Sanding, Under the Microscope

Scanning electron microscope reveals secrets of success

BY PAUL H. AXELSEN

Whether you view sanding as a tedious chore or a labor of love, a closer look at the process will help you give your next project a beautiful look and feel. In this case, I mean a *much* closer look, with a scanning electron microscope (SEM).

As a scientist, I use an SEM quite often, to examine everything from microorganisms to medical devices. As a woodworker, I decided to use this powerful tool to answer a long-standing question I've had: If cross-grain sanding makes a mess of a wood surface, why is it that a random-orbit (RO) sander—with scratches going in every direction—doesn't do the same?

When I sent my initial results and conclusions to *Fine Woodworking*, the editors suggested a number of related questions to explore with SEM photography. Among the questions were how hand-sanding differs from random-orbit sanding, how

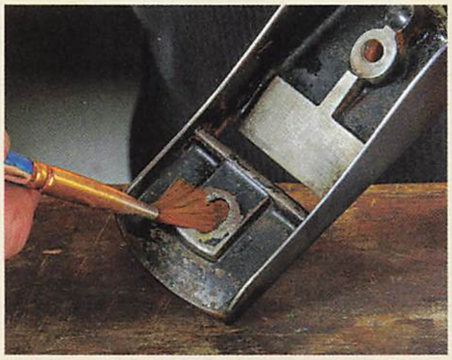
Micro-photos: Paul H. Axelsen; others, except where noted: Asa Christiana

Japanning is easy to touch up

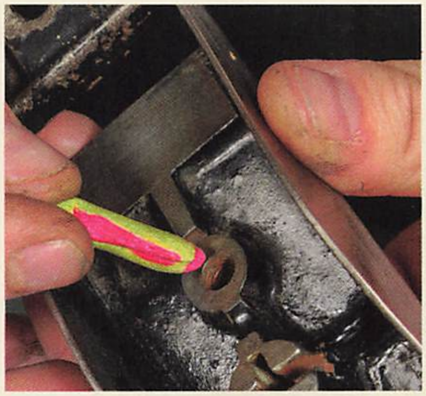
That black glossy finish on some of your hand planes and other tools is japanning. It started out as a furniture finish imitating Japanese lacquerware, but its uses expanded to protecting metal tools as well. Depending on how far you want to refurbish a tool, you may consider refreshing the japanning. My recipe is easy to make and apply, and it cures to a shiny brownish black, a correct antique look, so you won't ruin your plane's old charm with its new paint job. Just be sure to apply it somewhere with good ventilation, or even outside.

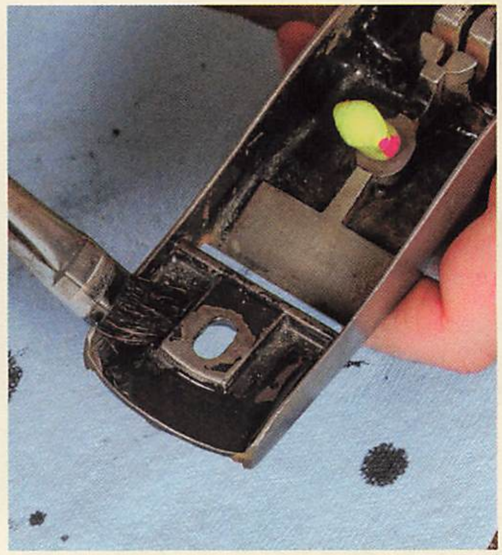
The steps are simple. First, strip off old paint, residual grease, grime, and oil, and old, flaky japanning. Next, apply the japanning. I make mine by combining one part linseed oil and one part thinner, then I mix in lamp black until the finish is opaque. Feel free to experiment with your own ratios.

My technique only touches up the old japanning. It's more about filling in cracks and gaps instead of doing a whole overhaul. To completely reapply japanning, you have to first sandblast the casting—and sandblasting is something I don't recommend to anyone except those who know exactly what they are doing and can take the proper precautions against lead paint and damaging the tool.



Strip and clean to prep for japanning. *To ready the surface, Rose brushes on acetone to strip any paint from previous owners and remove any remaining grease. For stubborn spots, she breaks out a wire brush, which also scratches off old japanning that's loose.*



