Modern Manufacturing Methods of Sailboat Masts

Kevin Schultz
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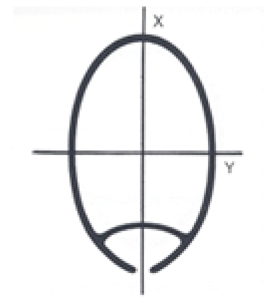
Summary – Today sailboat masts are constructed of either aluminum or carbon fiber and vary greatly in size, price, and quantity. Suppliers use several processes to satisfy different kinds of customers. An overview of these processes is presented as well as the economic rational for choosing between them.

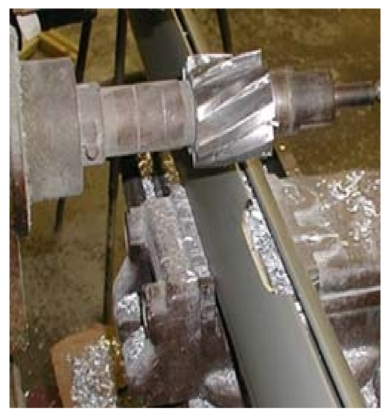
Process Summary:

Sailboat masts must be strong, stiff, and lightweight while standing up to high cycle fatigue and the harsh ocean environment. Only three materials have been used: wood, aluminum, and carbon fiber. Wooden masts were phased out in the late 1930s and today no manufacturer continues their production. From the 1930s until the early 1990s, the only choice was aluminum. In the mid 90s racing teams started experimenting with carbon fiber masts, and today both aluminum and carbon fiber masts are produced by various manufacturers. These manufacturers use several processes to create masts with differing properties to cater to various types of customers.

Aluminum masts begin as a simple extrusion of 6061-T6 alloy. The extruded shape is an airfoil to reduce drag, with an open sail track on the rear. (A rope is sewn into the front of the sale to add thickness, and the rope is fed up the track which then holds the sail in place.) An example cross section is shown to the right. The mast must then be prepared for mounting spreaders and the top and bottom end caps by drilling holes. A section of the sail track is milled wider to allow the sail to be fed in. Some masts may also be milled so that pulleys can be mounted in the side wall and lines led inside the extrusion. After machining the mast is anodized for protection. Finally hardware the caps and spreaders are riveted in place, while parts that will need to be replaced over time like pulleys are screwed in after the holes are tapped. [3]



Mast Cross-Section [1]



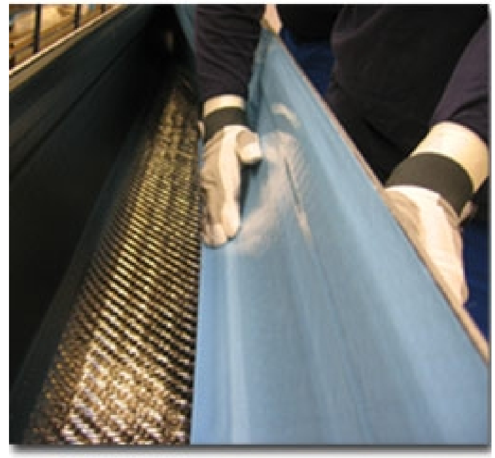
Sail Track Milling [2]

Most aluminum masts are also tapered. This process reduces the cross section near the top of the mast where the stresses are smaller. This lowers the center of gravity and reduces weight. Right after extrusion the mast is cut from the top own in long seems, and some sections are removed. The remaining sections are bent together, TIG welded, and the seems are ground smooth. It is an entirely manual operation and requires significant skill on the part of the welder. This makes tapered masts much more expensive, but the advantages are so great that most aluminum masts sold today are tapered.

Carbon fiber masts can be made in one of three ways. The simplest method is pultrusion. Round cross sections are pulled through a die. The sections are round rather than airfoil so that they can be used for applications other than masts due to the high capital cost of the dies. [4] This leads to higher drag but lower price for the customer. These mast are not tapered. Typically pultrusion is only used for smaller masts for dinghies and windsurfers because of its limitations and the price sensitivity of these markets.

