MATERIALS ■ MECHANICS ■ PHYSIOLOGY ■ ENGINEERING ■ AERODYNAMICS

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast©

DECEMBER 1987 $3.00

MATERIALS

TITANIUM LIVES!

What Do a Plasma Welder, a Trials Fanatic, A Gear-Head Tech Editor, an F-14, and Some Guy Named Gwyn Have in Common?

It appears that composites have a legitimate rival in the lightweight frame market—titanium framesets are once again available. And this new generation of titanium frames eliminates the most serious objection raised by previous attempts to utilize this favorite material of aerospace designers: sudden cracking and subsequent tubing failure.

The magic wand that's about to transform titanium's former (and deserved) bad reputation for notch sensitivity is the availability of newer, higher-strength, less-crack-prone alloys. I say "availability" with a very large grain of salt. As you'll see further on, it isn't easy to source appropriate sizes of construction-quality titanium alloy tubing, but at least the stuff *exists,* now.

Furthermore, these newer alloys are being evaluated and *utilized*. Fuji is no longer the sole supplier of titanium road framesets/complete bikes—Spectrum Cycles will soon be distributing Merlin Metalworks' road version of the highly successful titanium mountain bike it already makes for Marin. The BICYCLING/Merlin project bike shown on this cover is a forerunner of what we think will finally be large scale acceptance of titanium as a valid alternative frame material. Other manufacturers are already making plans to introduce titanium models, although at this time of year we can't say who! As usual, by the mid-winter trade shows, all the secrets will be out.

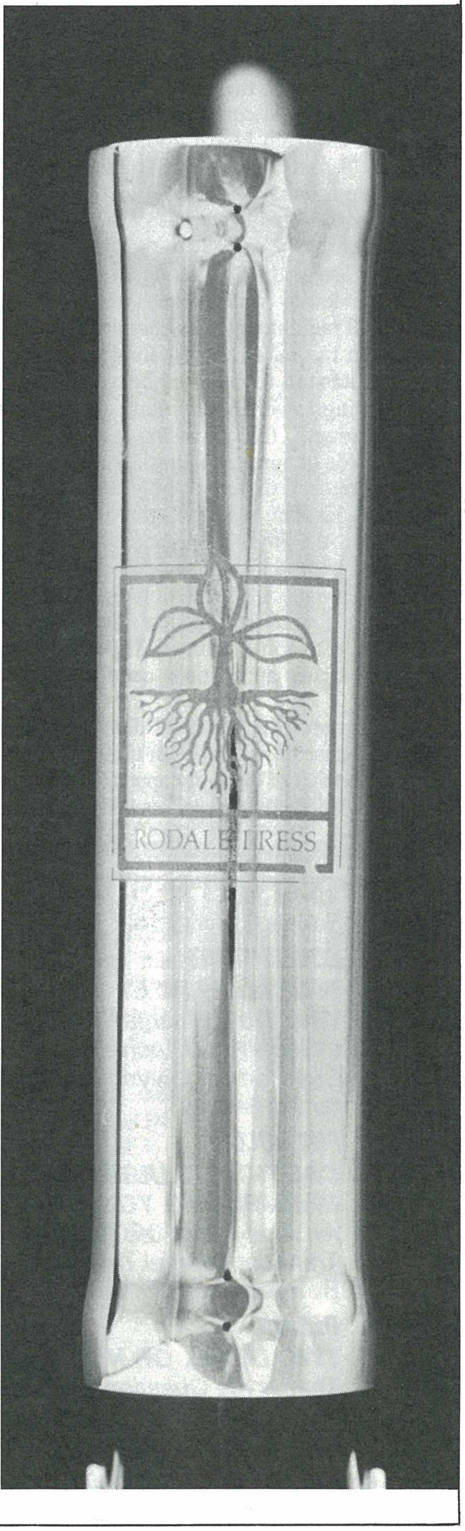
All this activity is refreshing and good competition for composites.

The Phone Chase

My own involvement with titanium was truly serendipitous. While searching for someone to write an article on TIG welding for *Bike Tech,* I was referred to one Gary Helfrich, a supposed TIG wizard who was doing the frame welding for Fat Chance Cycles. Gary and I discussed an article and Gary proposed sending some samples of TIG welding to *Bike Tech* for photography. The samples did it.

Enclosed with them was a blue-tinted tube welded to a facsimile bottom bracket shell, all of which felt almost weightless. The BICYCLING staff was intrigued, but then came the bad news. When queried, Helfrich informed me that the material was commercially pure grade titanium and therefore prone to cracking, and of lower tensile strength and modulus than chrome-molybdenum steels. I was disappointed, but not for long.