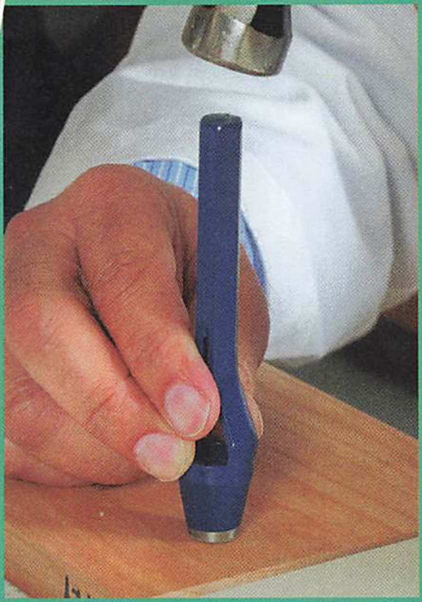


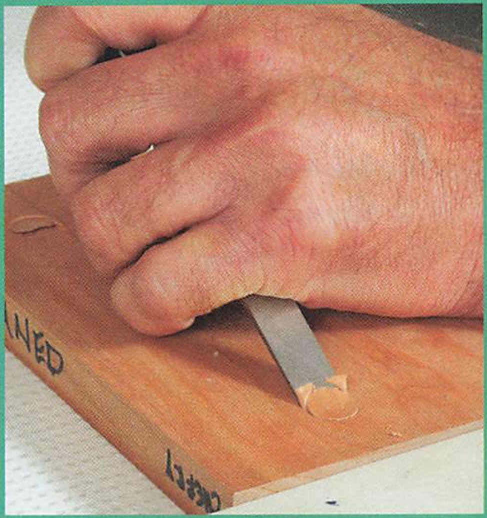
Brush on the japanning mixture. *Protect any holes with rolled-up earplugs, and avoid the sole and sides of the block plane. If japanning inadvertently gets on these surfaces, scrape it off with a razor blade and follow with sandpaper.*

Bake three times to cure the finish. *Rose's sequence is 300°F for an hour or two, then let it cool. Repeat at 350°F, cool, and then heat one final time at 400°F. A toaster oven works fine.*

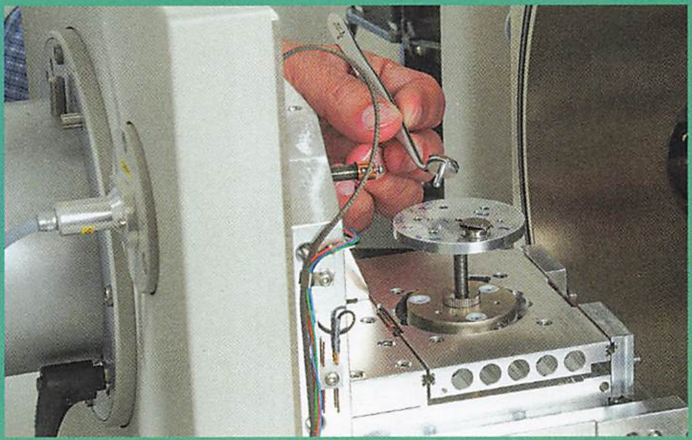
Scores of samples

We prepared many samples for micro-photography, in a wide range of woods using a random-orbit sander, sanding by hand, and surfacing with a hand plane.





A sliver of each. *Axelsen used a round punch and a chisel to create samples small enough to fit into the scanning electron microscope (SEM).*



Into the scope. *After applying an ultrathin metallic coating to each sample—required by the SEM—Axelsen loaded each into the microscope and examined its entire surface. He then chose the most representative area and best degree of magnification for each photograph.*

hand-planed surfaces differ from sanded ones, and how fine a grit one should sand to for best finishing results.

Prepping samples

My editor, Asa Christiana, and I sanded a number of hardwoods with an RO sander, keeping a shop vacuum attached, and applying gentle, even pressure to the sander. The surfaces were brush-vacuumed and rubbed lightly with a tack cloth after each grit, to make sure that the SEM images would reveal the surface of the wood, not loose sanding dust.

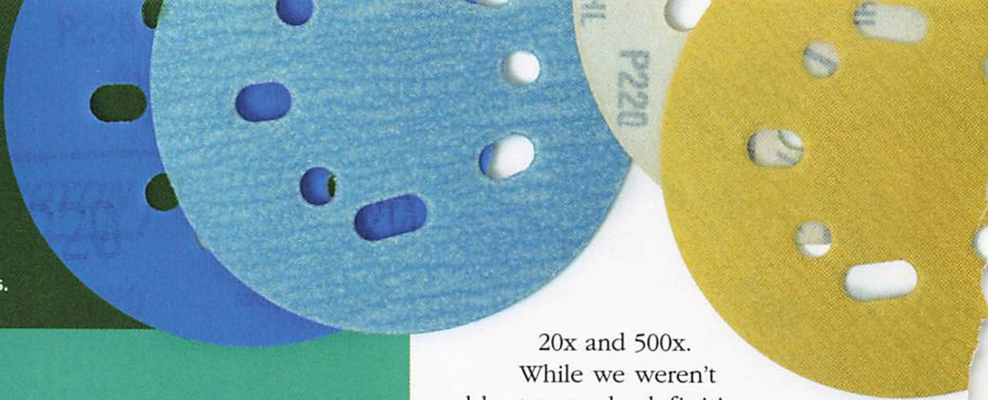
To create samples that would fit in the microscope, I punched out small chips (see photos, above right), and then coated them with an ultrathin layer of gold and palladium, which plays an important role in how the SEM works.