Pultruded Mast [5]

The second method is to make a female mold and lay resin pre-impregnated carbon fiber cloth in the mold by hand. The mast is made in two halves in separate molds. After laying up the cloth the mold is vacuum bagged and put in the autoclave for several hours. Then the two halves are removed from the molds and joined together. This is accomplished with layers of carbon fiber tape and epoxy applied by hand. This requires a skilled craftsman and introduces weakness and additional weight into the structure. However the mast does have an exceptional surface finish since the mold can be made smooth and gelcoat used for a gloss. [9] The masts must be ultrasonically tested before shipping to customers to check for voids around the seam.



Hand Layup in Female Mold [7]

The most advanced method for manufacturing masts is filament winding. A mandrel is made in the shape of the mast and then a machine is used to wind single fibers around the mandrel. Fiber orientation and wall thickness can be varied throughout the mast to finely controlled strength, weight, and flexibility. Since the fibers are wound under tension there are less voids and greater precision than the hand laid up method. After being wound on the mandrel, the mast is placed in an autoclave for several hours. After being removed the mandrel is pulled out of the mast from the bottom. However there is great friction in this process so a hydraulic ram is generally necessary to remove the mandrel. [9] The picture at right clearly shows the filament pattern and the inferior surface finish of the mast compared to the molded process. The filament winding process is generally used for performance racing boats while the hand lay up process is used for yachts where aesthetic is the overriding concern.

Filament Winding w/ Mandrel [8]

Both of these methods require exceptionally large autoclaves. They can reach over 150' in length [6], and even at that some masts may require more than one section. This requires significantly more capital than any other mast construction process, making masts made in this manner extremely expensive (approaching $1 million US).

For all three methods of carbon fiber mast manufacture, permanent fittings such as spreaders and end caps are chemically bonded to the mast with adhesive. The adhesive is stronger and eliminates the possibility of corrosion. Fittings that will need to be replaced over the life of the mast are riveted since the carbon can't be tapped.

Mast in Autoclave [9]

Economic Analysis:

Economics is the major reason why there are still five processes for creating masts. If performance were the only metric every mast would be filament wound and carbon fiber, but only a fraction of the masts made are.

One segment of the sailboat manufacturing industry are those companies selling custom or semi-custom boats in extremely low quantities, a price range of tens of thousands to millions of dollars. There are several dozen if not hundreds of companies like this. Today they are evenly split between tapered aluminum and autoclaved carbon fiber masts (hand laid or filament wound). Ten years ago tapered aluminum masts were near universal, but carbon fiber masts have fallen in price significantly. This is due to their gaining market share since the capital cost of the autoclave and filament winding machine is spread over more masts. This again lowers their cost and further increases market share. This cycle has lowered the cost of a carbon mast to only about 50% more than a tapered aluminum mast and price parity will probably be achieved in the future. Also the price of the tapered aluminum mast is constant regardless of the quantity ordered because the cost is primarily labor per mast since a skilled welder & fabricator are required. In contrast doing a run of carbon fiber masts can use single mandrel and be automated so the unit cost can drop as quantity increases. It is likely that the favorable economics and performance of carbon fiber masts will all but eliminate aluminum masts in the next decade or two.

The other segment of the market are those companies making high volumes of small boats and dinghies. Today due to mergers there are really only 4 companies left. They each make thousands of boats a year. The bulk of these are made by one company, Vanguard, in just two of their dozen models – the Laser and the Sunfish. They make over 5,000 boats a year of each type and there are about a quarter million of each produced over the last 40 years. Both of these boats use untapered aluminum masts because of their low price and since they were designed well before carbon fiber masts existed. The performance of the boats suffers for it, and lately the companies have experimented with pultrusion carbon fiber masts and will probably switch manufacturing processes in the near future. One other common design decision made for economic reasons is pooling the mast design across several models. You will see the same mast cross section on boats of similar sizes with varying length, despite massively different stresses on the mast due to sail size. It is far cheaper to overbuild the masts of most boats than to create a new die with the optimal die when they may only make 500 or 1,000 of a model over several years.

