A smooth bottom is a fast bottom

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Is the bottom of your boat smooth enough?

You can't be a sailor and not be a scientist. Every time you leave the dock, you become part aerodynamicist, part hydrodynamicist — even part cosmologist (when you get that urge to bang the left corner!).
Sometimes it's enough just to know that something is fast, without knowing why. But with more complex questions, such as how to minimize "skin-friction drag" on underwater surfaces, you will be bombarded with different theories. Some people will tell you to wet sand, others will say to polish. Stars & Stripes had micro grooves in '87, but maybe you need Teflon in '96. When faced with such a variety of opinion, the only solution is to charge ahead, fearless of the complex science involved, and try to discover the truth. You'll be surprised to find that the subject isn't that complicated after all.

Basic Science

The No-Slip Condition

The term "skin friction" is misleading when used to describe drag on hull surfaces. When we think of friction, we normally think of two surfaces sliding against each other. This does not happen underwater. Fluid dynamics textbooks usually begin discussions of this topic by explaining the no-slip condition. This stipulates that the fluid molecules against a moving surface do not slide (slip) over it. Instead, they are pressed against it and adhere to it. This occurs regardless of the type of surface (gelcoat, paint, plastic), how smooth the surface is, or whether water beads up on it. In fact, if you could figure out how not to adhere water to a hull, getting it to slide by, you would have discovered a major scientific breakthrough.

Boundary Layers

To visualize what happens as a result of the no-slip condition, imagine yourself in a scary situation: an overcrowded subway station. You are part of a crowd pressed up against a train which is now full and starting to move slowly. The people who are touching the train have no choice but to move along with it, and they push those pressed up against them as well. You are 6 feet back from the train, but you, too, are bumped and pulled along, though not as fast as the train and those against it. Somewhere behind you, farther out from the train, the effect ends, and the train's motion does not cause people to move.

What you just imagined (except for the panic) is what happens to the water molecules against the hull of a sailboat. The region of water pulled along with the hull is known as the boundary layer, and it can take one of two forms — laminar or turbulent.

When the boundary layer is "laminar," it's thin and presents little drag. It's also fragile, so it quickly breaks up into a thicker "turbulent" boundary layer as it flows aft on the hull or foils. When turbulent, the boundary layer pulls more water with it, creating more drag. Therefore, the first goal of bottom preparation is to extend the laminar boundary layer as far aft as possible on your hull and appendages by creating practically perfect surfaces in the areas where it can exist.

The second goal is to minimize drag aft of the transition to turbulence, and this is a little easier to do. Most of the turbulent boundary layer consists of chaotic, swirling eddies, but there is a thin layer next to the hull known as the "laminar sub-layer." Any surface roughness small enough to be immersed in this layer is "hydrodynamically smooth." In other words, making it any smoother will have no benefit. This means that the hull does not have to be as smooth in the aft sections, where you know the boundary layer will be turbulent, as it does in the forward sections, where you hope to preserve laminar flow.

Let's take a look at two examples: a boat traveling at 2 knots and one moving at 12 knots. Laboratory experiments with flat plates indicate that the transition from laminar to turbulent flow in the boundary layer should occur in the first 6 feet at 2 knots, and within the first foot at 12 knots. Boats are not flat plates, however, and they don't sail in calm test tanks, so we need to search further for evidence of the true transition point. What the lab results do teach us is that the greatest opportunity for laminar flow is at low speeds. Note that this is also when most of the total drag of a hull is due to skin friction (as opposed to wave drag in heavy air). So the smoothness of the forward sections of your bottom and foils is most important when sailing in light air.

As for what is “hydrodynamically smooth” aft of the transition point, when sailing at 2 knots, it’s any scratch smaller than 4 mils (thousandths of an inch). At 12 knots, the “admissible roughness” reduces to under 1 mil. A human hair is approximately 2 to 3 mils in diameter, and a bottom finished with 400-grit sandpaper should have a hydrodynamically smooth finish aft of the transition point for speeds up to 7 knots. So, for most keelboats, a bottom which is finished with 400-grit sandpaper in the aft sections is adequate. For planing dinghies, which sail faster, the aft sections of the bottom need to be smoother.

The Real World

Hulls in Waves

When sailing in real conditions, the shape of a hull or appendage works to enhance laminar flow. However, the condition of the water acts to destroy it. Visualize water flowing past a sailboat hull. It is deflected outward by the forward part of the hull, and accelerates until it reaches the widest and deepest part of the hull. This acceleration creates a “positive pressure gradient” that stabilizes and prolongs the laminar boundary layer. The same effect exists on keels, and has led to foil sections and bulbs with their maximum thicknesses moved aft to delay the transition from laminar to turbulent.

The worthy opponent of these positive effects is the state of the water. Turbulence at the surface from waves, micro organisms, and contaminants can all be disruptive. Yacht designer David Pedrick, who has dealt with this question during several America’s Cup efforts, feels that the imperfect sea state usually wins out. “We’ve used electronic sensors and microphones to test for laminar flow,” he says. “You can get some, but not much.”

The best chance for laminar flow is on the keel and rudder, both because of their convex shape and because they are immersed below much of the disturbance. Aerodynamicist and dinghy designer Frank Bethwaite questions “whether any surface is ‘smooth enough’ for a racing dinghy,” when it comes to foils.

Smoothness vs. Fairness–So far, we have concentrated on the smoothness of surfaces, but not fairness. By fairness we mean whether the hull has highs and lows that deviate from its designed continuous curves.

On this subject, Karl Kirkman, a well-known hydrodynamicist with extensive tank-testing experience, found that hulls can be forgiving of gentle variations in shape as long as there are no sudden changes in curvature. “If there is a step or a dent in the hull,” says Kirkman, “of course that has to come out. But hulls can be forgiving of a gradual waviness unless it is in a place where it could cause flow separation.”