The SEM scans the surface with an electron beam much like those in old cathode-ray television tubes, and the super-thin metal layer reflects the beam back to a detector to create a crisp, black-and-white image. Although an SEM can easily magnify to 1,000,000x, the effects of sanding were best seen at magnifications between

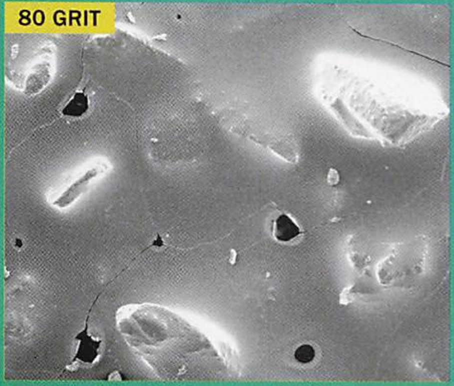
Photos, this page (right): Barry NM Dima

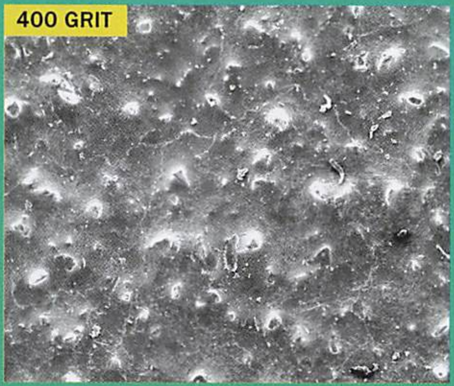
The mechanics of random-orbit sanding

A close examination of random-orbit sanding disks and the surfaces they produce offers a number of revelations.



SANDING DISKS

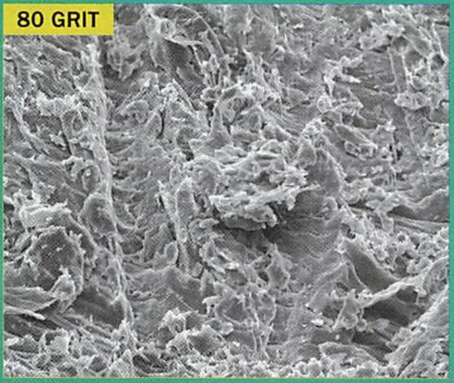


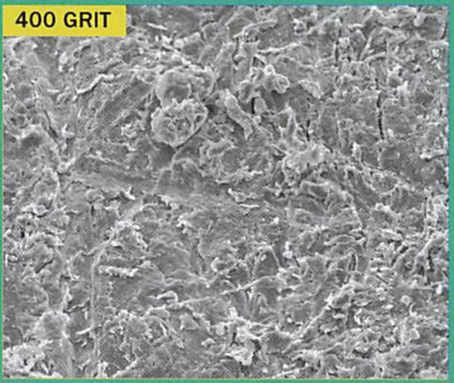


Consistently sized abrasives. *Photos of sanding disks at 50x magnification show that the grains of zirconia-alumina are compact in shape and roughly uniform in size, with sharp edges.*

SANDED SURFACES

Thousands of tiny arcs. *In these photos of sanded surfaces, taken at the same 50x magnification, we can see that individual grains cut more effectively in some directions than others, producing small arcs rather than full loops. The disk rotates as it moves eccentrically, which makes the scratch pattern even more complex. Note also that the scratches are much smaller than the abrasive grains that created them.*





Finer is smoother. *Viewed at 500x magnification, these samples of sanded surfaces show how progressively finer grits leave a progressively smoother surface, as expected.*

20x and 500x.

While we weren't able to reach definitive answers to each question we explored, our efforts yielded very instructive results. Aside from examining the SEM images, we also learned a lot simply by sanding, touching, and viewing so many samples.

How RO sanders work

The SEM revealed that the abrasive grains in RO sanding disks are compact in shape and relatively uniform in size, with sharp edges, and are partially embedded in a layer of adhesive. It also enabled me to measure the size of various abrasive grains.

Then I began looking at samples of random-orbit-sanded wood, viewing them at a wide variety of magnifications.

Thousands of tiny arcs—One of the most important things I noticed is that the gouges created by random-orbit sanding tend to be tiny arcs, not complete loops, likely because the chiseling action of each grain tends to be more effective in some directions than in others.

As expected, the radius of each arc corresponds to the radius of the eccentric bearing in the sander, which causes the disk to oscillate 12,000 times per minute. The disk also rotates at the same time—much more slowly than it oscillates—which is why each grain creates a new gouge, in a new location, with every oscillation.

Another thing I learned is that the gouges made by a random-orbit sander are much smaller than the grains that create them. This is obvious when you compare the size of the grains on a sanding disk with the size of the scratches they make in wood, at the same magnification. The relatively small size of the gouges is also confirmed by SEM images of sanding disks after use, in which each speck of dust left on the disk is much smaller than the nearby abrasive grains.

Number of grains determines depth of the scratches, not grit size—Interestingly, and somewhat counter-intuitively, the cutting depth of different abrasive grains is determined primarily by the number of grains in contact with the wood, and the pressure applied to the sander (or hand-sanding block), as opposed to the size of the grains.

