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BIKE TECH

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SPECIAL REPORT

"Heat-Treated" Rims — Are They Worth The Money?

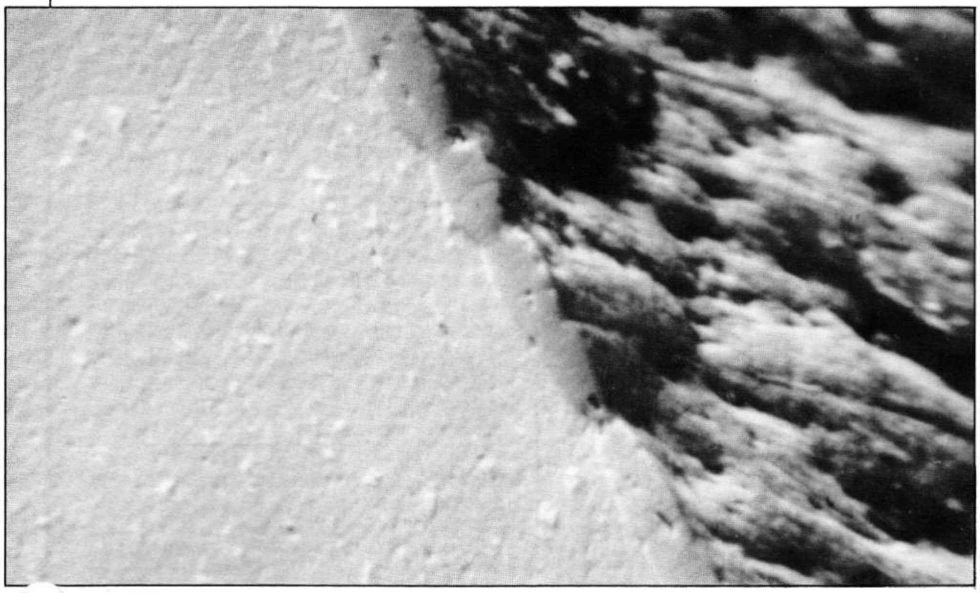
Mario Emiliani

In the early to mid-70s the fad in cycling was to minimize weight. Aluminum and titanium bolt kits replaced factory-equipped steel bolts, components were drilled out, frames were made from the lightest tubing, and wheels were as light as possible.

Recently, however, more emphasis has been placed on efficiency and durability. Frames have become heavier, home-drilled chainrings, seatposts, and brake levers are rarely seen, and the search for more durable wheels has seen the introduction of what are popularly called "heat-treated" rims.

These rims are much more expensive than ordinary rims, so I decided to find out why. What I discovered was that the so-called heat-treated rims I tested aren't heat treated, and they aren't much better than ordinary rims.

Rims, as we know, must endure a brutal environment. The constant pounding from bumps and potholes can lead to out-of-true wheels, flat spots, and dents. And the added weight that tourists carry can worsen the situation. Good wheels can be expensive and, even with regular maintenance, the rims can lead very short lives. Stronger rims are the sensible solution to more durable wheels.



A close look at a "heat-treated" rim reveals a hard-anodized layer over soft aluminum. 500 times magnification.

IN THIS ISSUE

FROM THE EDITOR

Changing of the Guard

This issue of *Bike Tech* is the last one in which Crispin Miller will have a direct managerial hand. Crispin is leaving us for the Massachusetts Institute of Technology — a place that's "like taking a drink from a fire hose," he tells us — where he will pursue an assortment of advanced degrees in mechanical engineering. Should the fire hose run dry, he'll reappear on these pages with the analytical articles which bear his distinctive style.

Replacing Crispin as executive editor is Doug Roosa, whom we plucked from a physics teaching job at Greenville Technical College in Greenville, South Carolina. Doug has also worked on the design of a high-temperature solar energy collector and storage device, on passive solar techniques, editing and production work of an annual 56-page astronomical calendar, and, oh, yes, seven years as moped and bicycle mechanic at the Great Escape bicycle shop in Greenville. We're glad to have found him.

Doug inherits a job which has come a long way in less than two years. Crispin has given *Bike Tech* a high level of credibility — typified, I think, by Shinpei Okajima's article in the August 1983 issue, in which he gave such a thorough presentation of Shimano's research and development in biomechanics, and by Mario Emiliani's article in this issue, in which rigorous chemical analysis dispels a lot of folklore about expensive aluminum rims.

