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TECH NOTES

Precision Cutting - The Science of the Cut

By: Andrea Johnson, Don Fisher, & George Vander Voort

Introduction

Metallographic studies usually require parts to be sectioned, a destructive technique that is often unavoidable. Sectioning, the first step in the metallographic preparation procedure, produces a damaged layer; the extent of this damage is a function of the sectioning technique and machine chosen, the material being cut, the nature of the "wheel" or blade selected (abrasive type, size and size distribution, bonding agent, thickness, etc.), and the cutting parameters utilized (feed rate, rpm of blade, coolant flow, etc.). Machine shop cutting procedures produce substantial damage. Power hack saws, band saws, and shop abrasive saws (generally run without a coolant) are very aggressive sectioning devices that generate considerable damage at the cut interface. Likewise, metal shears also produce substantial damage. This damage must be removed if we are to see the true microstructure.

Laboratory sectioning devices produce less damage than machine shop devices, when properly used. There are essentially two types of laboratory cutting devices used by metallographers. The first is the abrasive cutter, generally using consumable "wheels" made of SiC or Al2O3 abrasives. Wheel diameters range from about 9 to 14 inch (229 – 356mm); laboratory style cutters with larger diameter wheels (up to 18 inch/457mm diameter) exist, but they are generally used outside the laboratory due to their large physical size. The second device is the lowspeed saw which has evolved over the last 30 years into the precision saw. The original ISOMET low-speed saw, which is still made, although in a third generation model, has a maximum speed of 300 rpm and uses gravity feeding. The current "top of the line" ISOMET 5000 saw has a maximum speed of 5000 rpm and uses linear feeding, along with other options, such as automated dressing of the blade and automated serial cutting. These saws use both non-consumable and consumable blades. The former utilize diamond or cubic boron nitride abrasives while the latter utilize SiC or Al2O3 abrasives.

Precision sectioning, the topic of this Tech- Note, is used when the cutting damage and "kerf " loss (the material removed during sectioning, roughly equal to the blade width) must be minimized, or the specimen must be sectioned at an exact location, or when the specimen is fragile or friable. The surface finish is also better than that produced by other cutting methods. Thus, the steps following precision sectioning do not require use of excessively coarse abrasives to remove the minor damage produced during precision sectioning.

This Tech-Note provides the reader with a background on the machines available, the blades available and their proper application, sectioning variables that must be controlled, and the important role of the coolant. The goal is to help the user obtain more consistent, higher quality cuts in minimal time.

Wafering Blades

The choice of wafering blade is the first and perhaps most important decision that needs to be made in the precision cutting procedure. There are several types of blades for precision cutting: metal-bonded diamond, metal-bonded cubic boron nitride, and abrasive blades. The most popular is the metal-bonded diamond blade. This blade has a steel core that is plated to minimize corrosion. The diamond is held in a sintered alloy composite which is brazed to the edge of

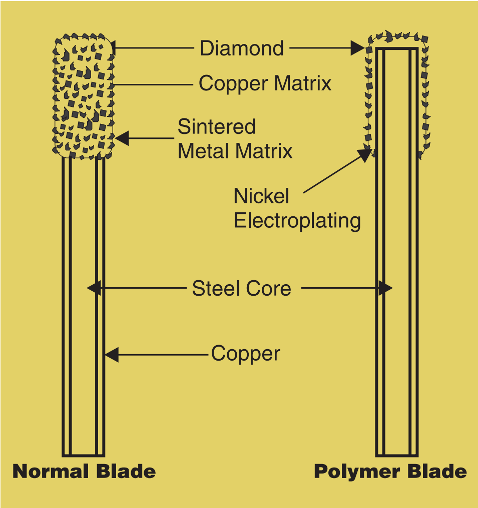

Figure 1: Cross section diagram of a Normal Wafering Blade and a Polymer Blade

the blade as shown in Figure 1. The diamond permeates the sintered metal matrix so that if diamond is pulled out during sectioning, fresh diamond will be exposed by dressing the blade. There are two different types of metal-bonded blades. One is made for general sectioning of materials; the other is made specifically for polymers. The blade for polymers is nickel plated with diamond only on the very surface of the blade, also shown in Figure 1. This specific design exposes a larger surface area of each diamond allowing it to cut more aggressively. This same production method does not work for other metal-bonded diamond blades because of the relative hardnesses of the sample and the metal matrix that holds the diamond. If this method was employed for non-polymer blades, the life of the blade would be dramatically reduced.