I know this because the width of the scratches didn't change in SEM images of wood sanded with different grits. Variations in pressure could have changed the width of the scratches, but I kept consistently light pressure on the sander when prepping sample boards, eliminating that as a factor.

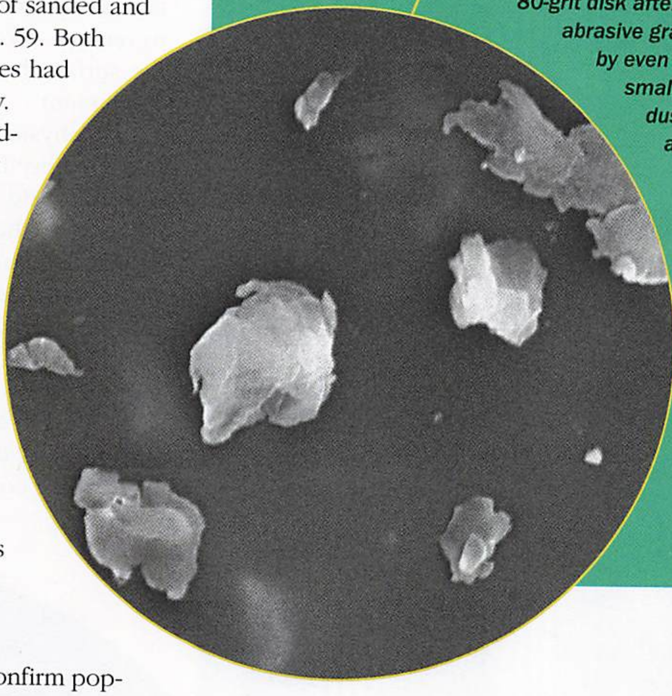
In short, the reason finer sandpaper leaves shallower scratches is that finer grains are closer together on the disk (or sandpaper), which translates to lower pressure on each individual grain.

Pores are packed with dust—As I looked through hundreds of SEM images, I noticed that the gouges left by RO and hand sanding were packed with fine dust even after vacuuming. You can see this clearly in the side-by-side images of sanded and hand-planed samples on p. 59. Both were taken after the surfaces had been vacuumed thoroughly.

The SEM shows that hand-planing produces a cleanly cut surface that is largely dust-free, with wide-open pores. Sanding, on the other hand, whether by hand or machine, packs those pores with dust that cannot be removed by vacuuming or wiping with a tack cloth. Also, the finer the grit used and dust created, the more packed the pores remained.

Collect the dust with active suction

Fine sanding dust is dangerous.



Dust is much finer than expected. *The 50x image above, of an 80-grit disk after sanding, shows the difference in size between abrasive grains and the dust they generate. Particles produced by even the coarsest random-orbit sanding can be as small as 1 micron or less (see image at left). These fine dust particles are the most dangerous to lungs and airways, so HEPA-level filtration is a must for your shop vacuum and dust collector.*

Initial revelations

Many of these discoveries confirm popular wisdom, but confirmation can be a benefit in itself.

Move the sander slowly, in straight paths—The goal when sanding, regardless of method, is twofold. First, you want to completely remove machine marks, or the larger scratches left by the previous grit. Second, you want to remove a uniform layer of wood, leaving the surface as level as possible, avoiding depressions that will be obvious after applying a finish, when light reflects off the surface.

SEM images highlight the mechanics of random-orbit sanding. First, the disk oscillates extremely rapidly, so users who rub the sander back and forth like a sanding block are wasting their efforts. Worse, they are making it very hard to track their progress and remove wood in a uniform layer.

Instead, you should move a random-orbit sander slowly and gradually across the surface in straight, slightly overlapping paths, which will remove a uniform layer of wood. If your first series of passes hasn't removed the marks from milling, or a specific defect, or the scratches from the last sanding grit, avoid bearing down in any one area; instead, make a new series of passes over the entire surface.

Light pressure—A random-orbit sander's cutting action changes when you bear

Expert advice confirmed

SEM photos, plus our experience prepping and finishing so many samples, confirmed a number of expert tips for successful sanding, by power and hand.

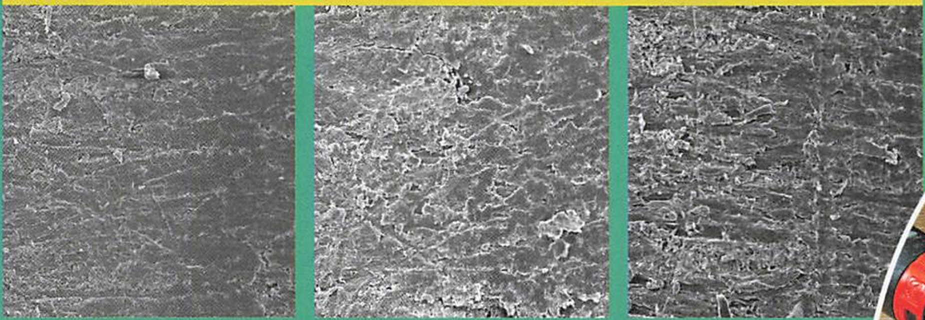
EFFECTIVE SANDING

Light grip and a steady path. *Because a sander moves thousands of times a minute, you don't need to rub it back and forth like a sanding block. Instead, move it in straight, slightly overlapping passes to ensure that you are removing wood evenly. A light grip is best, as pushing down hard or tipping the sander will impede its proper operation.*

