr>
<td>Half-page, Either Size, Black/2nd Color</td>
<td>$1960</td>
<td>$1710</td>
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<tr>
<td>Half-page, Black &amp; White</td>
<td>$1710</td>
<td>$1580</td>
</tr>
<tr>
<td>1/3 page, 2-3/8&quot;W x 10&quot;H, 4 Color</td>
<td>$1840</td>
<td>$1710</td>
</tr>
<tr>
<td>1/3 page, 2-3/8&quot;W x 10&quot;H, B &amp; W</td>
<td>$1710</td>
<td>$1580</td>
</tr>
<tr>
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<td>$1580</td>
<td>$1440</td>
</tr>
<tr>
<td>1/4 page, 4-3/4&quot;W x 4-3/4&quot;H, B &amp; W</td>
<td>$1440</td>
<td>$1360</td>
</tr>
<tr>
<td>Back Cover, Full-page, 4 Color Only</td>
<td>4X Only</td>
<td>$5380</td>
</tr>
<tr>
<td>Inside Front Cover, Full-page, 4 Color Only</td>
<td>4X Only</td>
<td>$5100</td>
</tr>
<tr>
<td>Inside Back Cover, Full-page, 4 Color Only</td>
<td>4X Only</td>
<td>$4980</td>
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- PAGE SELECTION $175 additional charge____
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- $170 - non-members _________ All 2-1/4"W x 2-1/4"H

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<tr>
<th>Issue:</th>
<th>Editorial Feature*:</th>
<th>Closing</th>
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<tr>
<td>Summer 2017</td>
<td>INTERTECH 2017 Review &amp; Paper Synopsis</td>
<td>June 1, 2017</td>
</tr>
<tr>
<td>Fall 2017</td>
<td>Superabrasives Grinding &amp; Education</td>
<td>Sept. 1, 2017</td>
</tr>
<tr>
<td>Spring 2018</td>
<td>New Technology and Applications</td>
<td>Mar. 1, 2018</td>
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<tr>
<td>Summer 2018</td>
<td>Machine Tools &amp; IMTS Preview</td>
<td>June 1, 2018</td>
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*Editorial topics & closings subject to change

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Provide names of principle officers or partners: __________________________________________

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FINER POINTS
Superabrasive Grinding & Education
Surface is inferior even to that of the D50=0.5 µm grinding as far as is confirmed. Similarly, TEM images reveal that the depth of the damaged layer of the lapped wafer (D50=0.1µm) is larger than that of the grinding (D50=0.5µm). These results are likely caused by an aggregation of ultrafine diamond powder in the abrasive slurry. On the other hand, thanks to the special dispersion technique, it doesn’t occur in ground wafers. Furthermore, clear damages are hardly found on the wafer ground by a wheel with D50=0.1µm. This damage-free grinding technique can be applied to SiC device thinning, where wafers are expected to be thinned to less than 100µm and cracks of thinned wafers frequently occur.

From the results of EBSD, it is clarified that both grinding and polishing resulted in compressive strains on the wafer surface. The depth of strain on the wafer ground by the D50=0.5µm wheel was 3 to 4µm at best, which is not comparable to that of the polished wafer (around 2µm). However, while the strains on ground wafers are uniform in depth and spread evenly, some localized and deep strains are observed on polished wafers. This fact may lead to a conclusion that grinding has potential to reduce CMP time more. This is because the total removal of CMP should be set to remove the deepest strain.

SEM observations shown in Figure 4 reaffirmed the above. On ground wafers, geometric patterns or grinding mark are present, and they look uniform in depth. On the other hand, the polished wafer has random patterns and looks smooth on first glance. However, the presence of deep and localized scratches is apparent. This is assumed to correspond to the deep strain observed in EBSD. Note that those scratches are commonly seen regardless of fields of SEM.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Grinding</th>
<th>Lapping</th>
<th>Polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Ground</td>
<td>Grinding #2000</td>
<td>Grinding #8000</td>
<td>Lapping (D50=1.0µm)</td>
</tr>
<tr>
<td>In-Feed Rate (µm/min)</td>
<td>20</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Removal Stock (µm)</td>
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<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Process Time (min)</td>
<td>1-2</td>
<td>1-2</td>
<td>2</td>
</tr>
<tr>
<td>Surface Roughness Sa (nm)</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
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| Cross Sectional TEM Image (x200,000) |  |
| Depth of Residual Strain (µm) | 4-6 | 3-4 | – | – | 2-3 |
Summary

In this section, finish grinding of SiC wafers with various diamond abrasive diameters was performed, and the qualities of the wafer surface were evaluated. It was shown that smoother and overwhelmingly more efficient thinning than the conventional lapping process is possible by grinding. Also, by applying a proper dispersion technique, grinding can reduce damages on wafer surfaces over lapping. The average depth of strain on ground wafers was not comparable to that of polished wafers. However, uniform strain and scratch-free features of grinding may be preferred in mass production.

4. Conclusion

Studies were made to overcome the obstacles lying in the SiC wafer thinning process and the following is understood:

1. As wafer diameter transitions to 6", the machinability becomes greatly more difficult.
2. By applying newly developed grinding wheels that are designed to prompt the minute fractures of the wheel surface, the wear of rough grinding wheels and consequently the machining cost of SiC wafers can be reduced significantly.
3. Roughness and depth of the damages on finish ground wafers are smaller than that of lapped wafers.
4. Average strains on ground wafers are deeper than that on lapped wafer. However, uniform strains of ground wafers may work better. Yet further detailed analysis is required.

These progresses in machining of SiC wafers are expected to further accelerate SiC device industries and contribute to a more ecological society.

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