Helfrich mentioned that there was another alloy of titanium, called 3-2$^{1}/_{2}$, that was almost as strong as the 6-4 used in most military aircraft construction, but *atmosphere weldable!* Gary had been experimenting with weld-



BICYCLING's one-of-a-kind, 15-pound titanium project bike doesn't signal a new commercial effort for Rodale Press — it celebrates the beginning of a bright, shiny future for titanium bicycle frames.

PHOTOGRAPHY BY JOHN P. HAMEL

	ANNEALED		COLD WORKED AND STRESS RELIEVED	
	ksi	MPa	ksi	MPa
Ultimate T.S.	85 Min.	586 Min.	125 Min.	862 Min.
Y.S. at 0.2% Offset	70 Min.	483 Min.	105 Min.	724 Min.
Elongation in 2″	15% Min.		10% Min.	

ing commercially pure titanium in a converted sandblasting cabinet that he would purge with inert gas before TIG'ing. The process seemed to work fine with the unalloyed titanium tubing, but the super-strength alloys like 6-4 were still considered off limits. That is, until Helfrich heard about 3-2½. The phrase "3 dash 2½" began to take on mantra-esque powers.

There was one significant problem with 3-2½: it was very difficult to find in tubing diameters larger than 1 inch, unless they were accompanied by wall thicknesses like 0.065 inches. Traditionally, the chemical industry has been the major market for corrosion-resistant titanium tubing, and because 3-story condensing towers, etc., don't have to fly, lower-strength, thicker-walled (i.e., heavier) tubes made of pure titanium alloy have always been commercially acceptable (not to mention cheaper than high-strength, alloy tubes).

What little production there has been of high-strength tubing was intended for aircraft (which *are* supposed to fly), in order to lower the weight of their complex hydraulic systems. Even non-geniuses know that not many hydraulic applications call for 1¼-inch tubing.

And larger-than-standard diameter tubes are the order of the day with titanium, which has a modulus of elasticity approximately half that of steel. Real life experience supports the theory, as titanium frames built with standard-diameter tubing are some of the most flexible frames we've ever seen.

So Helfrich and I both wanted larger-diameter 3-2½ tubes, and he could have them from tubing processor Nikko Wolverine—but only if he would buy a mill run of seamless tubing, or about 1,000 feet at anywhere from $15 to $30 per foot, *in each size!* He didn't order any, but picked up trimmings and other odd pieces so he could continue to experiment.

For our part, we wrote off titanium yet one more time to the dream pile and went about our business.

One Year Later...

When we used titanium as one of our theoretical materials in BICYCLING's CAD/CAM article (April, 1986), the old excitement was renewed, especially when we saw the design potential for higher-strength titanium alloys.

For his part, Helfrich mentioned that he and some friends had been riding (and racing) a mountain bike with a 4-pound frame and fork made of commercially pure titanium tubing for about a year, *without a failure!* Considering Helfrich's 200-plus-pound size and the fact that commercially pure tubing supposedly isn't much stronger than mild steel, the implication was obvious: 3-2½ could make an even lighter frame and still have enough fatigue strength for abnormal abuse.

Unfortunately, at this time supply was just as thorny a problem as it was previously. Helfrich and company still couldn't get "small" quantities of tubing to make test bikes.

The BICYCLING Project Bike

At this point we proposed to Helfrich that he make a titanium bicycle frame for us from the 3-2½ tubing we would persuade Nikko Wolverine to provide him. Helfrich would get his tubing, we would get a ridable titanium frame as concrete proof of the viability of our designer fanatasies, and Nikko would get some publicity.

There were 2 hitches: First, I wanted specific diameters and wall thicknesses so that we finished with a frameset that wouldn't weigh any more than necessary and still be as strong as a steel frameset; and second, I wanted a frame that looked as "normal" as possible. To me that meant tapered stays, at least, and fork blades if at all possible. Nikko does not have tooling to do the tapering, but True Temper does. True Temper was willing to sign up for our project because they wanted to find out how difficult it would be to supply builders with finish-drawn tubing.

It should have been easy—3-2½ owes much of its success in hydraulic fittings to its substantially better formability compared to its nearest metallurgical "relative," 6-4 alloy. That meant we could expect few prob-