Vacuum between grits. *Although connecting your sander to a shop vac will capture most of the dust created by random-orbit sanding, it's also important to vacuum the surface between grits, using a brush attachment. The goal here is to collect loose abrasive grains from the previous disk, which will cause problems during the next sanding pass.*

PENCIL LINE GUIDES THE WAY

80 GRIT



Trust the pencil test. *After being sanded with an 80-grit disk, these (from left) oak, cherry, and walnut samples were marked with a soft lead pencil, a common method for tracking progress with the next sanding grit. The dark area on the right side of each 200x image is a small portion of a pencil mark, showing how the graphite dust fills the sanding scratches, leaving a smoother surface on top. When the marks are no longer visible, you've reached the bottom of those scratches with your next grit.*

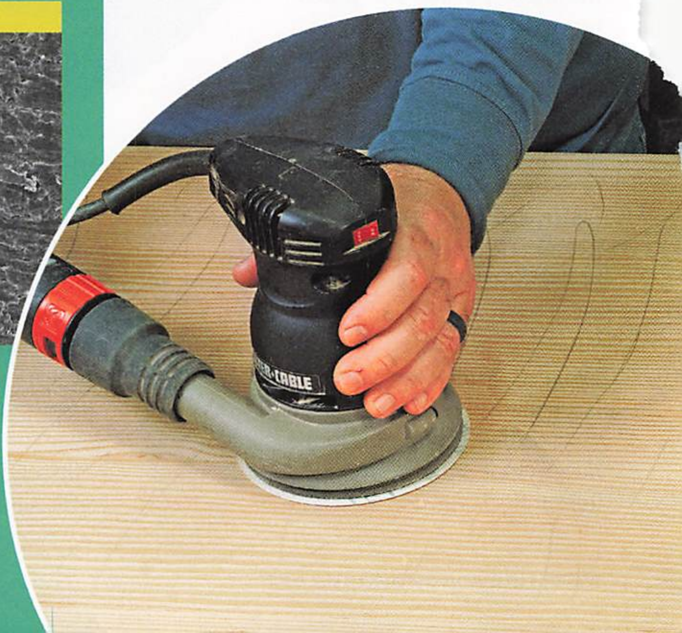
down hard on the sander, or worse, tip it sideways to push down harder on the edge of the disk.

Those methods can create deep gouges, which are much harder to remove with the next finer grit. Pausing along your path and bearing down on the sander will also create those hollows we are trying to prevent.

Best practice is to keep the sander level and apply light pressure, relying on the weight of the unit to produce the downward force.

Vacuum the surface—The SEM shows us that random-orbit sanding dust is not only smaller than the grains that create it, but also smaller than the next finest sanding grit in any series. So there is little danger of leftover dust creating overly deep scratches if you leave it behind. Instead, it's rogue abrasive grains you should worry about. These are grains that have broken free from the disk, and can roll around under the next one, creating deep, corkscrew scratches that will be very hard to remove. So it is important to vacuum the surface between grits using a brush attachment.

As a physician, I must also point out that the very fine wood dust created by sanding, and especially random-orbit sanding, is the most dangerous to your health, hanging the longest in the air and penetrating deepest into your lungs and airways, where it can both irritate and damage your lungs; exacerbate asthma, emphysema, or chronic bronchitis; and even cause cancer. So it's important to trap sanding dust in a HEPA-rated vacuum or dust collector.



Pencil marks track progress—It's difficult to know when you've sanded enough to remove the gouges left by the previous grit. To make that clearer, some woodworkers make light marks on the surface with a soft pencil and sand until the marks are gone before moving on to the next grit.

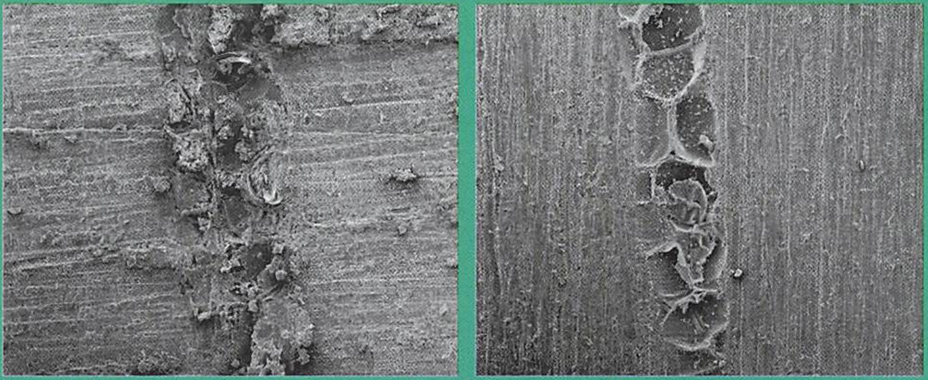
So I made some pencil marks on sanded wood, sanded those away to various degrees, and viewed the marks with the SEM. It's clear in SEM images (see facing page) that the pencil graphite fills the gouges to the brim, making marked areas look much smoother than nearby ones. These images, along with practical experience, suggest that the pencil marks will remain visible until the next sanding grit has reached the bottom of those scratches.