Another blade for cutting hard alloys is called the ISOCUT® blade. The ISOCUT blade, utilizing cubic boron nitride (CBN) abrasive, is very useful for cutting hard metals, particularly iron and steel. This is because the carbon in steel reacts with the carbon in diamond, quickly dulling the diamond cutting surface and slowing the material removal. Cubic boron nitride blades give significantly reduced cutting

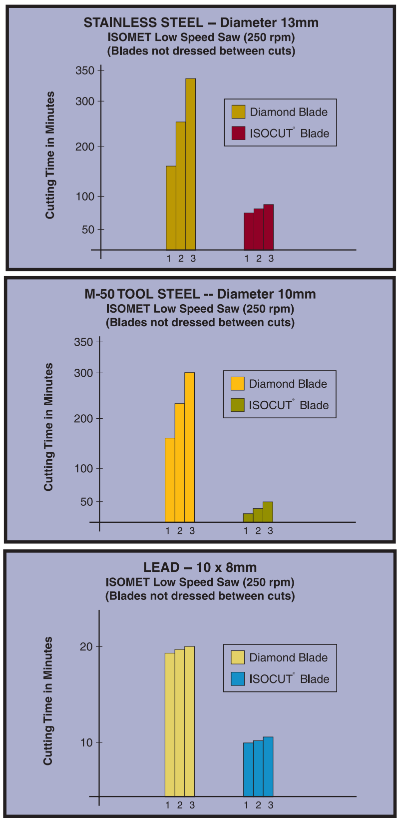

Figure 2. "Super-pure" aluminum electrolytically etched with Barker's reagent and viewed with polarized light plus a sensitive tint filter revealing an equiaxed, recrystallized grain structure. There are some fine impurity precipitates in this specimen, however, that cannot be seen with this etch and magnification (50x).

times for tough, gummy materials, such as lead and titanium, but are not recommended for ceramics or non-metals. Figures 2a, b and c reveal reduced cutting times for stainless steel, M-50 tool steel and lead using an ISOCUT blade as cut on the ISOMET® Low Speed Saw at 250 rpm. This is the simplest, least expensive saw in the ISOMET family.

Metal-bonded diamond blades are available with either high or low diamond concentrations and with a variety of particle sizes. High-concentration diamond blades are recommended for cutting metals and polymers – ductile materials – cut by a ploughing mechanism. The diamonds plough through the sample and work hardened strips of material become brittle and break off. Therefore, it follows that the greater the number of diamonds by volume, the quicker the resulting cut will be. Increasing the number of diamonds also lowers the per unit force. For a metal where it is possible to induce deep deformation layers, a lower per unit force is desirable to reduce the deformation produced during the cut. In addition, it is necessary to consider the type of metal being sectioned as there are several different high concentration blades supplied by Buehler that are metal specific (see selection guide shown in Table 1).

Although it may appear to be intuitively wrong to offer blades with a low diamond concentration, there is justification as a different cutting mechanism results when sectioning ceramic materials – brittle materials – cut via a fracture process. With a reduced diamond concentration, the pressure on each diamond contacting the ceramic is higher which yields enough stress to chip off small flakes in the cut.

Besides the high or low diamond concentration, blades are made using a variety of mean diamond particle sizes, using an arbitrary scale from 5 (finest) to 30 (coarsest). These numbers do not directly correspond to a linear scale such as microns. A blade with a rating of 10 will have larger abrasive particles than one with a rating of 5,