PARAMETER	SYMBOL	UNITS	FORMULA	STEEL		ALUMINUM		TITANIUM			
MATERIAL PROPERTIES				**col. 1**	**col. 2**	**col. 3**	**col. 4**	**col. 5**	**col. 6**	**col. 7**	**col. 8**
alloy				4130	4130	6061	6061	6AL-4V	3AL-2.5V	3AL-2.5V	15-3
modulus of elasticity	*E*	lbf/in^2	per mfgr.'s data sheets	3.0 x 10^7	3.0 x 10^7	1.0 x 10^7	1.0 x 10^7	1.7 x 10^7	1.7 x 10^7	1.7 x 10^7	1.7 x 10^7
GEOMETRIC FACTORS:											
outside diameter	*OD*	inch	***GIVEN***	1.125	1.125	1.125	1.500	1.125	1.375	1.250	1.375
wall thickness	*T*	inch	***GIVEN***	0.024	0.040	0.079	0.060	0.04	0.028	0.035	0.028
inside diameter	*ID*	inch	*OD*-(*T* x 2)	1.077	1.045	0.967	1.380	1.045	1.319	1.180	1.319
buckling factor	—		*OD*/*T*	47	28	14	25	28	49	36	49
cross-section area	*A*	inch^2	Pi x (OD^2-ID^2)/4	0.0830	0.1363	0.2596	0.2714	0.1363	0.1185	0.1336	0.1185
section modulus	*Z*	inch^3	*I*/(*OD*/2)	0.0224	0.0357	0.0635	0.0940	0.0357	0.0391	0.0395	0.0391
moment of inertia	*I*	inch^4	Pi x (OD^4-ID^4)/64	0.0126	0.0201	0.0357	0.0705	0.0201	0.0269	0.0247	0.0269
WEIGHT FACTORS:											
density	*D*	lbm/ft^3	per mfgr.'s data sheets	484	484	173	173	276	276	276	276
weight per unit length	*W*	lbm/ft	*D* x *A*/12^2	0.28	0.46	0.31	0.33	0.26	0.23	0.26	0.23
relative weight	*W'*	percent	*W*/*W* for base case	100%	164%	112%	117%	94%	81%	92%	81%
STIFFNESS FACTORS:											
bending stiffness	*EI*	lbf x in^2	*E* x *I*	377,538	602,726	357,069	704,777	337,527	451,666	414,502	451,666
relative bending stiffness	*EI'*	percent	*EI*/*EI* for base case	100%	160%	95%	187%	89%	120%	110%	120%
STRENGTH FACTORS:											
ultimate tensile strength	*TS*	lbf/in^2	per mfgr.'s data sheets	100,800	100,800	38,000	38,000	150,000	125,000	125,000	155,000
tensile yield strength	*YS*	lbf/in^2	per mfgr.'s data sheets	89,600	89,600	35,000	35,000	140,000	105,000	105,000	145,000
max. principle stress applied	*S*	lbf/in^2	from BT CAD project	23,061	14,445	15,954	10,777	14,330	13,088	12,965	13,088
stress as % of yield strength	*S**	percent	*S*/*YS*	26%	16%	46%	31%	10%	12%	12%	9%
relative strength in bending	*S'*	percent	*S** for base case/*S**	100%	160%	56%	84%	251%	206%	208%	285%
FATIGUE FACTORS											
fatigue strength (10^7 cycles)	*FS*	lbf/in^2	from mfgr.'s *S/N* curves	35,000	35,000	12,500	12,500	52,000	45,500	45,500	105,000
max. fatigue stress applied	*VM*	lbf/n^2	from BT CAD project	25,237	15,808	8,992	6,074	15,142	13,830	13,700	13,830
stress as % of fatigue strength	*FS**	percent	*VM*/*FS*	72%	45%	72%	49%	29%	30%	30%	13%
relative fatigue strength	*FS'*	percent	*FS** for base case/*FS**	100% (Base Case)	160%	100%	148%	248%	237%	239%	547%

CHART BY ROBERT G. FLOWER

lems drawing and tapering 3-2$\frac{1}{2}$ tubes. The trade-off is that 3-2$\frac{1}{2}$ doesn't have quite as much tensile strength as 6-4.

So now we had 4 cooks stirring our titanium stew. To make a long story shorter, we all spent a lot of time on the phone trying to manage the tapering process without messing up the tubing, without much success. In the end, due mostly to personnel changes, True Temper withdrew from the project and Nikko handled finishing of our standard-gauge, non-tapered tubing. Sometimes you bite the bear...but not this time. Our project frame hasn't a single tapered tube in it.

Tapered stays are probably not considered as functionally and aesthetically necessary as previously, anyway—we're getting used to seeing straight stays on a lot of very expensive mountain bikes.

So the end product may not have the pedigreed lines we've grown accustomed to from years of exposure to 4130 frames, but it's still striking in its own way. The polished surface is almost mirror-like, and the welding is so clean and without any trace of a thermal process that it doesn't seem possible the tubes were actually welded together. And, it's a comfort only a cyclist can appreciate to know that the finish won't need any attention for the life of the frameset.

Strength to Spare

How strong can such a lightweight frame be? Table 1 shows tensile strengths and elongation for Nikko's seamless 3-2$\frac{1}{2}$ tubing in both annealed and "105 minimum" annealed and heat-treated condition. Note that even in the fully annealed state (which would be a "worst case" condition to estimate 3-2$\frac{1}{2}$'s "after welding" strength) the tubing shows strengths comparable to that of 4130 chrome-moly tubing after brazing.