Doug and I will be working hard to bring you more of the same. We hope you will find it as valuable as we do.

John Schubert

BIKE TECH

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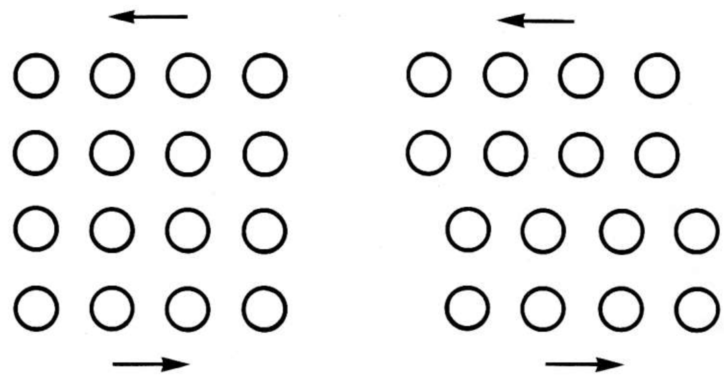


Figure 1: When sufficient stress is applied to a metal, rows of atoms slide past each other. If slip can be interfered with, the metal will be stronger.

In 1978 Mavic introduced their Special Service des Courses (SSC) rim to the European racing circuit. It was used by professional teams on some extremely rough courses with excellent results. Everyone praised the rim, which somehow became referred to as "heat-treated."

The rim was quickly copied by other European rim manufacturers — so was the price. Everyone I've talked to who rides "heat-treated" rims loves them. They say the rims don't dent easily and rarely need truing. Some won't ride anything else.

While these rims appear to be very good, is their increased performance worth their high price? And is their better performance due to heat treatment(s)? The latter question is very important because it is the basis upon which these rims are bought.

To determine whether "heat-treated" rims are really heat treated (as many are advertised to be by importers and bike shops) I hardness tested four rim samples and had them analyzed for chemical composition. The "heat-treated" rims in these tests were a Mavic SSC, a Nisi Ekip, and an Ambrosio Synthesis. A Fiamme Red Label was also tested; it was used as a standard for comparison. Table 1 lists the weights and retail prices of these rims. The SSC and Ekip were chosen because they are the most expensive regular cross section (non-aero) tubular rims. The Synthesis was chosen because it is more modestly priced, and the Red Label because it is an inexpensive ordinary rim. Additionally, these rims were selected because they are popular and highly regarded. The Ekip and Red Label rims tested were new, while the Synthesis and SSC had been ridden.

Heat Treating

Heat treating is a metallurgical term used to describe controlled heating and cooling of a metal for specific periods of time to obtain certain mechanical properties.[1] Thus, heat treatments can be used to strengthen or weaken a metal depending on the desired mechanical properties. Metallurgists normally apply the term "heat treatable" only to those aluminum alloys which can be strengthened by heat treatments.[2]

Whether or not an aluminum alloy is heat treatable depends upon its chemical composition. Of the seven aluminum alloy series from which rims can be made, only three are heat treatable for increased strength. These grades are aluminum-copper (2XXX)[3], aluminum-magnesium-silicon (6XXX), and aluminum-zinc (7XXX).

Table 1

	Weight Per Rim, grams	Retail Price, per pair
Mavic SSC	395	$196
Nisi Ekip	410	$133
Ambrosio Synthesis	410	$65
Fiamme Red Label	360	$25

Metals are made up of many crystals called grains, and each grain consists of a three-dimensional array of atoms. The atoms are arranged in a specific order which varies depending upon the type of metal. When sufficient stress is applied to a metal, a few rows of atoms slide past each other. This microscopic movement is known as *slip*. Figure 1 illustrates this situation.

If even greater stress is applied, more rows of atoms will slip past each other causing the metal to *yield;* that is, the metal un-

[1] *Mechanical properties are measures of a material's response when stressed.*

[2] Metals Handbook, *Vol. 2, 9th Ed., 1979, p.28.*

[3] *The first digit indicates the alloys series (e.g., aluminum-copper, etc.), the second digit indicates the degree to which impurities were controlled, and the third and fourth digits identify the different alloys in the series.*

dergoes a noticeable amount of permanent deformation.