Therefore, pencil marks are likely a very effective way to track your progress when sanding. They can also be a guide to which grit is needed for a particular workpiece: If the marks are lasting longer than your patience, that's a sign that you need a coarser grit.

Raise the grain before water-based finishes—Water-based stains, dyes, and finishes can "raise the grain" of bare, sanded wood, forcing woodworkers to re-sand, which can remove color from the raised fibers, creating an uneven look.

So woodworkers often raise the grain before applying water-based finishes, by dampening the surface with a wet sponge, allowing it to dry, and then re-sanding with the same final grit. The SEM

HAND-SAND WITH THE GRAIN



Same grit, different results. *Sanding by hand across the grain not only leaves more visible scratches, it also tears fibers and pulls them upward (above left), leaving the surface rougher to the touch. Sanding with the grain, on the other hand, leaves fibers lying down (above right), creating scratches that blend in with the grain lines.*

RAISE THE GRAIN BEFORE WATERBORNE FINISHES

Taken at 200x and 2,000x magnification, these SEM photos show how wetting (with water) and drying causes fibers to rise from the surface, and how re-sanding smooths them again.

confirms the effectiveness of this practice, showing how wetting the surface and letting it dry causes surface fibers, damaged and stressed by sanding, to loosen and curl upward. It also shows that re-sanding makes the surface smooth again.

Hand-sanding and more

Experts widely recommend hand-sanding after random-orbit sanding. While we weren't able to confirm that this step is absolutely necessary, we were able to compare a variety of random-orbit-sanded, hand-sanded, and hand-planed samples and reach a number of conclusions.

Hand-sanding vs. RO sanding—When I compared random-orbit and hand-sanded surfaces (both sanded to 220) in the SEM, it was easy to see how different the scratch patterns were. To the naked eye, however, those same surfaces, whether finished with a coat of oil or not, showed no easily discernible differences.

It would require much more extensive testing to tell whether hand-sanding delivers better finishing results than random-orbit. Practically speaking, of course, smaller and narrower surfaces should only be sanded by hand with a block, as a sander will round them over.

More efficient hand-sanding—Another question we explored is which grit to jump to when switching from random-orbit sanding to hand-sanding. While experts usually recommend repeating the last RO-sanding grit with the first round of hand-sanding, before switching to finer grits, SEM images showed that hand-sanding with 320-grit paper was just as effective at removing the 220 random-orbit scratches as hand-sanding with 220.

That's good news for woodworkers, who, after random-orbit sanding up to 220 grit, for example, can likely jump straight to hand-sanding at 320.

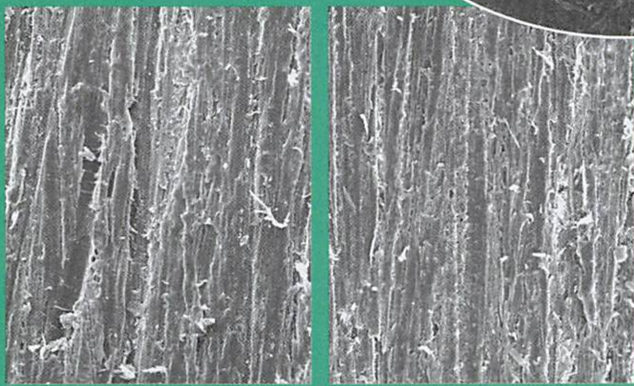
Higher grits for penetrating finishes—The editors also wanted to know if the SEM could tell us which grit to stop at when hand-sanding. So we prepped three more sets of samples, in three woods, cherry, maple, and oak, with one of each species hand-sanded to 220, another set hand-sanded to 320, and a third set sanded through 400, 600, and 800 grit.

New info emerges

Our investigation uncovered some relatively surprising information, and a number of helpful tips.

