The

Merlin Titanium Primer

BY ROB VANDERMARK

A BRIEF HISTORY

Titanium was discovered in 1790 by William Gregor, a clergyman and amateur geologist in Cornwall, England. However, it was not purified until 1910, and was not refined and produced in commercial quantities until the early 1950s. Since then, titanium production has grown by about 8% per year, and since the early 1960s its use has shifted significantly from military applications to commercial ventures.

Although pure titanium was valued for its blend of high strength, low weight and excellent durability, even stronger materials were needed for aerospace use. In the 1950s, a high-strength alloy called 6-4 (6% aluminum, 4% vanadium, 90% titanium) was developed, and found immediate use in engine and airframe parts. But 6-4's low ductility made it difficult to draw into tubing, so a leaner alloy called 3-2.5 (3% aluminum, 2.5% vanadium, 94.5% titanium) was created, which could be processed by special tube-making equipment.

Today, virtually all the titanium tubing in aircraft and aerospace consists of 3-2.5 alloy. Its use spread in the 1970s to sports products such as golf shafts, and in the 1980s to wheelchairs, ski poles, pool cues and tennis rackets.

In the 1970s, commercially pure, or CP, titanium was used for the first time in bicycle frames. The frames were light and resilient, but they were not nearly strong enough to withstand the rigors of racing. In 1986, the first frames made from 3-2.5 titanium were manufactured by Merlin Metalworks. 1990 saw the first double-butted 3-2.5 seamless tube set, also created by Merlin.

COST OF TITANIUM

Titanium is expensive, but not because it is rare. In fact, it is the fourth most abundant structural metallic element in the earth's crust, after aluminum, iron, and magnesium. It is extremely common in the form of titanium dioxide, and is widely used as a whitener in pigments, paper, and food colorings.

Titanium's high cost arises from three main factors:

- Refinery costs—titanium is never found in its pure form. It must be extracted from other compounds, which requires a significant amount of electrical energy and human labor.
- Tooling costs—whether pure or alloyed with other metals, titanium is a tough material that requires specially made forming equipment, and an oxygen-free atmosphere for heat-treating and annealing (heating and cooling at a controlled rate to eliminate work-hardening and restore ductility).
- Processing costs—titanium work hardens easily, and so must be annealed a number of times during the tube forming process.

Unfortunately, there are no market forces at work to cut the price significantly in the foreseeable future. The slowdown in the aerospace and defense industries has created a slight surplus in capacity, which in the short term should cause more competition and lower prices. However, if these industries keep shrinking, as all signs indicate, the market for titanium will also shrink. In addition, there are design forces at work, including fly-by-wire systems, that will further reduce the total consumption of titanium alloys in the aerospace industry. It is unlikely that the titanium sports industry can make up the difference. One Boeing 747 uses about 95,000 pounds of titanium, more material than all of the titanium bicycle frames ever made.

THE GRADES AND SOURCES OF TITANIUM

Titanium alloys vary widely in their properties and appropriate applications. The alloy most suitable for bicycles is 3-2.5, due to its strength, resiliency, and durability. In addition, 3-2.5 can be drawn readily into small-diameter tubing. Merlin bicycles also employ 6-4 titanium plate in the dropouts, and CP titanium for some non-load-bearing fittings.

CP

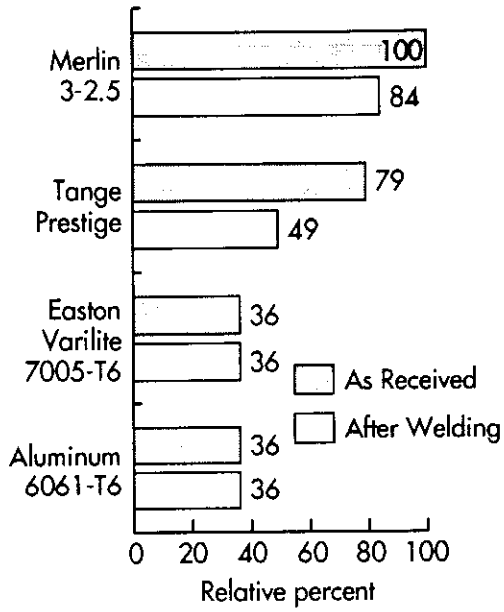
Commercially Pure, or CP, is titanium in its purest form, unalloyed with any other elements. It is available from many sources in the United States, Europe, Russia, and the Far East. It is relatively easy to form into tubing, and it is currently used in a few bonded bicycle frames in Europe and Taiwan.

Although CP has many industrial applications (primarily arising from its excellent corrosion resistance), its strength-to-weight ratio is substantially below that of 3-2.5, and actually worse than many modest steels. There are four grades of CP in the U.S., which are distinguished primarily by oxygen content. Although their strengths vary, none is well suited for lightweight bicycle tubing. CP's yield strength ranges roughly from 25 to 65 ksi (thousand pounds per square inch). Grade 4 has the highest yield strength; Grade 1 is the weakest.

3-2.5

Titanium 3-2.5 is an alloy of 3% aluminum, 2.5% vanadium, and 94.5% pure titanium. The strongest grade, called AMS 105, has a minimum yield strength of 105 ksi, and a minimum ultimate tensile strength of 125 ksi. It has an annealed elongation of 15-30%, and a cold-worked minimum elongation (ductility) of 10%. It does not respond well to heat-treatment. Instead, increases in strength come solely from cold working.

Its fatigue strength-to-weight ratio is roughly twice that of the 4130 chrome-moly steel used in bicycles.



Fatigue strength-to-weight ratios, normalized for AMS 105 3-2.5 titanium

It has excellent resiliency, which can be controlled by changes to the tube diameter and wall thickness, allowing the bicycle designer to accurately tune the ride. This latitude is a direct result of titanium's superb margin of fatigue strength, and is unique to the metal; neither steel nor aluminum enjoys the same "tunability."

As with most titanium alloys, 3-2.5 is corrosion resistant, and it does not need to be painted.

6-4

6-4 alloy (6% aluminum, 4% vanadium, 90% titanium) was the original miracle metal of the aerospace industry, due to its outstanding strength-to-weight ratio. Its primacy is such that it currently represents fully 50% of all titanium alloy usage in the U.S.

However, 6-4 has several severe drawbacks as a bicycle frame material. Compared to 3-2.5, 6-4's ductility is roughly 30% lower, which, combined with its higher strength, makes it extremely difficult to draw into seamless small-diameter tubing. Instead, most 6-4 tubing is rolled and welded from sheet, creating seamed tubing with potentially irregular properties. Cost is a limiting factor, too; 6-4 is more expensive to machine and process.

Finally, it should be noted that 6-4's modulus of elasticity is virtually identical to 3-2.5. Contrary to the claims of some manufacturers, a frame made from 6-4 is no stiffer than one with identical wall thicknesses and diameters made from 3-2.5.

Russian Titanium

Russia has recently been identified as a possible source of low-cost, high-strength titanium alloys. The appeal seems to be twofold:

First, in theory, Russia's costs of labor and electricity are lower than the West's. However, costs are also lower because those manufacturers offering tubing for sports applications have not invested in up-to-date equipment and processes for optimum quality.

Second, Russian producers reportedly have a more extensive array of high-strength alloys. This, however, is a misunderstanding that arises from Russia's labeling system for its 200 alloys. In fact, many Russian alloys are similar to U.S. alloys, but carry different names or slightly different formulations. For example, Russia's equivalent to 6-4 is called VT-6. The properties of these alloys are nearly identical. And Russia's VT-5 alloy has similar performance specifications to 3-2.5.

In 1993, the Raleigh Cycle Company began distributing a frame featuring tubing manufactured in Salda, Russia (the frame is welded in England). This tubing, called BT01, is a Commercially Pure titanium approximately equivalent to U.S. Grade 4, or Russian grade VT1-1 (64 ksi yield). The yield strength is roughly 70,000 psi, an increase of 40,000 psi over U.S. Grade 1. The tubing is strengthened to this level through oxygen induction (or "oxygen hardening"); oxygen content tolerance is 2.6 times higher for Grade 4 than Grade 1. Nitrogen induction is also employed in BT01 to increase yield. Although yield does increase with oxygen induction, ductility is reduced by about 80%; that is, elongation falls from 27% to 6%, creating a much more brittle structure. Fatigue strength is also reduced.

Merlin has worked with a few groups from Russia for the past four years, but so far the quality of their products has been unacceptably low. Raising the quality will require heavy investments in tooling, processing and equipment, which in turn will increase costs, probably to levels equal to or greater than those in the U.S.

Reliable delivery is also problematic, in part due to Russia's political situation. With no assurance of a stable supply or guaranteed shipments, the immediate future for Russian titanium seems questionable at best.

3-2.5 Tubing Comparison

In the U.S., the three most common grades of 3-2.5 titanium used in bikes are:

• 3-2.5 AMS grade 105, the same stuff you would find under the hood of a 747. This material must meet all AMS specifications (Aerospace Material Specifications, as issued by the Society of Automotive Engineers) for hydraulic tubing.

Theoretically, buying AMS 105 tubing directly from the mill allows the designer an unlimited choice of diameters and wall thicknesses. In reality, there are large minimum order requirements and long lead times involved, and only the largest titanium fabricators, such as Merlin, can afford this luxury.

Buyers sometimes add to or modify the standard specifications for AMS tubing. Merlin's tubing varies from AMS grade 105 in that it has more stringent tolerances for straightness and surface texture. Merlin's tubing also exceeds AMS specs for minimum ultimate tensile strength and minimum yield strength.

• 3-2.5 "sports grade." Sports grade tubing is marginally less expensive because it is subjected to fewer processing steps, which is supposed to cut costs. However, the cost savings to date have had a detrimental effect on material formability and surface texture, both inside and out.