To inhibit yielding, pure metals can be alloyed with one or more elements to produce a visibly distinct compound, or second phase, within the metal (see Figure 2a). A proper arrangement of second-phase particles within the base metal impedes the slip. This results in a stronger metal. The optimum size, shape, and distribution of second phase particles is controlled by heat treating.

To illustrate how heat-treatable aluminum alloys are strengthened, take the case of aluminum alloyed with 4 percent copper. Proper heat treatment produced an even distribution of zones where aluminum atoms have been replaced by copper atoms. These zones typically consist of 10 to 50 copper atoms. Since copper atoms are smaller than aluminum atoms, the bonds holding these atoms together are highly strained. This results in a stronger metal because it's more difficult to initiate slip through a region of strained atomic bonds. Figure 2b shows how heat-treatable aluminum alloys are strengthened by the strain between atomic bonds.

To strengthen a heat-treatable grade of aluminum, it must first be heated to a temperature high enough (~950°F) to dissolve the second phase. Fast cooling of the metal (by immersion into water, for example) traps the second-phase atoms within the aluminum matrix. If you were to look at the aluminum under a microscope at this point you'd see only grains of aluminum because the second-phase atoms have been dispersed into the aluminum matrix. In this form, the aluminum is not much stronger (i.e., not much more slip resistant) than pure aluminum, but this atomic arrangement is not stable, and if the newly quenched alloy is left at room temperature for a few weeks, the second-phase atoms will migrate and group into small particles. As this microscopic dispersion progresses, the aluminum gains strength.

Second Phase

The process of forming small zones of second-phase atoms after cooling from high temperatures is known as *aging*. Aluminum is a peculiar metal in that room temperature provides enough thermal energy for atoms to move about. Most other metals possessing unstable structures can be left at room temperature for thousands of years without any change in properties. Aging at room temperature is called *natural aging*.

If the aluminum is aged at higher temperatures (~350°F), it will reach full strength in shorter time. This is called *artificial aging*.

Tests must be performed to determine the times and temperatures required to produce *peak aging* (maximum strength) for the various heat-treatable aluminum alloys, because improper heat treatment will result in either *overaging* or *underaging*. Improper aging results in less-than-maximum strength because bonds between the aluminum and second-phase atoms are not as highly strained.

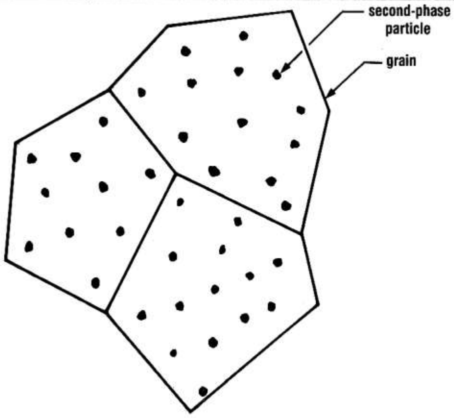


Figure 2a: Alloying pure metals with small amounts of other metals can produce a visibly distinct compound called the second phase. When viewed under a microscope at low magnification, second-phase particles can appear as spheres embedded within grains of the pure metal.

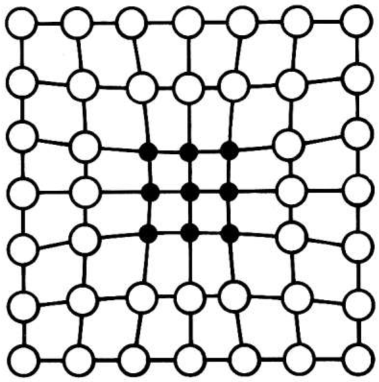


Figure 2b: Representation of strained atomic bonds created when a second-phase particle forms in the base metal.

Now let's make some general observations on what heat-treated rims might be, and what they really are. When something is made stronger, its thickness can be decreased to save weight. This is an engineering rule of thumb. Saving weight on wheels is a smart thing to do because it's much easier to accelerate and maintain speed with lighter wheels. So one might expect that a benefit to be gained from genuine heat-treated rims would be less weight and better performance compared to heavier non-heat-treated rims.

The Mavic SSC, Nisi Ekip, and Ambrosio Synthesis, three of the most expensive "heat-treated" rims, each weigh approximately 400 grams. The Fiamme Red Label, a rim known for its durability, weighs only 360 grams. Four-hundred-gram rims are going to be durable whether they're heat treated or not. Odd, isn't it, that in this top-of-the-line selection of "heat-treated" rims, none are even as light as an ordinary Fiamme Red Label!