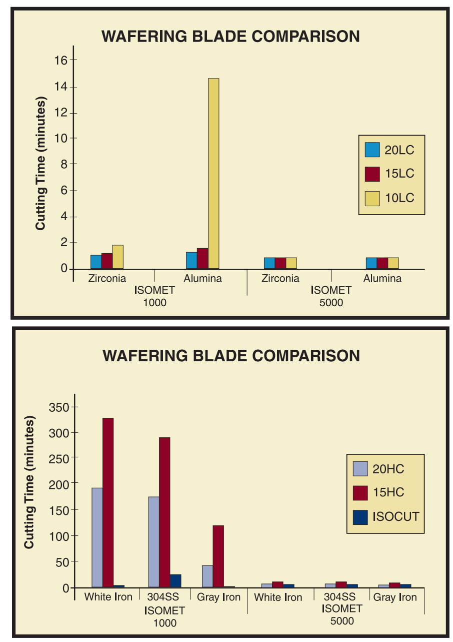

Figure 3a and b: Cutting times for ceramic (3a) and ferrous metals (3b) using the ISOMET® 1000 saw and the ISOMET® 5000 linear precision saw with different blades. See text for cutting parameters used.

yet they are not necessarily twice as large. A general rule for cutting is the smaller the abrasive, the lower the resulting deformation. However, this statement must be tempered with the consideration of the material being sectioned. Some materials require a larger abrasive to be cut effectively. Using a smaller abrasive would result in ineffective cutting action, increased deformation and excessive cutting times.

The other main class of blade types is precision abrasive cutoff wheels. Precision abrasive cut-off wheels are commonly used for metal samples. Frequently these wheels give shorter cutting times and provide good surface finishes. The drawbacks to abrasive cut-off wheels are that they have a significantly shorter life and are less versatile than precision diamond blades. The minimum effective speed for a laboratory type wet abrasive cutter is 1500 rpm. Although still a practical choice for precision cutting, the abrasive blades do cause more kerf loss than a metal-bonded wafering blade and for some materials, can produce more deformation. A general rule for cutting is the thinner the blade, either abrasive or metalbonded, the lower the resulting cutting deformation. Larger diameter blades cut larger specimens and generally cut faster than smaller blades. However, the thickness of the blade increases as the diameter increases, so deformation can increase for a given abrasive size. If the larger diameter blade is too thick, cutting rates can be reduced due to the decrease in unit force.

An experiment was conducted to demonstrate the difference between cutting with the ISOMET 1000 Saw, a gravity-loaded machine, and the ISOMET 5000 Saw, with linear feeding. The ISOMET 1000 Saw has a smaller motor and a maximum of 1000 rpm while the ISOMET 5000 (and 4000) Saw has a motor with much greater horsepower and a maximum of 5000 rpm. Zirconia, alumina, white cast iron, gray cast iron and type 304 austenitic stainless steel were sectioned using 7 inch (178mm) diameter wafering blades. For the ceramic specimens, we used 10LC, 15LC and 20LC blades; for the iron-based alloys, we used 15HC, 20HC and the ISOCUT blade. For the cuts made with the ISOMET 1000 Saw, a 400 g load and 700 rpm were used for the ceramics, while an 800 g load and 850 rpm were used to cut the iron-based alloys. For the ISOMET 5000 Saw, all cuts were made at 3200 rpm. The feed rate was set to the maximum value possible before the SMARTCUT™ sensor cut in to reduce the feed rate. This gave feed rates of 0.12 inch/ min, 0.15 inch/min. and 0.18 inch/min. (3.0, 3.8 and 4.6mm/ min.) for the 15HC, 20HC and the ISOCUT blades, respectively. In the case of the ceramic specimens, the Smartcut system did not come on, even at the maximum feed rate of 0.75 inch/min., so that feed rate was chosen. The metal specimens were 0.625 inch (15.9mm) in diameter and the ceramic specimens were 0.5 inch (12.7mm) in diameter. Five cuts were made for each material and condition and the time required to cut through each piece was recorded and averaged.

Figure 3a shows the results for the two ceramic materials. Note that the ISOMET 5000 Saw, with its greater horsepower, cut through each specimen in slightly less than 40 seconds (0.75 inch/min. for a 0.5 inch diameter piece), regardless of which blade was used. For the cuts made with the lower power ISOMET 1000 Saw, the times were fairly good, except for the 10LC blade on the alumina specimen, more difficult to cut than zirconia. As expected, the 20LC cut the fastest and the 10LC cut the slowest. However, the surface finish quality has the reverse trend, best for the 10LC and poorest for the 20LC. But, the surface finish differences were quite minor.