New dinghy designs use tapered aluminum masts. They may use an already available untapered section, but where ever a new investment is made in a die it is for carbon fiber pultrusion. Wind surfer manufacturers led the change because of their high volumes and sailboat manufacturers are following suit with all new designs.

Summary of Mast Manufacturing Economic Factors & Performance					
	Untapered Aluminum	Tapered Aluminum	Pultruded Carbon Fiber	Hand Layup Carbon Fiber	Wound Carbon Fiber
Price	$	$$	$	$$$	$$$$
Quantity	>10,000	>1,000	>10,000	>=1	>=1
Variety	New die per cross section, length variable	New die per cross section, taper and length variable	New die per cross section, length variable	New mold required per mast type, generally custom	New mandrel required per mast type, generally custom
Labor	Low	High	Low	High	Low
Capital Costs	Extrusion machine, dies, machining tools	Extrusion machines, die, machining tools	Pultrusion machine, dies	Molds, autoclave	Mandrels, autoclave, filament winding machine, mandrel press
Net Shape	Yes	No	Yes	Yes	Yes
Weight	High	Medium	Medium	Low	Lowest
Taper	No	Yes	No	Yes	Yes
Performance	Low	Medium	Medium	High	Highest

Lessons for New & Experienced Engineers

For new engineers, mast manufacturing shows how design decisions are often driven by economics, especially quantity. The designers of dinghies share masts across models to take advantage of spreading the capital cost of an aluminum extrusion die over more units even though the performance suffers. While tapered masts are superior in performance to untapered aluminum masts, they are never used on mass production boats because the per-unit cost is constant regardless of quantity.

It also shows how quickly technology can change a field and why college engineering programs focus on fundamentals and leave practical details completely out of it. Students often complain that nothing is practical, but a naval architect graduating in 1985 learned little about carbon fiber masts, and today deals almost entirely with them.

For experienced engineers mast manufacture shows how many variations there can be on a simple problem. A mast a fairly simple structure, it is just a tube under compression with some bending forces added in. But there has been a constant evolution in the technology driven by advances in manufacturing. Every one of these advances came from outside of the mast industry because it is too small to do raw research, and that shows experienced engineers how they should look beyond their competitors for new ideas to improve products and solve problems.

Learning:

I have spent thousands of hours looking up at a sailboat mast in my life and always wondered how they were made. When in high school I bought a boat with an untapered aluminum mast and I could see how it was extruded fairly easily before I had any real knowledge of manufacturing methods. But whenever I saw a carbon fiber mast I had no idea how they were made, I thought there was no way they could be made with hand layup since they were hollow and I didn't think a seam would be strong enough. I turned out to be wrong about that. I also had an incorrect idea about how tapered aluminum masts were made – I thought they were cast. I couldn't see how else you would get that shape, and was shocked to find out they were extruded first because I knew that an extruded shape has a constant cross section. I am amazed by the skill of the craftsmen who can weld a cut tube back into such a smooth airfoil after removing a significant amount of material from it.

I also never thought about the economics of it. I was following a design that originally was designed with a tapered aluminum mast, but after there were 50 orders before the design was finished, the designer switched to a filament wound carbon fiber mast. Everyone was surprised when the price didn't really change because we were all used to carbon fiber masts being more expensive. Now I see so easily that the designer traded the extra labor of a tapered mast for the capital expense of a mandrel, and 50 boats must have been over the break even cost of the upgrade even after paying for the more expensive carbon fiber material. Sometimes a “large” quantity doesn't have to be thousands of units to change what manufacturing process is the best fit. The difference between one and a dozen can be huge when you are talking about capital costs of a mandrel or mold.

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