Anodizing

Perhaps to distinguish it from all other rims at the time of its introduction, the Mavic SSC was *anodized* dark gray. Anodizing is simply controlled corrosion of a metal. A thick oxide film is grown by placing the rim in an electrically conducting liquid (called the electrolyte) maintained at a certain temperature (~70°F), and imparting a specific amount of current (called the current density) on the rim. Depending on the conducting liquid, its temperature, and the current density, the oxide layer can appear silvery or various shades of blue, bronze, or gray. The oxide layer formed is porous and must be sealed to preserve the finish. One way of doing this is to place the rim in boiling water for 15 to 30 minutes. Silvery oxide layers can be dyed various colors by placing them in dye baths prior to sealing.

The oxide film formed by anodizing differs from many other oxides in that it adheres well to its aluminum substrate—unlike rust (iron oxide) which flakes off easily. If the anodized layer is grown and sealed properly, it's highly resistant to corrosion. For example, most inexpensive aluminum rims aren't anodized and require periodic polishing to maintain an attractive appearance. Thus, rims are anodized for improved corrosion resistance, improved surface finish, and to provide a distinctive appearance.

Most so-called heat-treated rims have a special "hard-anodized" surface. This anodizing process differs from ordinary anodizing in that the temperature of the electrolyte is lower (~40°F), and the current density is higher. This process can add an extra $10 to $20 to the price of each rim because of the extra energy and handling costs, but it produces a much thicker and harder oxide layer. The extra expense for a colored rim that doesn't need polishing is worthwhile in the eyes of many riders.

Figures 3a to 3d are scanning electron micrographs of the rims tested showing the thickness of their oxide layers. The Red Label rim, Figure 3d, is not anodized, but it has a very thin oxide layer (not visible) formed naturally by exposure to oxygen in the air.

Misinformed

Since Mavic SSC rims are dark anodized and supposedly heat treated, many consumers have the false notion that all dark anodized rims are heat treated. This association is further strengthened when the rim is scored with a file to provide a rougher surface for tubular tire glue to adhere to. In doing this, it's impossible not to notice that these rims are more difficult to file than ordinary rims.

But it's assumed these rims are harder to file due to heat treatment. Well, the rim is harder not because it has been heat treated, but because it has been hard anodized. The oxide layer formed by hard anodizing is harder and more brittle than the aluminum from which it was grown because atoms in the oxide layer are bonded differently. If you get past the oxide layer, you'll find that the aluminum files as easily as in ordinary rims.

The manufacturers of "heat-treated" rims have engaged in a bit of creative marketing by simply not explaining their product. They make no claims, in print, that their rims are heat treated. Rather, some use buzz words which can sound like their rims have been heat treated. "Durex," used by Ambrosio, is a good example, which sounds like "more durable" or "harder." However, something of a disclaimer is also on the Durex decal. It says, in small letters, in Italian, "machio depositato allumag monocellulars." Translation: Durex is our trademark for aluminum anodizing.

So the job of informing consumers is left to salespersons who get their information from importers who get their information from company reps talking in heavily accented English.

Hardness Tests

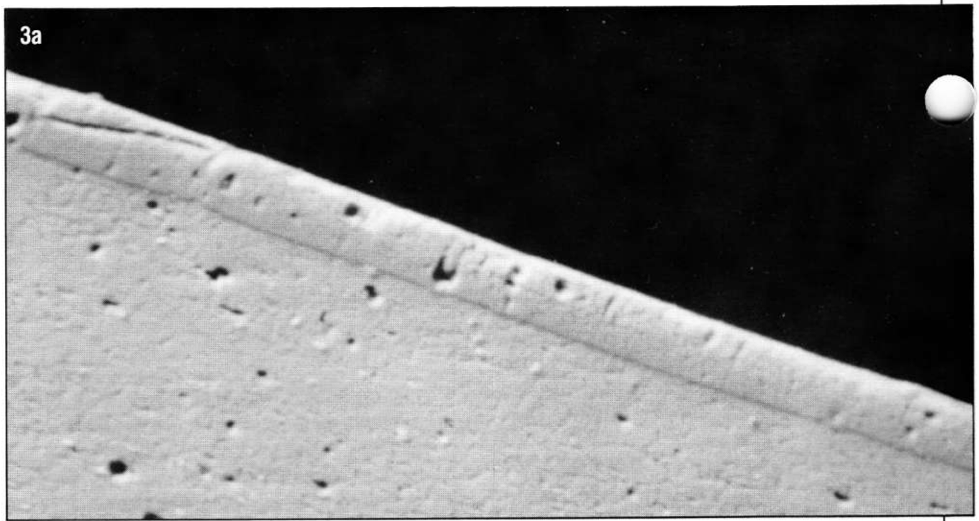
The hardness of a metal is related to its strength; the harder the metal, the stronger it is. If the SSC, Ekip, or Synthesis were heat treated for added strength, they would be harder than the Red Label rim. To investigate this assertion, I first removed the oxide layer from all the rims by sanding from 240-600 grit. I then performed hardness tests on a Wilson Digital Hardness Tester using the 30-T scale (30 kilograms major load with a 1/16-inch diameter steel ball indenter). The 30-T hardness data was converted to Diamond Pyramid Hardness (DPH) so the yield strength of the rims could be calculated using the equation