Figure 3b shows the results for the iron-based alloys. White cast iron is rather hard as it contains substantial primary cementite. Gray iron is quite easy to machine due to the substantial amount of graphite present. Austenitic stainless steels, such as 304, are not hard, but they are tough, gummy metals, rather difficult to machine. Again, we see the same clear differences in cutting time between the higher horsepower ISOMET 5000 Saw and the lower horsepower ISOMET 1000 Saw. With the cutting rates chosen, the ISOMET 5000 Saw should cut through these 0.625 inch diameter specimens in 3.5 to 5.2 minutes, and it did. On the other hand, cutting with the lower horsepower ISOMET 1000 Saw, using gravity loading with 800 g, revealed a substantial difference in cutting time between materials and for the three blades chosen. The vast superiority of the ISOCUT blade is demonstrated for all three cases; indeed, it cut through two of the three alloys faster on the ISOMET 1000 Saw than on the higher horsepower ISOMET 5000 Saw! In the case of the white iron and gray iron, the ISOCUT blade cuts more freely in the gravity-fed saw and actually cut faster than the linear-precision saw that has an upper limit to the feed rate, or a protective circuit, such as the SMARTCUT system, that protects the saw from overloading. However, the cut times with the ISOCUT blade for the iron specimens were fairly similar, regardless of the saw. The ISOMET 5000 Saw cut the gummy 304 stainless steel specimen substantially faster than the ISOMET 1000 Saw, due to its greater horsepower.

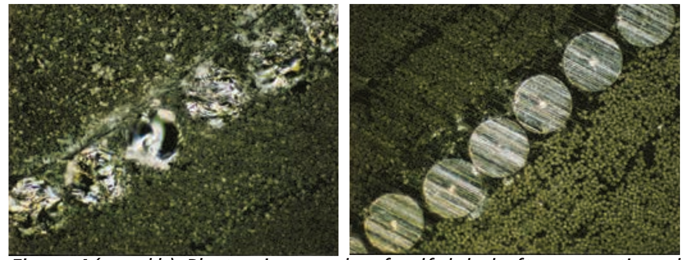

Figure 4 (a and b): Photomicrographs of golf club shaft cross-sectioned with (a) Series 15 and (b) Series 10 blades. Figure 4a reveals significant damage while Figure 4b illustrates undamaged fibers and matrix. Boron fibers. Darkfield, 100x.

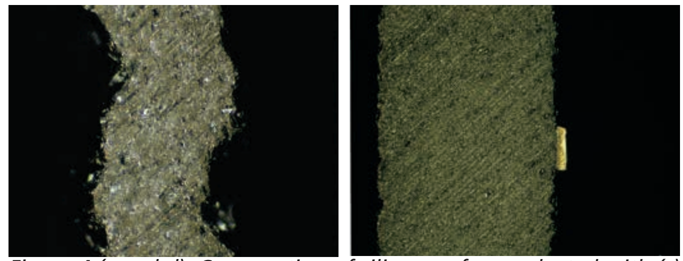

Figure 4 (c and d): Cross section of silicon wafer conducted with (c) Series 15 and (d) Series 10 blades. Figure 4c shows severe fracture of the silicon and microcircuitry. Figure 4d's silicon wafer and microcircuitry is intact. Darkfield, 200x.

It is interesting to note that both saws cut the ceramic specimens faster than the metals. Diamond is a more effective cutting abrasive for ceramics than for metals, particularly iron-based metals. In the latter case, the advantage of cubic boron nitride abrasive in the ISOCUT blade, over diamond, was well demonstrated.

Although linear feed and higher blade speeds reduce differences in cutting times for most materials, some materials are less forgiving of improper blade choice. An example of this would be boron fiber composites or silicon which can be cracked by use of an improper blade. Figure 4 shows the effects of blade choice on a boron fiber composite golf club shaft and a silicon wafer as cut on the ISOMET 2000.