• "Scrap" 3-2.5. This is material which has not met aerospace and/or sports grade specifications, or is simply a small amount of overrun. One of the problems in using scrap tubing is that there are no certifications or specifications, and thus no means for the buyer to determine whether any structural anomalies exist.

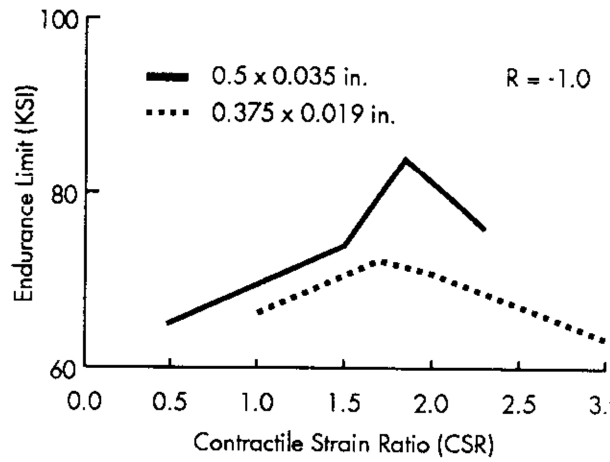
3-2.5 Tubing Processing Variables

Although AMS standards prevail for all certified aerospace tubing, there is a window of acceptable performance, and processing plays a large role in the quality of the final product. There are three manufacturers of 3-2.5 tubing in the U.S., and each makes its tubing in a different way. These processing differences create a wide range of 3-2.5 tube quality.

There are three main processing variables in U.S.-manufactured 3-2.5 titanium tubing:

1. The molecular grain orientation of titanium, sometimes referred to as its texture, affects some of its properties, and can be controlled by processing. Molecular orientation is measured by testing the material's contractile strain ratio (CSR), which is the ratio of diametral strain to radial strain. A small value, such as 0.3, denotes tangential crystalline grain texture, while values above 1.8 can be considered radially textured.

A CSR from 1.7 to 1.9 promotes the highest fatigue strength possible while maintaining excellent bending characteristics. Additional radial texturing can push the



Contractile strain ratio versus fatigue for 3/8 and 1/2 inch AMS 105 3-2.5 tubing. Note the sharp drop in fatigue endurance as CSR approaches 2.0.

CSR past 2.0, which improves bending even further, but only at the expense of fatigue life; fatigue endurance drops dramatically at CSR levels above 2.0.

For best results, CSR should be controlled and determined at the mill when the tubing is made. Tubing diameter and wall thickness are always reduced at the same time, but not always at the same rate, and it is the difference between diameter reduction and wall reduction that determines the direction of grain texture. Larger reductions in wall generate a radial grain texture, while larger reductions in diameter offer greater circumferential grain texture.

Tube texture can be detrimentally affected by cold working after the tubing has run through its final cold-worked, stress-relieved (CWSR) cycle at the mill. For example, forcibly reducing a tube (as by swaging or tapering) after it has completed its final CWSR cycle rotates the molecules out of their radial orientation and lowers CSR. Reduction processes like these, often used to taper main tubes and chainstays, diminish the endurance limit of the tube.

2. Surface finish, both inside and outside, is directly affected by processing. Titanium is more notch-sensitive than steel. A defect-free surface makes a significant contribution to longer fatigue life. The inside diameter of most titanium bicycle tubing also plays an important role in promoting fatigue endurance; typically, the tube wall is so thin that both the outside and inside diame-

ters undergo a cycle of relative compression and tension. The tension, or pulling, causes micro-cracking, which in turn can cause the tube or joint to fail. If the inside surface texture is much rougher than the outside, crack growth can begin on the inside.

3. Any surface or chemical defect will affect the tubing. The only way to avoid this is through rigorous quality-control procedures at the mill.

These factors, individually or in combination, greatly affect the longevity of a 3-2.5 seamless tube, and, in turn, the quality of the finished product.

Resiliency, Flexibility and Fatigue

Historically, titanium frames have been more compliant than most steel or aluminum frames, and this has given titanium a reputation for being inherently flexible. But the so-called flexibility of any material is measured by its modulus, or stiffness, per unit of mass. And the three most common frame materials—steel, aluminum, and titanium—actually have similar modulus-to-density (stiffness-to-weight) ratios. Steel's ratio is only about 10% higher than titanium's.

This similarity means that a titanium tube of the *same* diameter and the *same* weight as steel or aluminum will have similar stiffness. But of course, no one builds frames that way—nor can they, because modulus isn't the only governing variable. The other property that must be considered is fatigue strength.

Fatigue strength can be loosely defined as the number of cycles at a given stress level a material can take before it breaks. It so happens that titanium has exceptionally high fatigue strength. Since titanium can take many more cycles of stress without damage, bicycle designers can create resilient frames with less concern that flexure will cause failure.

Conversely, metals that have poor fatigue endurance cannot be given much room to flex. Aluminum has the worst fatigue endurance of these metals, and so aluminum frames tend to be very stiff—not because the metal itself is stiff, but because allowing an aluminum frame to flex will significantly reduce its service life.

For a simplified example of this phenomenon, compare two aluminum frames, one very flexible, the other very stiff. Assuming everything else is equal—rider weight, terrain, frame geometry, and so on—the flexible frame will fail from fatigue much quicker than the stiff frame. The ultimate failure of each frame is caused by the cycles of stress it endures, with the more flexible frame cycling through higher stress peaks than the stiffer frame (the greater the deflection, the greater the stress). The higher the stress peaks, the shorter the theoretical fatigue life.

Steel has much better fatigue endurance than aluminum, so allowing the frame to flex isn't as much of a problem. But steel is twice as dense as titanium, so it is more difficult to tailor the stiffness of the ride without running into weight problems. Put another way, since titanium is half as dense as steel, more of it can be used to tune the ride by juggling tube diameters and wall thicknesses, while still creating a frame that is lighter than an equivalent made from steel. And if the 3-2.5 frame were designed to be as stiff as the same steel frame and weigh roughly the same, it could have roughly twice the fatigue strength.

Thus, it is not resiliency per se that is the issue, but rather how the designer is able to exploit the fatigue properties of the material. Although the modulus-to-density ratios of the materials may be virtually the same regardless of strength or alloy, a bicycle's tubing diameter and wall can have a profound effect on the stiffness or resiliency of a frame—assuming the fatigue strength of the material allows this design latitude.

This model is simplified greatly, and there are many factors beyond material choice that affect fatigue life. The tube diameter, wall thickness, butted sections, surface finish, and tapering all influence fatigue life, as do frame geometry, weld quality, braze-ons, component choice, and rider style.

The net benefit of titanium's high fatigue life-to-weight ratio is the ability to modify the tube geometries in pursuit of a lighter frame that is stiff as a steel frame, or, alternatively, designing a more resilient frame without sacrificing fatigue life.

Finally, it follows that given the freedom to modify tube geometries, a titanium frame can be stiffer than a steel frame, too, if that is the goal.

Titanium Use and Abuse

Titanium's amazing strength, light weight and exotic origins have created a bizarre mythology, and led to its appearance in some odd places. As with any material, there are good applications and bad applications. The trick is to use titanium in the right place for the right reason.

Some of 3-2.5 titanium's strengths are:

- Excellent fatigue strength (twice that of 4130 steel)
- High strength-to-weight ratio
- Excellent elongation (ductility) of 15-30%
- Excellent corrosion resistance

Titanium's high fatigue strength gives the designer a wide latitude in choosing how the bicycle will perform. A frame can be made relatively resilient or very stiff, depending on the need, simply by modifying the thickness and shape of the tubes.

Unfortunately, there are many areas on a bicycle that have design constraints, due to the use of standardized components. Most of the geometries used in bicycle tubing were created to exploit the best properties of the steels available 40 or so years ago. Today, any deviation from those standards requires an enormous commitment of energy and resources to convince component manufacturers that a change is necessary, and retail dealers that it is worthwhile to carry a separate inventory of non-standard replacement parts.

Nevertheless, there is no current frame application that is not well suited to titanium, assuming the designer has the freedom to specify an appropriate tubing geometry. In areas of the bike where design latitude is restricted, the advantage of 3-2.5 titanium is not always as great.

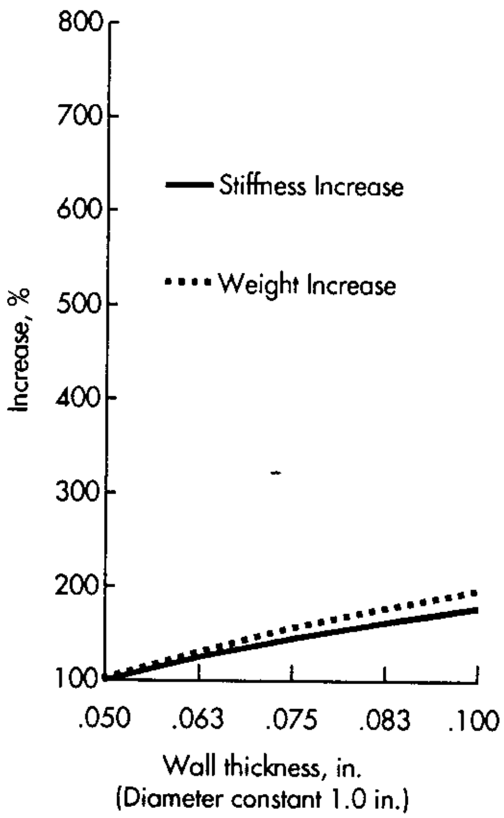
Forks are a good example of an area where geometry restrictions bias the material application toward steel. Assuming the designer is restricted to a one-inch steerer, and the goal is to create a titanium steerer as stiff as its steel counterpart, the titanium steerer will have to weigh over 60% more than the steel equivalent.