$$\text{yield strength (in psi)} = 377\ (\text{DPH})\ (B^n)$$

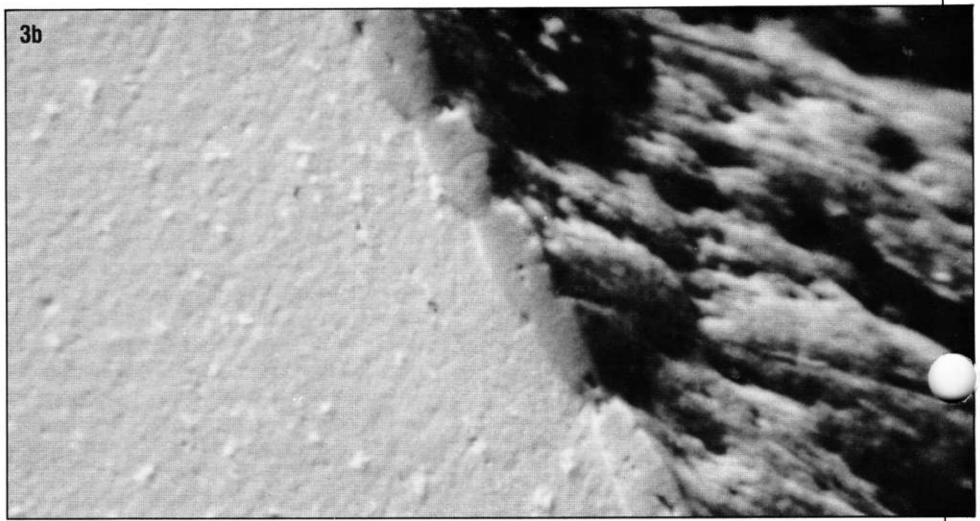
where B = 0.1 and n = 0.06 for aluminum.[4] The results are given in Table 2.

Table 2

	Average Rockwell 30-T Hardness	DPH	Yield Strength, psi
3004, fully annealed	~5	~30	10,000
Mavic SSC	58.2	111	36,450
Nisi Ekip	42.5	81	26,600
Ambrosio Synthesis	45.5	86	28,240
Fiamme Red Label	49.0	92	30,210



3a



3b

From the hardness numbers and corresponding values of yield strength, it's obvious that the Ekip and Synthesis rims could not have been heat treated for increased strength. It is possible, though, that they were subjected to improper heat treating (i.e., over- or underaging). The SSC is significantly stronger than the other rims, but is this due to heat treating? To clarify this situation it is necessary to examine the chemical composition of these rims to determine if they are even heat treatable.

Chemical Composition

Samples of all the rims were sent to a company specializing in metallurgical testing to determine their chemical compositions.[5] The results are given in Table 3.