Sectioning Parameters

The type of blade loading (gravity or linear feed), the blade speed (rpm), and the position of the specimen with respect to its contact area (Figure 5), are important parameters that must be optimized for any chosen blade. Precision saws should be chosen with specific applications in mind. Issues that need to be considered when choosing a saw include the type of materials sectioned, sample sizes, and desired throughput. The most versatile and powerful precision saws that Buehler produces are the ISOMET 4000 and 5000 Linear Precision Saws. These saws have a more powerful motor, a larger cutting area, and more advanced software than earlier models. They can cut samples up to 2 inches (50mm) in diameter and are designed to accommodate much larger pieces than previous saws. While these saws have a large cutting envelope, they are still precision cutters. If you are cutting a 2 inch (50mm) diameter thin-walled cylinder, that is acceptable. If you wish to cut a 2 inch (50mm) diameter piece of solid stock, then a larger abrasive cutter is required. All operating parameters are easy to set with a user-friendly software interface. Blade speed ranges from 200 to 5000 rpm with a linear feed control. If the saw cannot cut at the feed rate set by the operator, the Smartcut feature automatically adjusts the feed rate until cutting is possible. SMARTCUT is designed to protect the motor, sample, and blade.

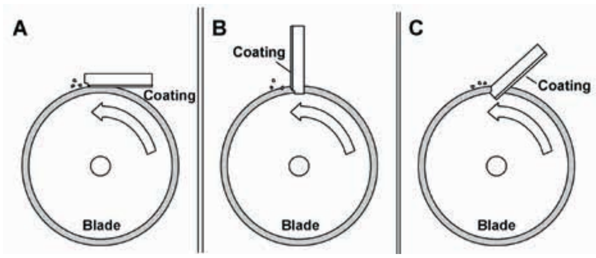

Figure 5: A) Incorrect positioning as the coating is not in compression through the entire contact arc and the sample presents a large contact area to the blade. B) Incorrect specimen positioning because the coating is in tension. C) Correct positioning, coating is in compression and presents small contact area.

Typically, increasing the load and blade speed decreases the cut time. Positioning the sample such that the minimum amount of surface area is in contact with the blade also reduces cut time. One should be careful not to fall into the trap of thinking that the heaviest load and highest speed will necessarily yield the fastest cut. For some materials, the use of extremely high blade speeds and loads or feed rates may increase the force of the diamond particles to such an extent that cutting-induced damage becomes excessive.

For some specimens, an example being coated specimens, the positioning of the specimen relative to the blade can have a very significant effect on cut quality. For coated specimens, position the piece so that the coated side is cut first, rather than last. This keeps the stresses on the coating compressive rather than tensile. If the piece is reversed, so that cutting begins on the substrate side and the cut ends on the coated side, the coating may be damaged by the resulting tensile stresses. The coating can be separated from the substrate in severe cases. Figure 5 illustrates two less obvious coated specimen-blade configurations that can produce damage to the coating, plus longer cut times, and a properly positioned specimen. Applications such as silicon wafers with circuitry or thermal spray coatings are good examples of parts where sample orientation and cutting in compression are especially important. Minimizing the area of contact with the blade is also important for fast, efficient cutting.

Coolant Care

The condition of the coolant is an often overlooked variable in obtaining consistent cutting results, high quality surfaces and good blade life. Recirculating tanks receive very little attention in the laboratory environment, allowing the coolant concentration to fall, the hardness of the water to increase, and the overall effectiveness of the coolant to fall off drastically. The role of the coolant is to lubricate the blade/specimen interface, carry away the heat generated during cutting, flush away swarf, and leave a corrosion inhibiting film on the cutter and the specimen. To get the most from cutter and blades, close attention should be paid to the following: quality of the water; coolant concentration; and maintenance of the coolant tank. The coolant should receive the same attention as other variables, such as blade selection and feed rate.