Increasing the size of the steerer and headset does not necessarily improve the equation. With a 1.25-inch headset, a titanium steerer is roughly 25% lighter than a steel steerer of equal stiffness. However, the 1.25-inch headset is heavier than a 1-inch version, and the larger head tube required is also heavier. Apart from expense, there is no net gain.

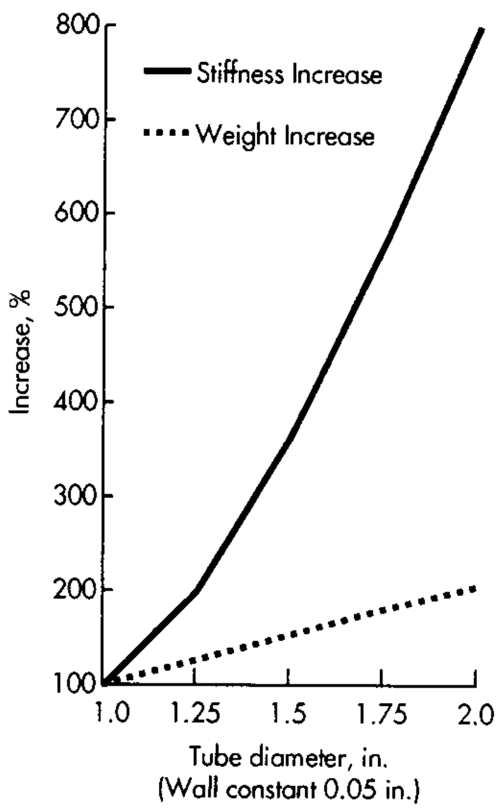
These complications occur because titanium's modulus, or stiffness, is roughly half that of steel (given identical tube cross sections). To explain the steerer issue another way: Doubling the wall thickness of a given tube almost doubles its bending stiffness. That is, the relationship is close to linear. However, doubling the diameter of the same tube—without altering wall thickness at all—increases the bending stiffness by the third power, or roughly 800%!

Thus, the most efficient way to increase the stiffness of any metal is to enlarge the diameter, not the wall thickness. Of course, there is a limit to diameter increases versus wall thinning; if the ratio between diameter and wall becomes too great, the tube will collapse under pressure, like an aluminum can.

When designers run up against diameter and wall thickness limitations, they often turn to shape manipulation as a way to locally strengthen the tube. Flaring, ovalizing, and tapering are common strategies, but, as we will see in the following section, each has significant limitations and problems.



Doubling the wall thickness almost doubles stiffness, but only with a significant weight penalty



Doubling the tube diameter yields a dramatic increase in stiffness, with a minimal weight penalty

Ovalizing and Tapering

Ovalizing

An oval tube is stiffer in its major axis and more flexible in its minor axis. Although ovalizing is often touted as a major contributor to stiffness, it is actually more useful as a means to improve flexibility. Ovalizing does add some bending stiffness in the major axis, but at the same time it reduces torsional stiffness. Since most frame tubes see both bending and torsion, ovalizing is not a panacea.

Also, tubes see bending stress along their entire length. Ovalizing a tube over a very short section—for example, ovalizing a seat tube at the bottom bracket shell—results in marginal bending stiffness improvements along the tube's major axis while making it more flexible through its minor axis. And of course torsional rigidity suffers as well.

Tapering

Tapering was first used on steel bikes to help soften the ride over the poor road conditions at the turn of the century. At that time, virtually all bicycles had tubing with relatively thick walls, primarily because the cost of more accurately drawn thinwall tubing was prohibitive. Tapering was a less expensive way to bring resiliency to the frame, since a tube becomes more flexible as it tapers (that is, its moment of inertia drops). Tradition and cosmetics have continued this practice in modern bicycles, but tapering serves little purpose in improving the ride of any high-quality frame, whether steel or titanium.

Perhaps the easiest way to see why tapering is not generally meaningful is to imagine a hypothetical standard steel frame which has enough stiffness to ensure good ride characteristics. The only way to remove weight from this frame without altering the ride (ignoring fatigue issues for the moment) is to juggle tube diameters and wall thicknesses along the entire length of each tube; otherwise, the torsional and bending stiffnesses will change, spoiling the ride.

Flaring a tube can give thre illusion of greater overall stiffness, but it really depends upon which end of the tube you view. From the small end it appears as if you have increased the stiffness. From the large end it appears that you have created a more flexible tube.

Certainly, a down tube that has been flared at the bottom bracket shell will be stiffer in that area than the same tube with no flare. But it must also be thicker, and therefore heavier, to avoid upsetting the tube's diameter-to-wall ratio; otherwise, the tube will collapse.

Thus, the most weight-efficient way to limit flex is with a tube of constant diameter and wall thickness. For example, say you want to increase the stiffness of a 24-inch down tube by 50%. One approach would be to flare the first 12 inches of the tube until the 50% stiffness increase was met. This method would also increase weight by roughly 25%. A second approach would be to increase the overall diameter of the entire tube, which would raise weight by 20%. In the end, both tubes would display the same deflection under a given load, but the unflared tube would be lighter.

When resiliency is the goal, a better approach is to start with a smaller diameter tube with a thinner wall. This can give the same flexibility over the length of the tube while saving weight.

Tapering or swaging in titanium also creates problems with grain orientation in the metal (see "3-2.5 Tubing Processing Variables"). Swaging forces the molecules to align with the longitudinal axis of the tube, rather than to maintain their optimum radial orientation. This has a detrimental effect on fatigue life.

There are some good uses for tapering, however, particularly in the seatstays. The main function of seatstays in a rigid frame is to provide a place to put the brakes. A tube that is very rigid in bending and torsion at the brake mounts is useful, but the rest of the tube does not contribute much to the ride of the bike. A tapered seatstay could cut weight slightly without harming performance. Any weight savings would have to be carefully balanced against losses in fatigue endurance, however.

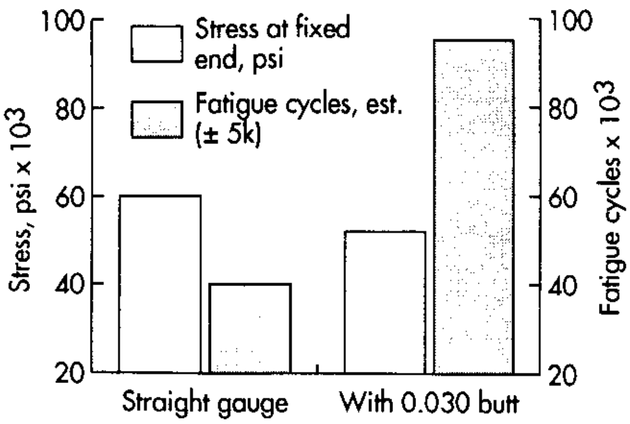
The evolution of suspension frames may trigger more applications for tapered tubing. Clearance issues arising from ergonomics and standardized components may require some interesting tube configurations.

Finally, it is worth noting the one drawback of a straight-gauge tube is that, compared to a tapered tube that is equally stiff in bending, the straight-gauge tube will have a higher stress concentration at the joint. This concentration can be resolved through butting.

Double Butting

The mechanical properties in the welded or brazed joints of any steel or titanium frame are always lower than in the unheated areas. This loss in strength is an important consideration because the joints are usually the most highly stressed areas on the frame, and most frame failures occur at the joints. Fortunately, titanium retains a greater percentage of its raw yield strength after welding than steel, so the drop in strength is not severe.

Nevertheless, it is desirable to minimize stress levels at the joints whenever possible. Butting the tube—making it thicker at the ends and thinner in the middle—is an efficient way to strengthen the heat-affected zone



Stress in a straight-gauge tube, measured at the fixed end, is higher than in a butted tube, and fatigue failure occurs much sooner (1.25 x 0.026 x 24 in. 3-2.5 titanium tube, left, and same tube with 0.030 in. butt, right. Fully reversed 75-lb. load).

(HAZ) at the joints without adding significant weight. Put another way, a properly butted thinwall non-tapered tube creates an extremely lightweight structure without sacrificing fatigue life.

This is not to say that butted tubing is always necessary. Since, under a given load, a stiffer tube has lower stress and, therefore, improved local fatigue life, there are some areas of the frame in which a tube can deliver the desired ride characteristics and also have more than enough bending stiffness at the joints. That is, the tube's geometry (its inside and outside diameter) can be adequate to keep joint stresses reasonable.

For example, the performance requirements for road bikes and mountain bikes are very different. A mountain frame built from a butted road tube set could have adequate fatigue life, but it would not be stiff enough in bending or torsion. Adding stiffness to this frame in any optimal way would also increase its ability to resist bending stresses, which in turn would help improve its fatigue life. In this case, the need for butted tubing would be greatly reduced.

However, when a tube is designed for a given application, there is usually more than one goal, and the goals often conflict: weight vs. stiffness, weight vs. strength, stiffness vs. resiliency, and so on. In these cases, butted tubing can be an excellent solution.

Engineering Principles of Butting

Butting is a process that varies the wall thickness of a tube to provide local reinforcement. It was first applied to steel tubing in the 1890s, and was patented by Alfred Reynolds and J.T. Hewitt in 1897.

When properly applied, butting can significantly enhance the fatigue endurance, and thus the service life, of a frame tube. Fatigue endurance is improved because the thicker tube wall in the butted area is stronger.

Butting can reduce weight, too, since the unbutted areas of the tube are lighter than the butted areas. And it can improve ride quality if the thinner center sections of the tube are allowed to flex somewhat.

Butting always makes a tube stiffer locally, at the butt, but *only* locally. Contrary to common opinion, any local stiffness increase gained through butting does not have much effect on overall tube stiffness. That is, frames with butted tubing are not automatically stiffer than frames with straight-gauge tubing.