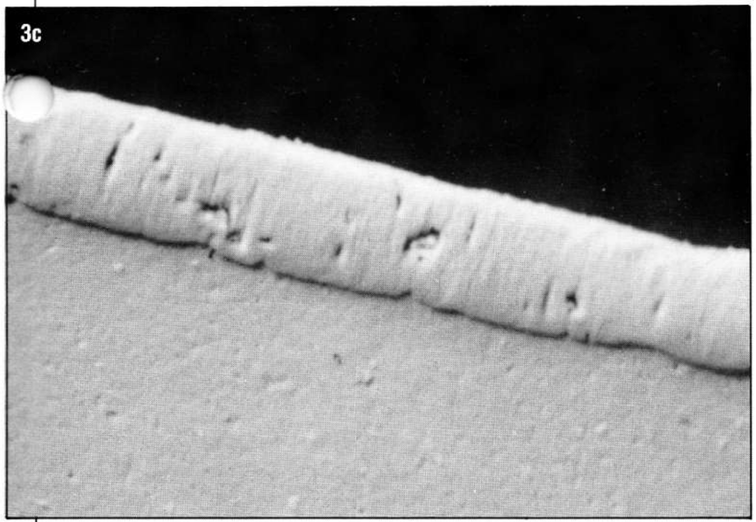
As mentioned earlier, the heat-treatable grades of aluminum are the 2XXX, 6XXX, 7XXX series. However, all rims tested were made from an aluminum-manganese alloy (type 3004). These alloys can't be heat treated! Since these rims aren't heat treated, they will herein be referred to as "hard-anodized" rims.

The yield strength of the Ekip, Synthesis, and Red Label are all approximately equal, but the SSC is significantly stronger. This discrepancy can't be due to heat treatment, since the 3XXX series of aluminum alloys can't be strengthened this way. If the chemical composition of the SSC varied greatly from the other rims, then that might account for some of the difference. But as Table 3 shows, there is little difference between the SSC and the others. Some other factor must be responsible for the SSC's superior strength.

Cold Working

Cold working is a very effective method of strengthening metals. For example, take a spoke and bend it 45°. Then get a good grip and try to bend it the opposite way. You'll notice that the spoke bends in a different place.

Cold working is simply permanent deformation of a metal at temperatures below



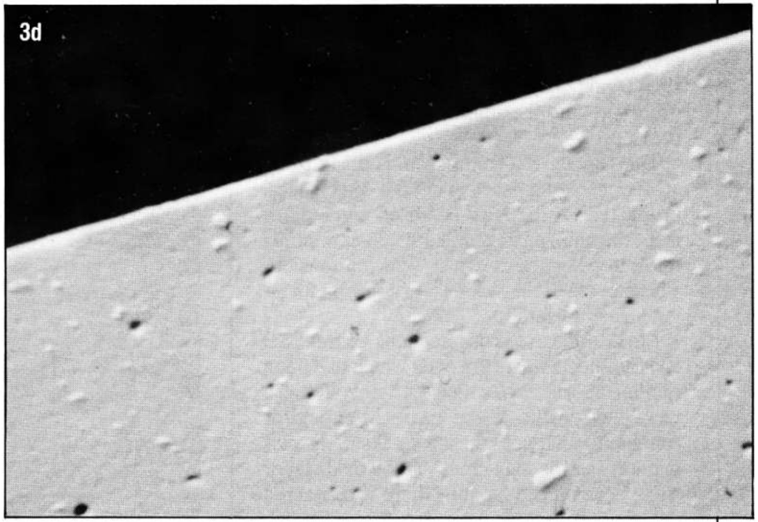


Figure 3: The hard-anodized layers of the SSC (3a), Ekip (3b), and Synthesis (3c) are 0.014-0.026-millimeter thick. The Red Label rim (3d) is not anodized. 500 times magnification.

about one-half its melting point. The spoke has been cold worked when it is bent to the point where it takes a permanent set. The principle by which metals are strengthened when cold worked is the same as that for heat-treatable aluminum alloys — millions of regions are created where atomic bonds are strained.

Cold working distorts the grains of a metal, so it's apparent (after special preparation) when a metal has been cold worked. Figure 4 is a schematic diagram showing what grains look like before and after cold work. The SSC rim tested had elongated grains indicative of a large amount of cold work (see Figure 3a). Thus, the large difference in strength between the SSC and the other rims is due to cold working.

While cold working can increase the strength of a rim, there is a simultaneous loss in ductility (the ability of a metal to deform permanently without breaking — a desirable property for wheel rims). Thus, once a rim is near its final shape, it may be helpful to remove some or all of the strengthening effects of cold working to make it more durable. This is done by heating the rim to about 500°F for a period of time — a process known as *annealing*. After annealing, the grains of the metal appear less distorted. The range of yield strengths given in Table 2 show that each manufacturer has a slightly different way of making rims. Some cold work more and anneal less, while others do the opposite.