SKIP A STEP WHEN SWITCHING TO HAND-SANDING

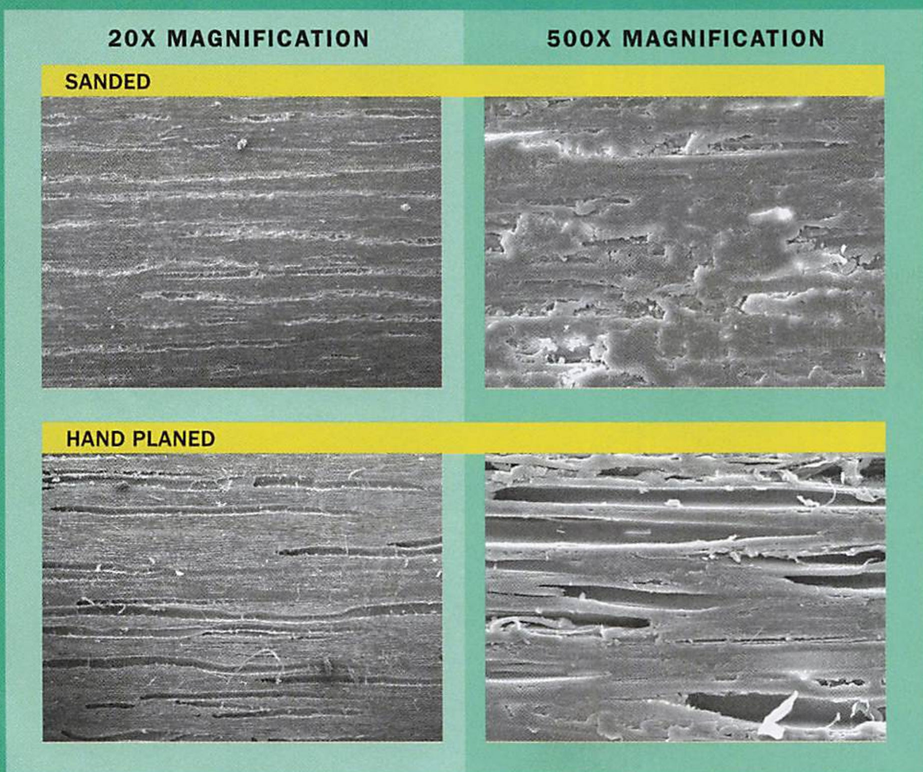
Conventional wisdom dictates that you follow RO sanding with hand-sanding, beginning with the last grit you used in the random-orbit sander. SEM photos suggest a shorter path.



Two paths tested. *We random-orbit sanded two cherry sample boards to 220 (top). Then we hand-sanded one (left) with 220 paper and the other (right) with 320 paper. Both grits were equally effective at removing all traces of random-orbit sanding, suggesting that woodworkers can skip the repeated grit when switching over to hand-sanding, and go right to the next one.*

PLANING VS SANDING

A sharp hand plane shears the fibers cleanly while sandpaper leaves ragged, feathered edges (and packed pores). This offers a clue as to why many woodworkers find that there is reduced grain-raising when a finish is applied to a planed surface rather than a sanded surface.



Sanded vs. planed. *The SEM photos at top show a hand-sanded surface, with fine dust still packed into the pores after vacuuming. The surfaces in the bottom row were shaved cleanly by a hand plane, leaving their pores wide open. Both are cherry.*

Differences between the boards sanded to 220, 320, and 800 were easily appreciated by touch: The most finely sanded boards had an almost glasslike feel to them. Visually, the pores on the 800-grit boards were much less prominent, and finer sanding created boards that reflected light beautifully—after just one coat of linseed oil—while the finished boards sanded to 220 had a matte look. The oil finish on the most finely sanded cherry boards also seemed less blotchy.

Overall, these results confirm popular wisdom that higher grits are better when prepping wood for penetrating oil finishes.

Why cross-grain sanding is so problematic—You don't need the SEM to see and feel the difference between hand-sanding with the grain and hand-sanding across it. But the SEM makes subtle features look as tall as bushes and trees.

SEM images show that hand-sanding across the grain not only leaves more visible scratches, but also a field of torn fibers. The scratches created when sanding parallel to the grain, on the other hand, blend in with the grain lines and leave surface fibers flat and smooth.

The answer to my initial question

After all my testing, I had the most likely answer to my initial question: Why are the cross-grain scratches made by a random-orbit sander virtually invisible to the naked eye, while cross-grain scratches from hand-sanding are so obvious? The mechanics of wood sanding are complex, but I believe the answer depends on a combination of the following factors.

First, during random-orbit sanding, the curved shape and random direction of each sanding scratch means that there are just as many scratches made in line with the grain as directly across it, and many, many more that are oblique to some degree. Second, the small size of each scratch means that no single one has a chance to do much damage, compared to the long, linear scratches made when hand-sanding. Third, the relatively high number of scratches made by random-orbit sanding—roughly 100-to-1 compared to hand-sanding during any given time frame—means that any minor cross-grain damage is smoothed milliseconds later by sanding actions in a variety of other directions.