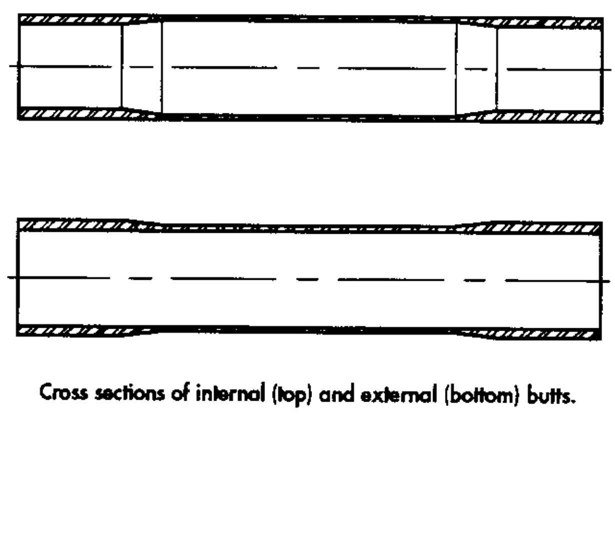
Tubing can be butted at one end ("single butted"), at both ends ("double butted"), or can have any number of wall thicknesses to solve specific problems (leading to "triple butting," "quadruple butting" etc.). Generally, true butted tubing is considered to be seamless and cold-worked to shape. Other externally or internally applied reinforcement methods, such as gussets or sleeves, are sometimes referred to as "butts," but this is a misnomer. In this discussion, butting will only refer to tubing made with seamless starter stock, and without gussets, sleeves, or other secondary reinforcements.

Internal and external butting

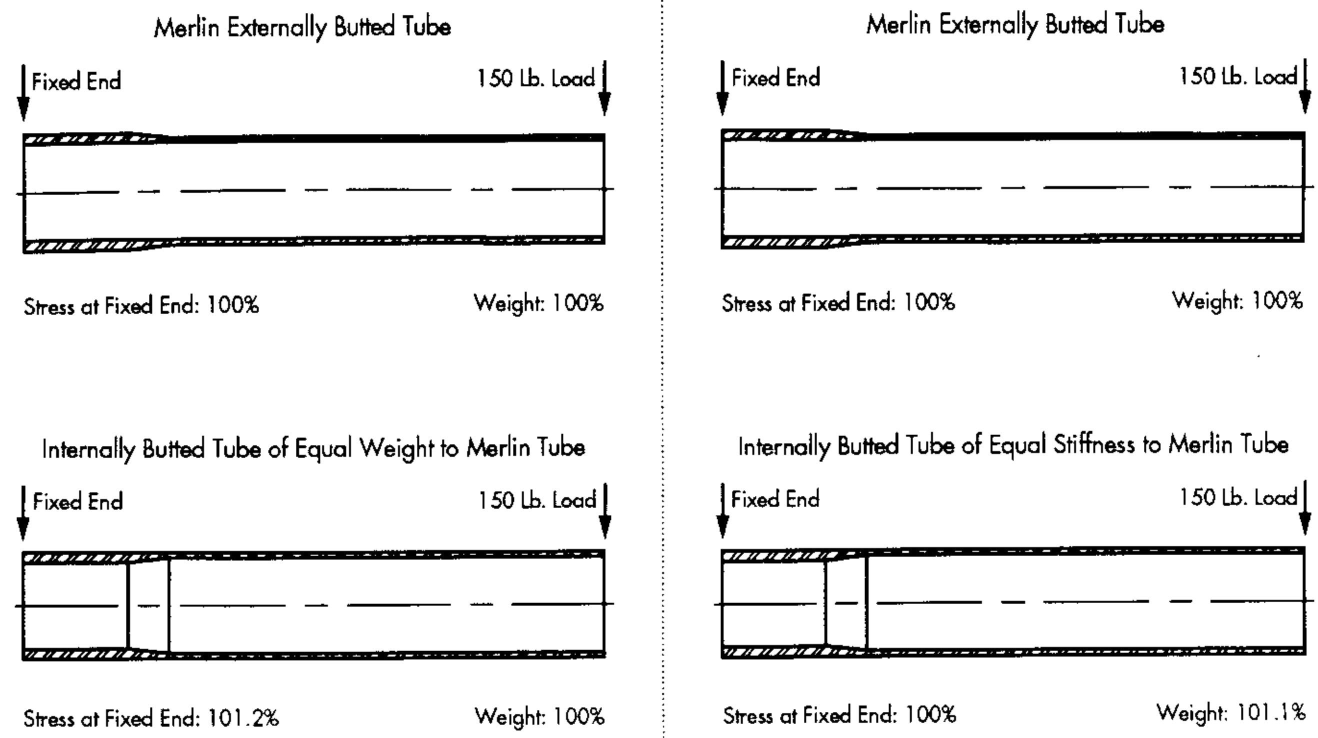
Tubing can be butted internally, which is the traditional method patented by Reynolds and Hewitt, or externally, which is a more recent approach. Internal butting is useful for lugged construction where the reinforcing lug slips over the outside of the tube. Internal butting is also cosmetically appealing, since wall thickness variations are not apparent to the eye. And the forming mandrels for internal butting are less expensive than external rolling dies.

However, external butting offers certain advantages, and is a superior method for tube reinforcement. If two tubes of identical bending stiffness and which offer equal fatigue endurance at the joint are butted, one internally and one externally, the externally butted tube will be lighter.

If these same tubes are modified slightly to offer identical weights, the externally butted tube will be



Cross sections of internal (top) and external (bottom) butts.



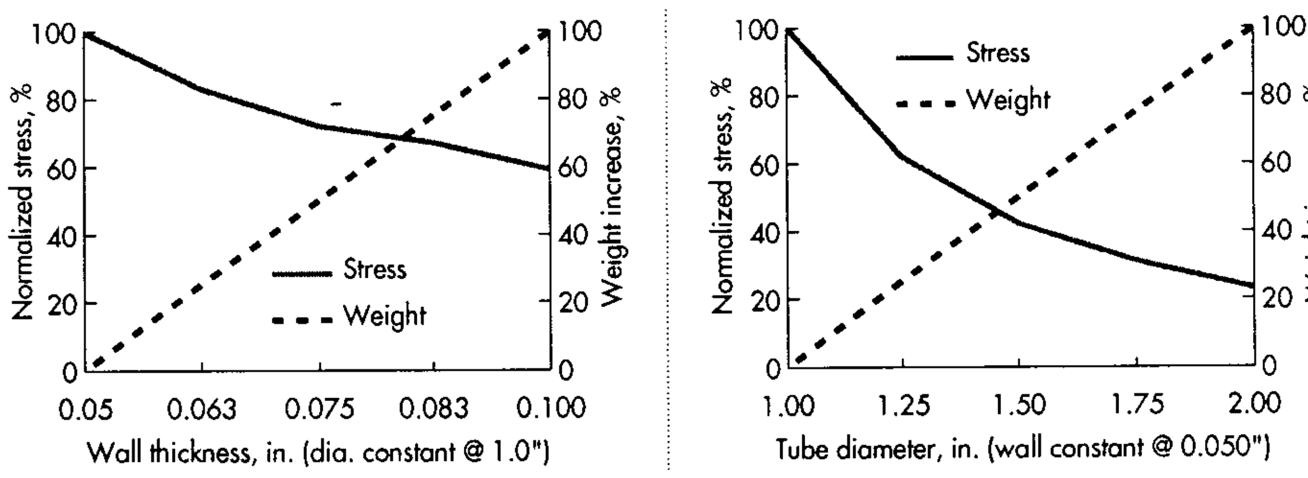
**Given two tubes of equal weight, an internally butted tube will exhibit higher stress (left).
Given two tubes of equal stiffness, an internally butted tube will weigh more (right).**

stronger, and will also exhibit lower stress at the joint.

To see why this is so, it is important to consider all of the variables that affect fatigue strength, stiffness, and weight. The most efficient way to improve the specific fatigue strength of a tubular joint is to make it stronger. A stronger tube handles loading better, and is generally more resistant to fatigue failure.

Strength can be gained by increasing the thickness of the tube, and indeed, an internal butt performs just that function. This is not an ideal strategy, however, because making a tube thicker adds strength and stiffness rather grudgingly. When wall thickness is doubled, for example, the stress level in the tube per given load is cut roughly in half. The most efficient way to improve strength without a significant weight penalty is to increase the tube's diameter, which improves the picture rapidly at a ratio of about 1.6:1, strength to weight.

If all things were equal, then, it would seem that the best way to butt a tube would be to simply flare the tube ends. Though this might be the case in a lower grade tube that has not been optimally designed, any tube that has been properly engineered for minimum weight and maximum fatigue endurance will already be at its maximum diameter limit. At this point, if the



**Making a tube thicker reduces stress (left), but only at a modest ratio.
Increasing the tube diameter, though, cuts stress levels dramatically (right).**

diameter is increased by flaring without a corresponding increase in wall thickness, the tube will surpass its buckling limit, and will collapse like an aluminum can when heavily loaded.

Thus, the optimum strategy is to simultaneously increase the tube wall thickness and the tube diameter in an ideal proportion—which is to say, to externally butt the tube. The external butt provides maximum strength with minimum weight. It cannot be surpassed.

External butting also offers the greatest flexibility in choosing optimum wall thickness differentials between the butted and unbutted sections. To see why this is so, it is important to understand that internally butted tubes are manufactured not by adding material to the ends of the tube, but by displacing material from the center of the tube to make the tube thinner in that area. When this process is complete, the internal mandrel that is used to thin the center sections must be withdrawn past the thicker ends. Typically, internally butted tubes are limited to a 40 percent thickness differential to allow the mandrel to be pulled out.

Externally butted tubes suffer from no such differential limitations. Indeed, only external butting allows every possible permutation of tube diameters and wall thicknesses, and an optimum strength-to-weight ratio.