This means that a frame made of 3-2$\frac{1}{2}$ with tubing diameters and wall thicknesses the same as a standard chrome-moly frame would have about equal bending strength as the steel frame, but weigh about $\frac{1}{3}$ less. That's a weight saving of approximately 1$\frac{1}{2}$ to 2 pounds! Unfortunately, the 3-2$\frac{1}{2}$ frame would also be about $\frac{1}{3}$ less rigid, an unacceptable condition for most riders.

This results from the fact that the specific modulus (elasticity per unit of mass) is about the same for most metals. That means if the density of aluminum is only $\frac{1}{3}$ that of steel, it follows that its modulus of elasticity (rigidity) is also only $\frac{1}{3}$ that of steel. The design implication is that you can't reduce weight in a constant-diameter tube by using a "lighter" metal without also sacrificing rigidity.

The obvious answer, as most of us know by now, is larger-diameter tubing. There are 3 general cases to consider:

1) In *case A* both diameter and wall thickness increase by a factor, k. Weight would increase by approximately k^2, strength by approximately k^3, and rigidity by approximately k^4.
2) In *case B* diameter would increase by k, but wall thickness would remain the same. Weight would increase by approximately k, strength by approximately k^2, and rigidity by approximately k^3.
3) In *case C* diameter would increase by k, while wall thickness would *decrease* by a factor of k. Weight would remain approximately constant, strength would increase by approximately k, and rigidity by approximately k^2.

If we posit the rigidity of a steel frame as an acceptable standard, the k factor required in *case A* to make our titanium frame as rigid as a steel frame would be:

$$k^4 = 1 \div 0.67$$
$$k = 1.11$$

Now our rigidity is the same for both materi-

Although extra light but roadworthy components played a part in our 15-pound fantasy machine, its 3.5-pound frame/fork combination is pure reality.

als, but our titanium frame weight has increased by a factor of k^2, up to 82% of the steel frame weight.

Similarly, in *case B*, our weight would increase to 77%, and in *case C* it would remain the same at 67%. Obviously, *case C* is the most desirable design change.

Unfortunately, all of these simplified scenarios ignore 2 very important design factors: **buckling**, which is a failure of the tube *structure*, usually caused by a ratio of tube diameter to wall thickness greater than 50:1; and the material's **fatigue limit**, which is the level of stress the tube can withstand either indefinitely or for a "reasonable" number of stress cycles, approximating the useful life of the frame. Either of these factors can bring a swift halt to extensive fantasizing about weight reductions or rigidity increases from changes in tube diameters and wall thicknesses. Table 2 shows the interaction between all of the above-mentioned design factors.

The figures in the first column of each material group (columns 1, 3, and 5) are taken from the *Bike Tech* poster and analysis of BICYCLING's CAD/CAM project (see BICYCLING, April 1986). Data in other columns for maximum applied principal stress and maximum applied fatigue stress are scaled according to subsequent changes in tube diameter and wall thickness and the resulting changes in I (moment of inertia). The results appear to support experience and accepted design practice.

Aluminum, as might be expected, finds its design limits in the strength factors of bending and fatigue. Looking at Table 2, we can see that although low ratios of diameter to wall thickness and extra-large diameters do manage to produce acceptable or even exceptional rigidities, potential weight savings are sacrificed to produce adequate levels of relative fatigue strength.

At first glance, the aluminum model's relative fatigue strength seems very good, but remember these important *caveats*:

1) Unlike steel and titanium, which have true fatigue limits (i.e., they have a minimum fatigue strength), aluminum's fatigue strength declines continuously with increasing cycles. This dictates a greater design safety factor (*FS/VM*) as a precaution against greater-than-expected use.

2) Aluminum's fatigue mode is catastrophic, rather than gradual. This factor also calls for a larger safety factor.

There's no mistaking the fact that in bending strength, our small-diameter tube aluminum model falls a little short. Most small-diameter aluminum tube frames use higher strength alloys than 6061, however, which would raise the relative strength number in column 3 to an acceptable level.

Titanium, on the other hand, has no problems in bending strength or fatigue strength. In fact, there's little point in trading away some fatigue strength for less weight via thinner walls—columns 6 and 8 are already at the buckling limit for tubing. So figure you can save about 20%, or a pound, over your average butted-tube, chrome-moly steel frame.

There is one application where titanium should have a greater advantage: mountain bike frames. Anything that increases bending strength will decrease the possibility of crumpling up your favorite mount when you land after that 4-foot paving break. One tangible benefit of alloys like 3-2$^1/_2$ and exotic 15-3 (or 15-3-3-3, to be precise) is that they have so much strength that you don't have to increase wall thickness (and weight) to achieve "gonzo" levels of bash resistance—a "bulletproof" off-road frame needn't weigh much more than your average lightweight road model. Look for a number of titanium mountain-bike models this coming year. ■ —*J.R.*