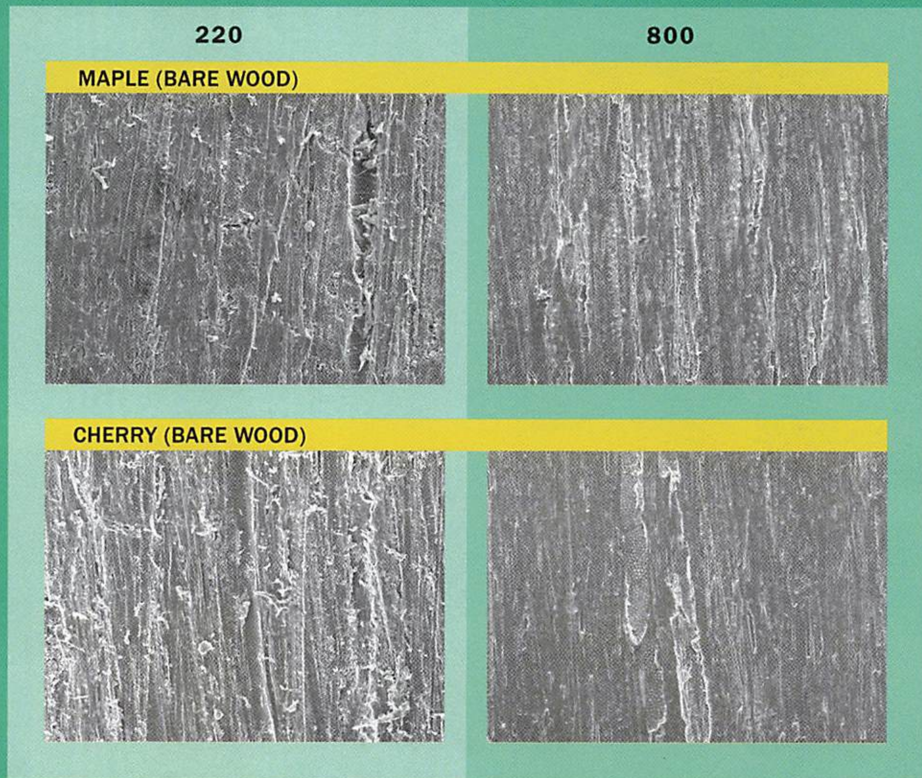
Last, when you follow one random-orbit sanding pass with another, the abrasive grains are not contacting linear wood fibers or linear sanding scratches, but rather a surface that is filled with curved gouges from the previous grit. This also minimizes cross-grain damage, I believe.

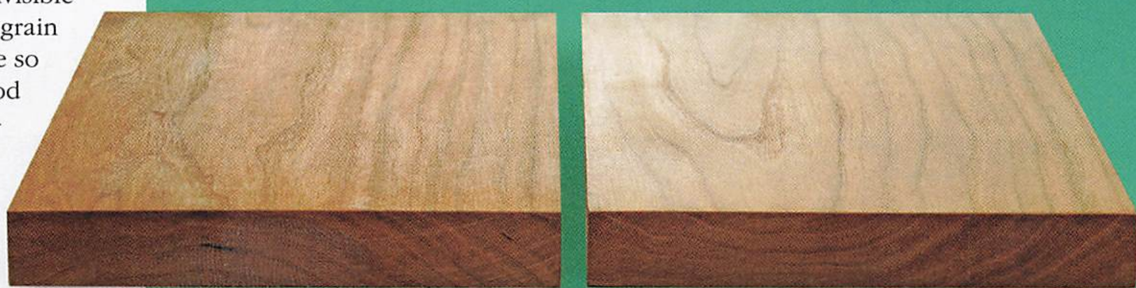
These factors give random-orbit sanding a number of practical advantages over hand-sanding, including neutrality when wood grain changes directions, at joint junctions, for example. □

Woodworker Paul Axelsen is a professor of medicine, pharmacology, biochemistry, and biophysics at the University of Pennsylvania.

Sand to a finer grit before a penetrating finish

Film-forming finishes fill sanding scratches in the wood surface, so you can save the finest grits for leveling the finish between coats. Penetrating oil finishes, on the other hand, do not fully level the wood surface, so it's important to make the bare wood smoother before finishing.





***Reflected light tells the tale.** Both of these cherry sample boards were given a single coat of boiled linseed oil. The board at left was sanded to 220 grit, and looks matte in reflected light. The sample at right was sanded to 800, and reflects the same light with a buttery sheen.*

Elegant Table Comes Together at the Corner

Where veneered aprons meet a gunstock-miter leg

BY MIKE KORSAK

Boring furniture makes for a bored furniture maker. One of my pleasures in making furniture is figuring out how to detail a piece in such a way that a common form is translated into something that dazzles me, that takes on a life of its own. I delight in developing the details that serve this purpose, and in the technical challenges that often accompany those details.

When I was approached to build a dining table for two, I jumped at the opportunity to design a simple table that would stand out, with just the right amount of dazzle. I chose solid walnut with a rippled figure for the top and straight-grained walnut for the legs. I put the real pizzazz in the aprons, gluing shop-sawn crotch-walnut veneers over Baltic-birch plywood. To help frame the crotch veneer, I gave the apron a bottom edging that is proud of the veneer but flush with the face of the leg. And I used a gunstock miter joint so the inner line of the leg would flow right into that bottom edging of the apron. Twin slip tenons provide the muscle connecting the aprons and legs. I'll focus in this article on the cluster of technical and aesthetic details involved where the aprons meet the legs.

Taking stock and cutting leg joints

My first step was to select and rough out stock for the legs and for the edging that would be

Photo, this page: Mike Korsak