Butting considerations in titanium

With the possible exception of mercury, no metal likes to be pushed around too much, but titanium is especially sensitive to manipulation. In fact, its properties are radically altered by cold working. This is both good and bad. It's good in the sense that strength increases can be achieved through simple means, such as cold working. But it's bad in that any cold work after final anneal and stress relief will change the tube properties, often for the worse.

At the root of this behavior is titanium's crystallographic texture (CT), which is determined when the tubing is made. The measure of crystallographic texture is called "contractile strain ratio" (CSR), which is determined by comparing the tubing's diametral strain to its radial strain.

The tubing's CSR, and thus its CT, is optimized by controlling the rate of size reduction. During the manufacturing process, a reducing die is rolled over the outside of the tube while the inside of the tube is supported by a mandrel. The titanium is squeezed between the die and mandrel like cookie dough under a rolling pin. As deformation occurs, the titanium molecules are forced to rotate and realign.

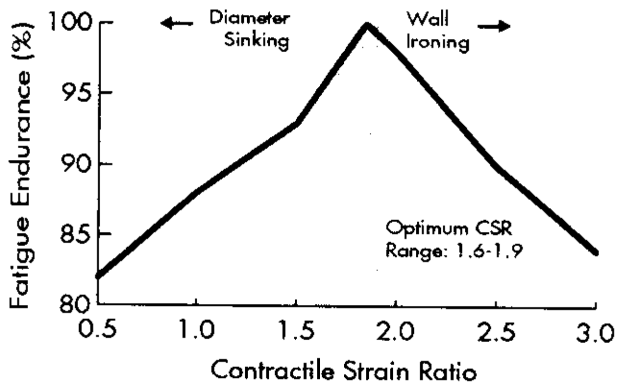
Only so much of this manipulation (called "rocking," because the die rocks back and forth along the tube), can take place at one time. For Merlin MTS325 tubing, the process starts with titanium "tube hollows" roughly 2.375 inches in diameter, with a wall roughly

CONFIGURATION	Internally Butted Tube	Swaged Tube	Merlin Butted Tube
REDUCTION PROCESS	Wall Ironing	Diameter Sinking	Wall & Diameter
MOLECULAR ORIENTATION (Tube Cross Section)			
CONTRACTILE STRAIN RATIO	Too High	Too Low	Optimal
MOLECULAR TEXTURE	Radial	Circum-ferential	Preferred
PROPERTY RESULT	Poor Fatigue	Poor Fatigue	Optimal Fatigue

0.8 inches thick—a long way from the thinwall small-diameter tubing used in bicycle frames. Getting to the final dimension takes many reducing, or "pilgering," steps, each step followed by a trip through an annealing oven to eliminate excessive hardness and loss of ductility due to the cold working of the tube. The rate of pilgering is the primary way in which CSR is controlled.

Pilgering control of CSR can be accomplished through either "wall ironing" or "diameter sinking." Wall ironing takes place when the reduction in wall thickness is proportionally greater than the reduction in diameter. Diameter sinking results when the reduction in diameter is proportionally greater than the reduction in wall. Ironing pushes CSR up. Sinking forces CSR down.

Cold working is, therefore, a good way to fine-tune the tubing's bending characteristics and fatigue strength. But too much cold working at the wrong rates can destroy those properties, weakening and embrittling the tubing significantly—even radically. The useful window for CSR in bicycle tubing is narrow, and tubing that



The effect of CSR on fatigue endurance.

falls outside a CSR of 1.6 to 1.9 suffers from poor fatigue endurance.

The only way to obtain a consistent CSR of 1.6 to 1.9 throughout the tube is to create a constant wall thickness and a constant diameter. It is not possible to change the dimensions of the tube through material manipulation without affecting molecular structure, and thus CSR. Both wall ironing and diameter sinking destroy the ideal CSR of the starter stock and thereby shorten the service life of the tube. The effect can be dramatic, with the drop in fatigue endurance alone exceeding 10 percent.

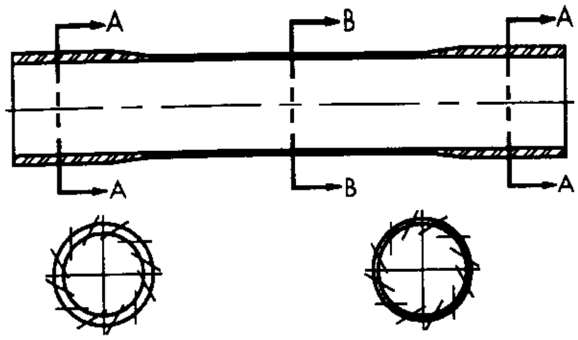
Internally butted tubes are created at the mill through wall thinning, or ironing. Tapered tubes are created by diameter sinking. Even though the tube may have had ideal properties before pilgering, the ironed or sunken sections of the internally butted or tapered product will exhibit significantly poorer properties than the starter stock.

Merlin MTS325 butted tubing is created through proprietary processes that do not alter the ideal CSR range. Because CSR remains constant, there is no loss of fatigue strength or ductility.

What of the claim that CSR should be altered for different parts of the frame? Under this argument, chainstays that need to be bent would use tubing with a different CSR, or radial texture, than, say, the down tube, which does not require bending. Although this argument may sound plausible, further examination reveals a fundamental problem: the CSR that offers the highest fatigue strength also offers excellent ductility. High ductility supplies the best bending characteristics. Thus, while enhanced bending properties are sometimes touted in higher CSR tubes, ductility actually falls as CSR rises.

From where, then, did an argument for using a range of CSR values arise? Most titanium bicycle frames are built with tubing obtained from more than one mill, and the range of CSRs is an inevitable byproduct of this multiple sourcing. To make the best of a bad situation, some manufacturers have touted these varying CSRs as a virtue. In reality, however, there is no advantage to using tubing with any CSR outside the optimum range.

Tubing production speed, and thus final cost, also plays a role. Tubing costs can be reduced through faster pilgering. Unfortunately, though, running the tubing



SECTION A-A

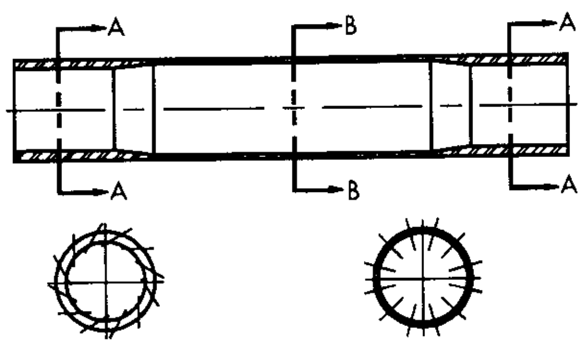
Optimal Molecular Orientation

Optimal Fatigue Endurance

SECTION B-B

Optimal Molecular Orientation

Optimal Fatigue Endurance



SECTION A-A

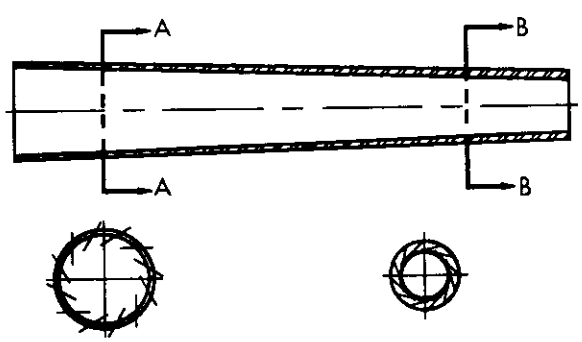
Optimal Molecular Orientation

Optimal Fatigue Endurance

SECTION B-B

Radial Molecular Orientation

Compromised Fatigue Endurance



SECTION A-A

Optimal Molecular Orientation

Optimal Fatigue Endurance

SECTION B-B

Circumferential Molecular Orientation

Compromised Fatigue Endurance

TOP LEFT: Externally butted tubes maintain optimal molecular orientation and CSR in both the butted and unbutted sections.
MIDDLE LEFT: Internal butting forces the titanium molecules into a radial orientation, altering CSR and compromising the tube's fatigue endurance.
BOTTOM LEFT: Tapering also alters CSR. The process rotates the titanium molecules into a circumferential orientation, compromising the fatigue endurance and thus the useful lifespan of the tube.

through the mill faster also leads to higher CSR values and greater radial texture. To keep costs down, most "sports grade" tubing is produced in this way, and the high radial texture that results is sometimes proclaimed a benefit. However, slower pilgering and lower CSRs create a stronger, more durable frame.

Comparison of butted properties

There are three common types of butted titanium tubing. Two are butted internally and one, Merlin MTS325, is butted externally. To distinguish the internally butted methods, we have designated the configurations type 5I and type 3I.

Type 5I tubing: This internally butted tube is made with high-strength starter stock (125 ksi UTS). The tube is butted by wall ironing. As noted above, wall ironing disturbs the titanium's molecular grain structure; thus, only the thick, unironed ends of the tube retain the starter stock's original properties.

The tubing will also be subject to internal scratching, gouging, or notching, due to the action of the supporting mandrel. Notched surfaces create stress nodes in the tubing, leading to premature failure. Unfortunately for the consumer, once the frame is built there is no nondestructive way to determine whether the tubing has a poor internal finish.

Notches, gouges and scratches are of less concern in the thin center sections of the tube than in the transition zone, or butt taper, between the thin center and the butted tube ends. This area is highly stressed and extremely sensitive to surface degradation. Notching here will lead to almost certain tube failure.

Type 3I tubing: Another internally butted tube, but made with annealed or low-strength starter stock. Butting is also performed by wall ironing. The thinned section of the tubing has slightly better properties than 5I tubing, but the thicker end sections suffer from extremely low strength.

Type 3I tubing is less expensive than 5I tubing, because the low-strength starter stock is easier to manipulate. Aside from price, it offers no real advantages. Like 5I tubing, 3I tubing is subject to notch failure from damage caused by the supporting mandrel.