Stress Raisers

Whenever a load-bearing structure is designed it is important to distribute stresses evenly. Thus, care is taken to minimize the presence of discontinuities called *stress raisers*. Stress raisers are produced by irregularities such as file marks, machining marks, keyways, cracks, etc., and should be avoided because they can raise the local stress to well beyond the yield strength of the metal. When this happens small cracks develop. Repeated application of the load causes the cracks to grow until the part fails. This type of failure is called *fatigue failure*.

In addition to showing the thickness of the oxide layer, Figure 3b also shows its surface appearance. Notice how irregular it is.

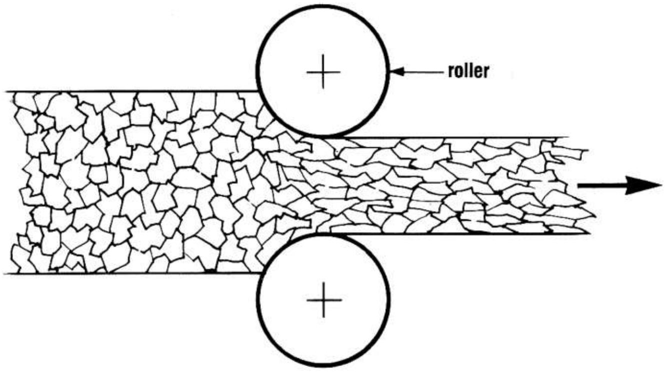


Figure 4: The grains of a metal devoid of cold work will be approximately the same size in all three dimensions. It's obvious when a metal has been cold worked because its grains are elongated.

Table 3 Chemical Composition, %

	Manganese	Magnesium	Iron	Copper	Silicon	Zinc	Aluminum	Alloy Type
Mavic SSC	1.22	0.98	0.51	0.18	0.17	0.10	balance	3004
Nisi Ekip	1.28	1.10	0.48	0.23	0.26	0.17	balance	3004
Ambrosio Synthesis	1.30	1.09	0.53	0.21	0.26	0.13	balance	3004
Fiamme Red Label	1.26	1.15	0.54	0.21	0.23	0.14	balance	3004

[4] *Cahoon, J.R., et al.,* Met. Trans., *Vol. 2, July 1971, pp. 1979-1983.*

[5] *Consulting Chemists of Florida, Inc. Tampa, FL. Testing was done in conformance with National Bureau of Standards.*

There are numerous pits which can act as stress raisers. If the applied stress is high enough (due to rider weight, spoke tension, road conditions, etc.), cracks can initiate and propagate into the aluminum causing rim failure.

The highest stress on a rim is going to be at the spoke holes. Since the mechanical properties of the hard-anodized layer differ from the aluminum, it will stretch at a different rate when the rim is stressed in tension. This can crack the oxide layer thereby forming stress raisers.

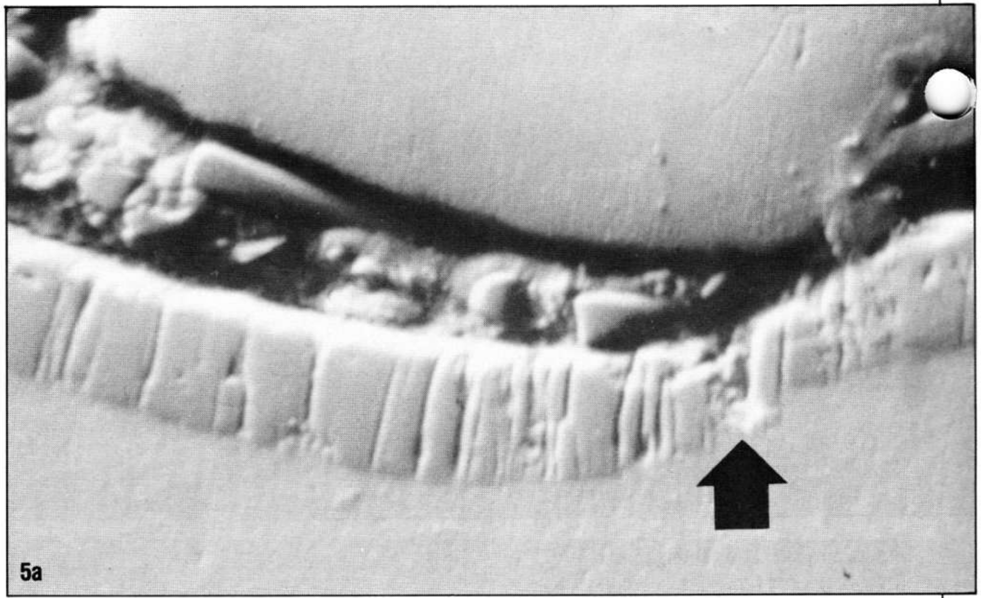
I took a look at cross sections of the SSC and Synthesis rims (the ones which had been ridden) at the spoke holes to see if there were any cracks in the oxide layer and/or aluminum. I did not find any cracks in the aluminum, and the only cracks in the oxide layer were beneath the ferrule where it contacted the rim. These cracks were formed when the ferrule was attached to the rim. Figure 5a shows the cracked oxide layer, while Figures 5b and 5c show its location on the rim.