Pedrick agrees, but adds that, for keels and rudders, both smoothness and fairness are critical to performance.

Beading vs. Wetting

Any discussion of fast bottom surfaces eventually leads to the question of whether water should bead up on a hull or “wet” the hull so that it flows off in a sheet. “Beading has no relevance,” says Kirkman. “It’s a function of the surface tensions of the water and hull surfaces, and nobody has been able to explain to me how it has any relation to skin-friction drag underwater.”

Even so, both Pedrick and Kirkman suggest that waxes are not a good idea because they seem to attract and/or react with contaminants in the water and can be hard to get as smooth as a finely wet-sanded surface.

What About Riblets?–Riblets were used on the bottom of the 12-Meter Stars & Stripes during the 1987 America’s Cup. They are tiny v-shaped grooves that were applied to the hull on a vinyl tape (from the 3-M company). Soon after their televised debut, they were outlawed by the racing rules, which now prohibit “specially textured” surfaces that alter “the character of the flow of water inside the boundary layer.”

Fine. But what if you are painstakingly wet sanding your new bottom paint to achieve a “hydrodynamically smooth” surface. You might wonder whether you could sand carefully in a fore-and-aft direction using 220-grit paper, and then “just launch the damn thing.”

Fortunately for protest committees everywhere, this does not appear to be a smart approach. Early papers on riblets show that their effectiveness is sensitive to the geometry of the tiny grooves, and that rounded grooves are likely to increase drag.

They have also been shown to trip laminar boundary layers into turbulence sooner than smooth surfaces. As Kirkman points out, the optimum height of the riblets changes with speed, so any riblet choice is a compromise. So it seems likely that large scratches left in a surface from sanding with 220-grit sandpaper will increase drag rather than reduce it.

Bottom Finishes

By now we should agree on a few things. The foils should be mirror smooth. For keelboats and non-planing centerboarders, if you want to go fast in light air, the hull should be highly finished at least back to the midsection. Aft of that, a 400-grit finish is adequate for keelboats. Polish a high-performance dinghy from head to toe.

But what is the best finish? Should you use paint or gelcoat? And how do you maintain that finish? Here are some things to consider.

Magic Bottom Paints

We hear about paints that repel water, paints that bond water "because water sliding over water gives less drag," and paints with low-drag coefficients. When faced with such claims, remember that the chemistry of a paint can only reduce drag if it leads to a smoother finish — either by allowing the paint to be sprayed on more smoothly, by creating a harder surface for finer wet sanding, or by preventing growth and contaminants from adhering. Any other claim runs into the no-slip condition. It may well happen that someone will figure out how to allow water to slide over surfaces, but until then, assume the no-slip condition is alive and well, and smoothness is what really counts.

As for advertised test results showing the drag reduction of a bottom paint, common sense says to be sceptical. For instance, a 10-percent drag reduction would lead to a huge speed advantage in a one-design fleet. If that happens, you'll know it.

Gelcoat

Sailors with production boats often worry if their gelcoat hulls are fair enough. Even if reflected light seems to "flutter" as you move your head to look at the hull, chances are that your surfaces are adequately fair. Your eye tends to be over-sensitive to this, and glossy surfaces show everything. Another boat with a duller, wet-sanded bottom may look perfectly fair; but if it were glossy, chances are that reflections would dance a bit on its surfaces, too. Unless you can actually feel roughness or unfairness, your efforts are better spent on your keel, centerboard and rudder.

Sometimes, excessive "orange peel" or "print through" is visible in the gelcoat. This means that, although the surface is often fair enough, it may not be smooth enough. If you decide to wet sand a gelcoat hull, it's best to have a boat shop refinish the underwater surfaces with another layer of gelcoat, or an epoxy barrier coat.

Don't sand gelcoat without good reason, however. Untouched gelcoat has a thin, resin-rich layer on the outside that helps to protect it from weathering. Removing this layer will not only cause quicker fading, it may expose porosity that is trapped in the gelcoat. This porosity is not much of a drag problem (tiny protrusions such as road dirt are much worse), but it will leave the gelcoat less effective as a water barrier to the laminate and core.

With gelcoat, the best way to maintain the finish is with soap and water. Many sailors put a layer of liquid soap on a hull before launching to keep the bottom clean while sailing out of a polluted harbor. While this is effective, the soap also adds to the pollution. As an alternative, some sailors polish the bottom. Do whatever it takes to keep the bottom free of contaminants. Remember, wax is not recommended.

If the bottom is finished in an epoxy primer, you can also wet sand it to maintain a clean, smooth finish. But a wet-sanded bottom will get dirty more quickly than a polished or shiny gelcoat surface. Here's how they do it in the America's Cup:

The Perfect Hull

Perhaps the best way to discover what the experts do is to check the hulls of America's Cup contenders. These boats are drysailed, and thus do not need antifouling protection or paints that can be left immersed for long periods. However, there are still lessons to be learned.

At least among the American syndicates, there seems to be little variation from what Pedrick describes: "We start by getting the hardest surface possible. Since Courageous in 1974, we have used Awlgrip on the boats because the catalytic urethane chemistry yields an ultra-hard surface. We wet sand this to a 600-grit finish, and finish it off by sanding in the streamline directions — just to do the least amount of harm. Before launching, we put detergent on the hull to keep any oil or contaminants off."

In the end, it's not that complicated. Your appendages should be as smooth and fair as possible, and your hull should be just as flawless in the forward areas. Aft of where you expect transition on the hull (certainly by amidships), the surfaces need only be "hydrodynamically smooth." Finally, when faced with the myths, remember the no-slip condition.

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