Merlin MTS325 tubing: Merlin tubing is externally butted without mechanically altering material properties or CSR. No internal notches or stress nodes are created during or after butting, so full fatigue strength and CSR are maintained.

Tapering versus external butting

As noted earlier in "Ovalizing and Tapering," tapering is a convention inherited from traditional frame design, where it was used to provide a softer, more flexible ride over the rough roads common at the turn of the century. It is of limited value in a modern titanium frame.

Titanium tubing can be tapered by diameter sinking; the tubing is forced through a die (swaged) until the final dimensions are reached. Tapered tubing can also be created by rolling titanium sheet into a tapered tube form and welding the seam.

Both processes have drawbacks. The molecular structure of the metal is severely affected during the tapering process, altering the CSR and thus the fatigue endurance and the ductility of the tubing. Diameter sinking reduces CSR, and decreases fatigue strength. In fact, the negative effects of diameter sinking on fatigue endurance are quite dramatic.

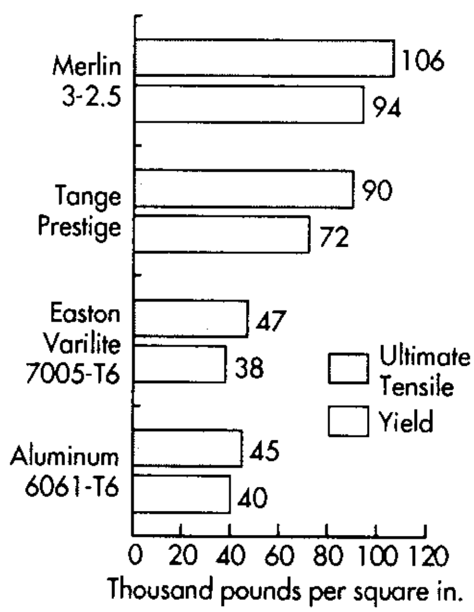
Tapered tubing can be of some use where severe clearance restrictions exist due to component design or geometry constraints. However, every effort should be made to employ untapered tubing instead, with the need for tapering to be carefully weighed against the shorter service life of a tapered tube.

WELDING

Material strength is always lower within a welded joint, whether the metal involved is titanium, steel, or aluminum. The drop in ultimate tensile strength (UTS) for 3-2.5 titanium in the heat-affected zone (HAZ) is roughly 12-15%. Note that UTS drops 40-50% in a high-quality steel tube. Aluminum also suffers a significant loss, but in many alloys strength can be recovered by solution heat-treating and aging.

Titanium weld quality depends on many factors:

1. Cleanliness has the single biggest impact on



Strength of materials after welding

weld quality. The surface metal must free of grease, chlorides, and all contaminants, and the entire weld area must be free of oxygen, nitrogen, and hydrogen during the process of welding. Even fingerprint oil can contaminate the weld area, so scrupulous cleansing standards must be maintained at all times.

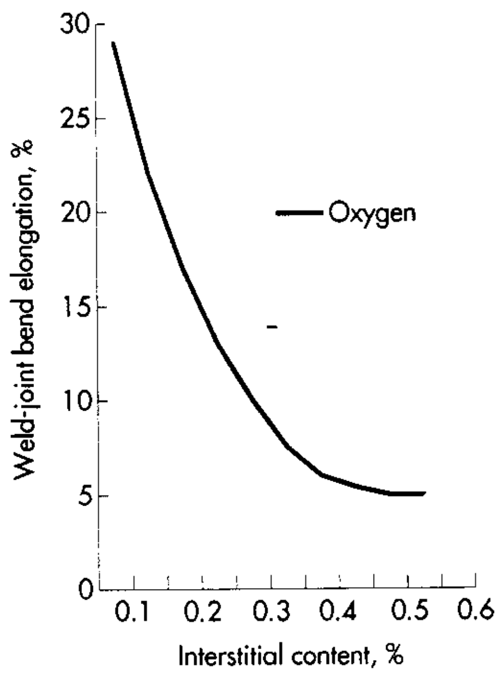
2. Complete penetration of the filler material is critical. Only a highly skilled welder using proper welding equipment on a well-designed joint can assure that the base metal has been properly fused with the filler material.

3. The type of bead plays an indirect role in penetration, and thus in final welded strength. A smooth bead disperses heat, and makes full penetration harder to achieve. Puddle welds heat a smaller area, focusing the bead and improving penetration. An excessively thick or uneven bead will create a harsh transition in relative stiffness between the bead and tube. Since the weld bead acts as a stress riser in any case, it is best to minimize the sharpness of the transition area.

4. The rate of post-weld cooling theoretically affects weld quality, but there is no evidence that cooling rate plays a large role in post-weld fatigue strength.

Welding versus Bonding

The loss of strength due to welding begs the question of substituting bonded lugged joints for welded beads. The primary drawback to bonded construction is added



Even slight contamination with oxygen, whether through poor welding procedures or anodization, greatly reduces elongation (ductility)

weight. For example, the titanium lugs used in the Specialized Epic Ultimate carbon fiber/titanium mountain frame, designed for minimum weight, weigh 1.5 pounds per set. If the frame were built from welded Merlin Extralight double-butted tubing, the butted sections would weigh a fraction of the titanium lug set. This relationship is true of any material, whether metal-matrix composite, aluminum, steel, or carbon fiber.

Anodizing

There are many different types and purposes of anodization, but for titanium bicycles the primary use is decorative. The process creates an anode out of the titanium in a chemical bath and progressively builds an oxide film through electrolysis. As voltage is varied, the oxide thickens and a color spectrum is created. The final product is a dense adherent titanium oxide film.

There are three basic variations of this oxide, determined by voltage levels and electrical dispersion. The titanium oxides are composed chiefly of anatase and/or rutile crystals; anatase and rutile are the main ores from which pure titanium is separated.

Unfortunately, titanium oxide is extremely brittle (regardless of color), and the oxide film is not easily separated from the titanium substrate due to titanium dissolution into the oxide. The normal bending loads seen in a frame will cause slip lines in the brittle colored surface and ultimately create cracks in this anodized shell. The failed oxide film propagates the cracks through the dissoluted titanium oxide mixture and finally into the uncontaminated titanium below the oxide. Once the cracks have moved into the tube wall, they propagate further, ultimately causing frame failure.

Thus, it can be seen that an anodized titanium substrate acts in exactly the same way as an oxygen-contaminated weld zone. The outermost titanium fibers, which see the greatest stress and therefore need the best ductility, become the most brittle. The potential for stress failure is vastly increased.

For these reasons, Merlin strongly suggests avoiding the anodization of any structurally important titanium part. Merlin's lifetime frame warranty is voided if the frame has been anodized.

3-2.5 versus Other Materials

Steel

Although the ultimate tensile strength of many premium steels is greater than 3-2.5 titanium, this raw strength is meaningless in the final bicycle frame because:

1. The strength advantage is lost in welding.

2. Steel's strength-to-weight ratio is lower than that of titanium, both before and after welding.

When comparing materials, strength after welding, or heat-affected strength, must be considered first, because the highest stresses in a frame are at the joints or heat-affected zones. For example, Columbus SL steel tubing has a cold-worked (as received) ultimate tensile strength of roughly 135 ksi, making it equal to Merlin 3-2.5. Ignoring for a moment that Merlin's strength-to-weight ratio is almost double that of the Columbus SL, we find that SL's yield strength drops to 70-78 ksi after welding. Merlin 3-2.5 has a post-weld yield of 90-93 ksi. In addition, for a given weight 3-2.5 titanium has roughly twice the post-weld fatigue strength of 4130 chrome-moly steel.

External and internal reinforcements, such as gussets, butts and lugs, can improve steel's fatigue strength somewhat. Internal butts move the weakest points away from the areas of highest stress. In some cases, however, it is not possible with current manufacturing equipment to create a butt of optimum thickness. The maximum differential between the butted and unbutted sections of a production premium steel tube is about 40%; any improvement beyond that must be achieved in some other way—with gussets, lugs, or other external reinforcements.

An optimally butted steel tube will outperform a gusseted or lugged tube because:

1. A gusset or lug does not reduce the heat-affected zone (HAZ) at the sides and end of the reinforcement. An ideally butted tube provides equal strength and equal or lower weight with no HAZ.

2. Gussets and lugs create stress raisers at their endpoints, with a further reduction in fatigue life due to the HAZ. An ideal butt with a properly designed taper eliminates the stress raisers and also saves weight.

Whether gussets and butts are employed or not, there is still a wide gap between the fatigue strength-to-weight ratio of 4130 steel and 3-2.5 titanium. Claims that it is possible to create a steel frame of comparable weight and strength as a titanium equivalent are unsupportable, as proven by raw objective data, and by the fact that no such frames exist.

Aluminum

Unlike titanium, aluminum's fatigue strength declines continuously with increasing cycles. Therefore, aluminum designs must include a greater design safety factor, which inevitably increases weight and bulk.

A related issue is the failure mode of aluminum, which is catastrophic, rather than gradual. Again, the design safety factor must be increased to compensate.

Aluminum is a good material for low-stress components that see little to no fatigue cycling.

MMC (Metal Matrix Composites)

There are many available types of MMCs, but only one, a particulate-type from Specialized/Duralcan, is presently being used in bicycle frames.

Particulate-type MMCs are the least-expensive form in current production. The Duralcan MMC is an aluminum oxide particulate matrix in an aluminum medium. Other MMCs under development for bicycle use are also particulate types. One employs silicon carbide, the other boron carbide, both in an aluminum base.