Different geographic areas have different water hardnesses. Water

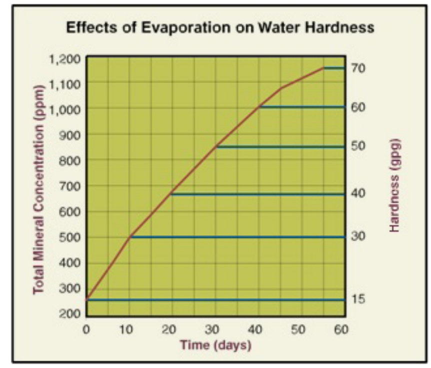

Figure 6: Illustrates normal plant water that initially had only 15 grains per gallon (gpg) but can double its hardness to 30 gpg in only ten days due to normal evaporation. By day forty, the water hardness has quadrupled.

containing less than six grains of dissolved minerals per gallon is considered soft water; water containing more than seventeen grains per gallon is considered hard. The best water to use in a coolant system is chemically pure water, which is free of all dissolved solids. Chemically pure water can be obtained by three methods: distillation, deionization and reverse osmosis. Reverse osmosis is the method most recommended by coolant manufacturers, but is not readily available. Deionized water offers much improvement over available plant water.

It is important to realize that as the water in the tank evaporates, the remaining water becomes harder (see Figure 6). Hard water affects coolant capabilities in many ways: decreased capability of the rust inhibitor, increased foaming, formation of a sticky residue (see Figure 7), and increased bacteria counts.

Coolant concentration should be controlled and maintained to ensure that the coolant is being used at optimum efficiency. Too little coolant in the tank will lead to corrosion and rancidity, while too rich of a concentration can also cause foaming.

Maintenance of the recirculating tank is also critical to coolant performance. Cleaning the tank is a dirty job, but if done often enough and thoroughly, it can increase the performance of your precision cutter. Keeping the coolant tank clean will ensure that you are getting the most from your coolant, keeping corrosion and bacteria growth at bay while providing the necessary cooling, lubrication and protection to your blades and specimens.

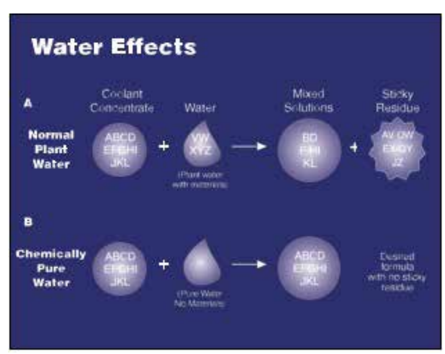

Figure 7: A) With normal plant water, the minerals combine with critical elements in the coolant concentrate to form a sticky residue, and result in reduced rust inhibition, increased foaming, and increased bacteria counts. B) Chemically pure water without minerals gives the desired protective formulation with no sticky residue.

Conclusion

Sectioning is a critical step in specimen preparation; inability to observe the true structure after preparation is often traced to failure to remove all the cutting damage. The low-speed saw and the precision saw produce the lowest amount of sectioning damage and minimal kerf loss. Hence, they are important tools of the metallographer, depending upon the nature of the materials they study. Set up, blade selection, feed rate and coolant flow are important variables to control, as demonstrated in this Tech-Note.

Tech-Tips

Question: How does Smartcut work on the ISOMET 4000 and 5000 saws?

Answer: Smartcut is a proprietary Buehler software that monitors the load on the motor. With Smartcut, you are able to set the feed rate to any desired value and it will cut continuously at that value unless it exceeds the recommended motor amperage. If the motor amperage is exceeded then Smartcut will back off the feed rate until the amperage is within the recommended values. Smartcut provides an easy means to ensure that you cut your sample all the way through every time without stalling -- even if you don't know an initial feed rate to try. Smartcut protects your motor, specimen and gives you more effective cutting.

Question: Can I set the feed rate at maximum and allow Smartcut to control the feed rate so I can achieve a faster cut time?

Answer: With the exception of some very soft materials, setting the feed rate at the maximum setting is not advisable to give reduced cut times. Using higher speeds, and feed rates, results in faster cutting. Ferrous and non-ferrous materials will cut faster using an ISOCUT blade or a precision abrasive cut-off wheel. Dressing the wafering blades every 4-5 cuts helps too, especially with diamond abrasive. Smartcut monitors the machine stress conditions and decreases feed rate and wheel contact when overload conditions are detected. If the feed rate is set extremely high, there may not be enough time for the machine to decrease the feed rate before the overload condition causes the cutoff wheel to bind in the specimen or cause the circuit breaker to trip. Additionally, while the ISOMET 4000 and 5000 saws may successfully complete the cut, a given material may be friable and prone to damage at high feed rates.