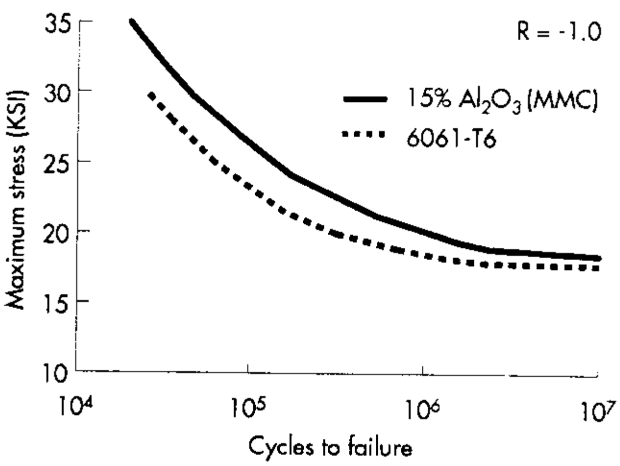
MMCs vary in the base metal from aluminum to titanium to copper, and in matrix additives as noted above. The formats of the additives also vary, from particulates, whiskers and wires to continuous and discontinuous fibers. Each factor plays a large part in the strength and other mechanical properties of MMCs. One thing common so far to all particulate and whisker MMCs is a loss of ductility and fracture toughness, which has had a negative effect on potential fatigue life.

Duralcan's 6061-T6 15% particulate MMC has the following advantages over pure 6061-T6 aluminum:

- Tensile modulus is increased 30% to 12.7 ksi. The higher modulus helps offset the material's low fatigue life, since a stiffer frame has a lower stress cycle.
- Yield is increased by 15%, from 40 to 46 ksi.

Disadvantages of the Duralcan MMC include:

- Elongation hovers at a meager 5.4%, potentially decreasing fatigue life. (Theoretically, if the frame were designed for no flexure whatsoever, elongation would not affect fatigue life, since the joints would not move. In practice, however, this seems unlikely.) Elongation drops another 50% or more for other MMCs. The lower the number, the less ductile the material. 6061-T6 aluminum has 14-17% elongation after welding and heat treatment. High-quality bicycle steel is 10% before welding, 20-25% after welding. Titanium's elongation is 10-19% before and 15-30% after.



Axial fatigue S-N curve comparison of Duralcan 6061-T6 MMC and standard 6061-T6 aluminum

Stress vs. Number of cycles (S-N) fatigue curves remain almost identical to off-the-shelf 6061-T6: 17 ksi at 10^7 cycles for Duralcan MMC vs. 16 ksi for 6061-T6. Therefore, the fatigue strength-to-weight ratio is almost identical to standard 6061-T6. Note that this fatigue strength is hypothetical because, like monolithic aluminum, MMCs do not have true fatigue endurance. Instead, they must be designed with a much more conservative safety factor.

Fatigue strength is the most important consideration in frame design, regardless of which frame material is under consideration. Most frames fail through fatigue, not from one-time overloading, as in a crash. Ultimate strength is of secondary importance, because a high UTS alone does not and cannot make a durable frame.

The most obvious theoretical benefit of any MMC is the potential to create a stiffer material, as in an engine block where rigidity can reduce noise and vibration. This, however, is not necessarily desirable in a bicycle frame. Ride quality is an important consideration that must be incorporated, even if the fatigue issues are satisfactorily resolved.

Welding is also a complication. Most MMCs lose strength after welding, and some of that strength remains unrecovered after heat treatment. In the area closest to the weld (as well as in the weld itself), the particulates become dispersed, which can cause anomalies and strength problems. Heat treatment cannot restore these particulates to their pre-welded state because the metal does not liquefy during heat treatment.

Finally, it should be noted that a bonded MMC frame can never match the weight of a welded MMC frame. Thus, it is doubly unfortunate that many MMCs have serious mechanical degradation after welding.

Titanium Metal Matrix Composites

There are very few titanium-based MMCs in current production, with only two basic types of matrices. One, intermetallic-matrix composite (IMC), uses continuous fiber. The other is formed from titanium carbide particulates. Both have been developed primarily for high-temperature applications, as in engine components and skins for military aircraft.

IMCs are formed from a series of titanium-aluminide foils consolidated with boron-coated silicon carbide continuous fibers. With a starting price of $2000-3000 per pound, it is unlikely they will soon find applications in the bicycle field. Interestingly, raw ingots of titanium cost only $10-12 per pound, so the processing costs to create IMCs are obviously formidable.

Titanium carbide MMCs present similar cost issues. They also suffer from a severe loss of ductility which arises from the induction of carbon into titanium.

Titanium-aluminides are another newly publicized group of aerospace alloys. Strictly speaking, these are not MMCs, but they do boast very high strength and good resistance to loss of mechanical properties at high temperatures. However, they suffer from abysmal ductility at room temperature and exorbitant cost. The ductility issue may soon be resolved; cost, however is unlikely to drop within the foreseeable future.

Beryllium

Beryllium is a light, stiff, and expensive metal that has received recent attention as a potential frame material. Merlin began cooperative work with a beryllium tube manufacturer two years ago, but our preliminary investigation revealed that the stiffness-to-weight ratio of beryllium is extremely high—so high that it would be difficult to build a frame with adequate flex for good ride characteristics. Furthermore, beryllium's cost is so prohibitive that the financial wherewithal necessary to develop a frame is beyond the resources of the bicycle industry.

Even those alloys that incorporate beryllium as their major element are so expensive that it is doubtful any of them will ever find their way into the frame tubing market. In addition, beryllium is toxic, although this can be managed with proper manufacturing procedures.

Carbon Fiber

"Carbon fiber" is a blanket term for a wide variety of carbon-impregnated polyesters, graphite fibers, and polymerized carbon fibers that are used within a matrix of adhesive to create a clothlike structural material.

Within the family of fibers considered appropriate for bicycle frame use, the raw fibers' stiffness-to-weight ratio is roughly 3.5 times higher than 3-2.5 titanium. The ultimate tensile strength is roughly 70% higher.

However, these figures apply only to the raw fiber strand, before it is impregnated by and retained within an epoxy resin matrix. The epoxy adhesive's structural properties are significantly lower. Moreover, epoxy normally occupies 50% or more of the cross-sectional area of a sheet of carbon fiber cloth. This ratio of resin to carbon must be maintained to hold the fibers together; a lower epoxy content reduces the fiber weave's layer-to-layer shear strength. A 50% volume of adhesive reduces the finished product's strength-to-weight ratio by a factor of two.

In addition, carbon fiber is anisotropic, which means that it displays directional properties. For example, a fiber with a modulus of 20,000 ksi when measured longitudinally will have, at best, a transverse modulus of 4,000 ksi. Similarly, the ultimate tensile strength may measure 220 ksi longitudinal, but will be, at best, 10 ksi transverse.

This anisotropic property can be exploited beneficially in some structures, such as leaf springs. However, bicycle tubes must be able to carry stress loads in many planes at once—in tension, compression, fully reversed bending and clockwise and counterclockwise torsion. Thus, it is virtually impossible to utilize anisotropy to any significant extent in a frame.

In addition to the modest structural properties displayed by the epoxy resin, carbon fiber has extremely low ductility and poor abrasion resistance. Historically, low ductility in those bicycle frames that do not use separate lugs has led to joint failure and stress cracking. Abrasion is a particularly thorny problem since composites are notch-sensitive, such that even minute inconsistencies in the material can develop into large cracks, eventually leading to failure.

Abrasion problems can be reduced at the cost of added weight by a protective skin or veil of fiberglass or, at higher cost and somewhat greater strength, Kevlar fiber, but the abrasion resistance of these and similar polyester and aramid fibers is also low. Abrasion and impact damage can be repaired with epoxy-based fillers and additional cloth. However, since the integrity of the structure is dependent upon continuous fibers in tension, the strength of the repaired area will be lower than the original material, and the weight of the repair will be higher.

Carbon-wrapped Titanium and Aluminum

Titanium or aluminum tubing wrapped with a bonded layer of carbon fiber composite has been proposed as a method to achieve a synergistic improvement of material properties. (In fact, carbon-wrapped aluminum tubing was produced by Easton for Raleigh for two years, before the withdrawal of that frame from the market.) The main objectives of this approach are:

- To improve the performance of a low-strength tube. Aluminum's low strength-to-stiffness ratio, for example, can be boosted appreciably with a layer of high-modulus composite fiber.
- To protect the abrasion-sensitive carbon within a metal exoskeleton.

These approaches have a number of drawbacks:

- External carbon wraps do not solve the problem of abrasion damage to the composite.
- Internal carbon wraps do not necessarily protect the composite from impact failure either. To create a frame of reasonable weight, the titanium or aluminum tube must be very thin, and consequently not resistant to denting. Since titanium is very ductile, it can spring back from minor impact with no appreciable damage. However, the internal wrap will suffer local cracking, which can spread into a serious fault.

In addition, delamination of the composite from the tube surface is a serious long-term problem. It has at least three sources:

- Delamination can occur from impact. Once the composite has cracked, it will continue to fail along the fiber orientation. The fissure created by the initial fault becomes a point for peeling or cohesion.
- Delamination can occur at the ends of the supporting tube due to applied bending and torsion during use. Adhesives are weakest in peeling and cleaving.
- Delamination can occur from stress. When used in a wrap, the adhesive must perform two duties, first as the bonding agent between the fibers, and second as the glue between the composite and the tube. Ideally, two different adhesives and primers would be specified, but this is not always possible.

Carbon-wrapped tube frames also suffer from a weight disadvantage, since these tubes cannot be welded once the composite has been applied, and so must be bonded in a lugged frame.

Honeycomb-Reinforced Titanium

Honeycomb-reinforced titanium tubing is conceptually similar to internally wrapped composite tubing, with the primary objective being increased stiffness. The only frame that currently employs this construction uses a lightweight fiberglass honeycomb bonded to a carbon fiber skin, which in turn is bonded to the inside wall of a thin titanium tube. The frame is lugged.

In the current design, the honeycomb lends anisotropic reinforcement properties to the tube. Unfortunately, it is not possible to create layers of directional honeycomb, as can be achieved with carbon fiber. Thus, the honeycomb is inevitably unidirectional, but lies within a structure that demands more isotropic properties.

Since the frame must be lugged for assembly, frame weight is not ideal; a current 54-cm example weighs 3.0 pounds, with the honeycomb and carbon representing 0.75 pounds of this total. A 54-cm Merlin Extralight, with double-butted tubing and similar rigidity, weighs 2.6 pounds.

Titanium Parts

No discussion of materials is complete without considering the reasonable cost of improvement. When does improvement, in any material, fall so far behind its price to a consumer that it can no longer really be termed improvement?

Forks

The biggest hurdle to building a titanium fork that is as stiff as a steel fork and lighter than an aluminum fork is the steerer tube, as discussed earlier under "Titanium Use and Abuse." There are other geometry restrictions that make titanium forks unattractive:

- The compact shape of the conventional road fork crown was optimized for steel, and has been modified somewhat for aluminum. Duplicating the shape of an aluminum crown in titanium will make it stiffer, but not lighter. Removing enough weight from the titanium crown to make it competitive with aluminum involves considerable casting or forging complexities that raise the cost significantly.
- To compensate for the lower modulus of 3-2.5 (compared to steel), the fork legs need to be larger in diameter. This creates an opportunity to save weight, but tire clearance can become an issue.
- The dropouts must be larger to fit the oversized fork legs, adding weight.

At best, then, a titanium fork can weigh about the same as an aluminum fork, with the stiffness of a steel fork, at a cost of five conventional forks. Unless the titanium fork can demonstrate some additional advantage, it appears to be a bad bargain.

Seatposts

The important properties in a seatpost are light weight, high strength, good failure resistance, and adjustability within the seat tube. Reliable aluminum mountain bike seatposts weigh as little as 220 grams. The lightest titanium post is around 195 grams. The titanium post will have better fatigue life, but it will also be more flexible.

A titanium seatpost is also very sensitive to head design and weld quality. Finally, if the titanium post is used in a titanium frame, it will gall, although proper lubrication can minimize the problem.

Chainrings

Chainrings must be light, stiff, and wear resistant. A titanium chainring of the same weight as an aluminum ring will not be as stiff for two reasons. First, aluminum's modulus-to-density is a few percent higher than titanium's. Second, to meet the weight restriction, the titanium ring must be 30% thinner.

A titanium ring of standard thickness could be more durable than aluminum, both in its wear properties and in its ability to survive impact damage from rocks and other trail debris. But this survivability comes at a significant premium in cost and weight.

Metal-matrix composites, whether aluminum or titanium-based, could be ideal materials for chainrings.

Brakes

Brake calipers need to be stiff, failure resistant, and light. Due to clearance issues and other design constraints, it is very difficult to make a titanium caliper that can match the light weight and stiffness of an aluminum equivalent. Aluminum or metal matrix composites appear to have the ideal properties here.

Bottom Bracket Spindles and Pedal Axles

The properties that are important in a spindle are failure resistance, precision, and light weight. A Shimano Dura-Ace or XTR spindle, made from heat-treated 4140 steel, has excellent fatigue characteristics, roughly twice that of current 6-4 titanium spindles. A 6-4 spindle can be considerably lighter, but its fatigue endurance is not acceptable.

An additional drawback is that titanium cannot be surface hardened to create a durable bearing surface. Thus, any titanium spindle must employ sealed bearings, leading to added weight, expense, and complexity.

Bolts

Lightweight titanium bolts, generally made from 6-4 alloy, have demonstrated excellent durability and strength in bicycle applications. Titanium's corrosion resistance is an added plus.

Titanium's lower modulus compared to steel is not a serious drawback, as virtually all bolts are used in compression against fully seated parts, where the bolt's flexibility is not an issue. However, titanium bolts will gall, or seize, when threaded into other titanium parts. This can be avoided by liberal application of anti-seize compound or other appropriate lubricant to the bolt threads before installation.

Handlebars

Titanium's high fatigue strength can be exploited to create mountain bars with excellent flexibility. The bars will transmit less shock and deliver a more comfortable ride. However, if the goal is to create bars of equal stiffness as existing bars made from steel or aluminum, then the weight of the titanium bars will be uncompetitive.

Stems

Forged aluminum road stems and welded steel mountain stems are light and rigid, and have a good safety margin. It is possible to make titanium stems as light, but rigidity suffers. Increasing the rigidity adds weight. A welded, one-piece bar and stem combination can be lighter and as rigid as any current equivalent; the only drawbacks are cost and adjustability.

Future of Titanium

Although new alloys of titanium are under development, the 3-2.5 alloy retains excellent potential. Double-butted steel was patented in 1897, but butting was never applied to seamless 3-2.5 titanium until 1990. The potential for advancement is further illustrated by the Merlin Suspension frame, which uses the chainstays as integral springs, eliminating the weight of a separate pivot and greatly simplifying assembly and maintenance. Similar advancements can be expected at least through the end of the decade.

As Chuck Teixeira, product engineer for Easton Aluminum, said in an interview in *Mountain Bike Action*, "If someone did [with titanium] what [Easton] is doing to aluminum [meaning butting], the game would be over insofar as finding the absolute top of the line material."

We are now at that point with 3-2.5 titanium.

Glossary

3-2.5 a titanium alloy of 3% aluminum, 2.5% vanadium, and 94.5% titanium, valued for its high strength and excellent ductility

4130 an iron alloy classified as a carbon steel, consisting of 0.95% chromium, 0.5% manganese, 0.3% carbon, 0.25% silicon, and 0.2% molybdenum. 4130 is the most common steel used in high-quality bicycle frames due to its high strength, acceptable formability, and low cost

6061 an aluminum alloy of 1.0% magnesium, 0.6% silicon, 0.28% copper, and 0.2% chromium. It is often tempered to T6 condition, which includes solution heat treatment and artificial aging. 6061 is the most common aluminum alloy for bicycle frames due to its reasonable strength, good formability, low cost, and good weldability

6-4 a high-strength titanium alloy of 6% aluminum, 4% vanadium, and 90% titanium

alloy a mixture of two or more metals, or a metal and other materials; 3-2.5 titanium is an alloy of 94.5% titanium, 3% aluminum and 2% vanadium

AMS aerospace materials specifications, a standard classification system issued by the Society of Automotive Engineers (SAE)

anneal to heat and cool at a controlled rate. Annealing is used for many purposes, such as to remove work-hardening and embrittlement. The term is often used to signify a reduction in strength of a material due to heating; a more precise term for this is "full annealing"

butt a thickened section of a tube that reinforces the tube in that area

butting a process that varies the wall thickness of a tube, either internally or externally, to provide local reinforcement

CP commercially pure; a designation for pure, unalloyed titanium

cr-mo (chrome-molybdenum steel) a high-strength steel with alloying elements almost identical to 4130 alloy

CSR contractile strain ratio; a numerical index of crystallographic texture (see "texture") determined by the ratio of diametral strain to radial strain in a titanium tube

CWSR cold-worked, stress-relieved; said of tubing that has been pressed to its final shape without the use of heat (while "cold"), and then annealed to relieve internal stresses from the forming processes

delaminate in a fiber composite structure, such as carbon fiber or fiberglass, the separation of the fiber from the epoxy resin that holds the fiber strands together; caused by stress, fatigue, or impact

density the ratio of mass to volume

double butting a tube that has two internal or external butts, or reinforcements, usually one at each end

ductility percent elongation of a material. Ductile metals are pliable and easily worked, and can be drawn, shaped and formed without cracking or breaking

elongation the length change found in a tensile test specimen from its initial length to its length at failure

endurance see fatigue endurance

fatigue endurance the stress level at which the number of cycles to failure is infinite. Aluminum has no fatigue endurance; steel and titanium do. Also called "fatigue strength"

flaring enlarging the diameter of a tube through mechanical action; a process that is the opposite of tapering, although the final shape may be the same. In titanium, flaring alters texture

HAZ heat-affected zone; the area around a miter or other frame joint that is potentially weaker due to the heat of welding or brazing

MMC metal-matrix composite; a material made of a base metal and other metallic or non-metallic inclusions that improve the properties of the base metal

modulus ratio of stress to strain within the elastic region of a material in tension or compression. High-modulus materials deflect less (exhibit less strain) under a given load (or stress) than low-modulus materials. Modulus is not affected by strength (i.e., a low-strength 4130 tube effectively has the same modulus as a heat-treated high-strength 4130 tube)

pilgering a reduction process used to create the final inside and outside diameters of a tube by rolling grooved dies back and forth ("rocking") along the outside diameter of the tube while the inside is supported by a mandrel

purity measure of contaminants in a given material, as compared against the material's specification index

resiliency the energy per unit volume that a material can absorb without yielding

rocking see pilgering

swaging the forced reshaping of a material through the use of a die or stamp, called a swage

tapering the process of shaping a tube into a conical section. Tapered tubing can be formed by swaging, or by rolling a conical section of sheet metal into a tube and welding the seam

texture in titanium, the orientation of the hexagonally shaped molecules of titanium in a tube. Crystallographic texture affects yield strength, tensile elongation, ductility and fatigue strength; it can be controlled during pilgering. Texture is measured by comparing the deformation of the tube under tensile strain in the radial direction to the deformation in the circumferential direction ("contractile strain ratio")

UTS ultimate tensile strength; the maximum load a material can withstand before breaking

work hardening the increase in hardness and strength exhibited when a material is machined, formed, or otherwise worked. Some materials exhibit extreme work hardening, titanium among them

YS yield strength; generally considered to be a point 0.2% beyond the material's upper limit of elastic deformation, where an applied load causes a permanent deformation