It is best to set the feed rate at lower levels or the recommended levels in the manual for a given material and observe how long the machine readout displays Smartcut. If Smartcut does not appear, adjust the feed rate upwards until Smartcut is activated. The ideal feed rate setting is when the readout shows Smartcut only while sectioning through the largest area of the specimen.

Question: Does the position of the specimen to the wheel have any effect on the cutting operation?

Answer: The ideal specimen position is located directly perpendicular to the circumference of the blade. Slight variations from this position, either above or below the center line, will work as well. If the specimen is located too low when entering the blade, it will have a tendency to cause the blade to slow down due to the "door-wedge" effect. If the specimen is located too high when entering the blade, the cutting time will increase accordingly.

Question: Can I use a single flange size for all of the blades?

Answer: Stability of the blade is very important during the cutting process. Too small of a flange will cause the blade to flex which will damage the blade and/or the specimen. Too large of a flange will reduce the size of the specimen to be sectioned because the usable blade area is reduced. The proper flange size will allow the specimen to be sectioned through while maintaining blade stability.

Table 1. Guide for Selecting Precision Saw Wafering Blades

Blade Series/ Size	Abrasive	Particle Size	Applications	Diameters Available
30 High Concentration	Diamond	Very Coarse	For polymers, rubber and othe soft, gummy materials	5, 7, and 8in [127, 178, and 203mm]
20 High Concentration	Diamond	Coarse	For aggressive cutting or ferrous and harder nonferrous metals	5, 7, and 8in [127, 178, and 203mm]
15 High Concentration	Diamond	Medium Coarse	For routine use, for metal-matrix composites, Pc boards, bone, most nonferrous metals and refractory metals such as titanium, and thermal spray coated specimens	3, 4, 5, 6, 7 and 8in [76, 102, 127, 152, 178, and 203mm]
20 Low Concentration	Diamond	Coarse	For use with very hard materials: ceramics, carbides and nitrides	5 and 8in [127 and 203mm]
15 Low Concentration	Diamond	Medium Coarse	For use with very hard materials (less aggressive than 20LC) pluss glass, electronic devices, and concrete	3, 4, 5, 6, 7 and 8in [76, 102, 127, 152, 178, and 203mm]
10 Low Concentration	Diamond	FIne	For use with lower hardness ceramics, electron devices and packages, GaAs, AIN and glass-fiber reinforced composites	3, 5, 7 and 8in [76, 127, 178, and 203mm]
5 Low Concentration	Diamond	Very Fine	For use with softer, friable ceramics, composites with fine reinforcements, CaF_2 MgF_2 and carbon composites	5in [127mm]
ISOCUT®	Cubic Boron Nitride	Medium Coarse	For iron and iron-based alloys, superalloys, nickle, cobalt and lead (and their alloys)	3, 4, 5, 6, 7 and 8in [76, 102, 127, 152, 178, and 203mm]
METABRASE™	Al_2O_3	NA	For iron-based alloys	7in [178mm]
METABRASE™	SiC	NA	For nonferrous metals and alloys	7in [178mm]
ACU-THIN™	Al_2O_3	NA	For hard steels, $\geq$45 HRC	5in [127mm]
ACU-THIN™	Al_2O_3	NA	For soft steels, $\leq$45 HRC	5in [127mm]

NA-not applicable

BUEHLER
An ITW Company
Connect with us:

BUEHLER Worldwide Headquarters
41 Waukegan Road
Lake Bluff, Illinois 60044-1699 USA
P: (847) 295-6500
www.buehler.com | info@buehler.com

BUEHLER Germany
info.eu@buehler.com

BUEHLER France
info.fr@buehler.com

BUEHLER United Kingdom
info.uk@buehler.com

BUEHLER Canada
info@buehler.ca

BUEHLER Japan
info.japan@buehler.com

BUEHLER China
info.cn@buehler.com

BUEHLER Asia-Pacific
info.asia@buehler.com