Thus, there is the potential for failure of hard-anodized rims because of the brittle oxide coating. Ordinary anodizing produces a softer and thinner oxide layer which should not act to instigate cracking (although ordinarily anodized rims have been known to fail in this same manner). I've heard of many failures of hard-anodized rims, but have not been able to examine any to determine the role of the oxide layer. Clearly this aspect needs further investigation because wheel failure at any speed can cause serious injury.

Conclusion

Most rims are manufactured in such a way that they receive a large amount of cold working and therefore must be annealed. So technically, the term "heat treated" could be applied to the rims I tested. But the aluminum industry normally applies this term only to aluminum alloys that can be strengthened by heat treatment(s) and, clearly, the Mavic SSC, Nisi Ekip, and Ambrosio Synthesis are not made from these alloys. While the manufacturers have not made any false claims, neither have they stepped forward to erase the misconception held by importers, salespersons, and consumers that these rims are stronger because of heat treatment. Whether this deception is intentional or not, I cannot say; but I wonder what other justification the manufacturers have for the high prices they charge for their rims.

All these rims perform well. The manufacturers have been in the business a long time and know how to make a strong and durable rim. But these rims are strong and durable for the same reasons that the Fiamme Red Label is—they are cold worked and annealed, and they are heavy. They differ from ordinary rims only in that they are hard anodized. While this surface finish is attractive, evidence suggests that if it cracks, it may in-



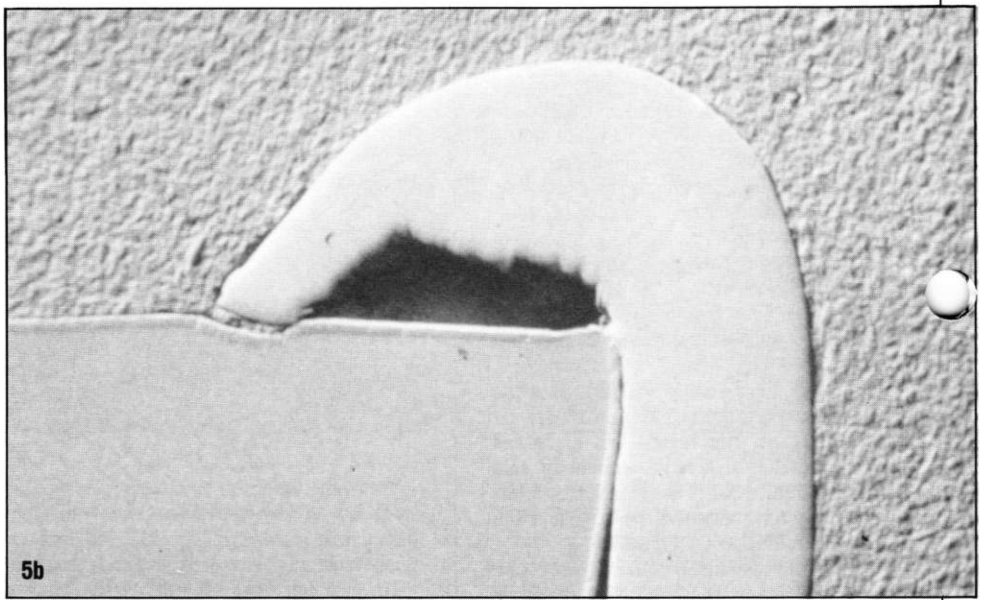
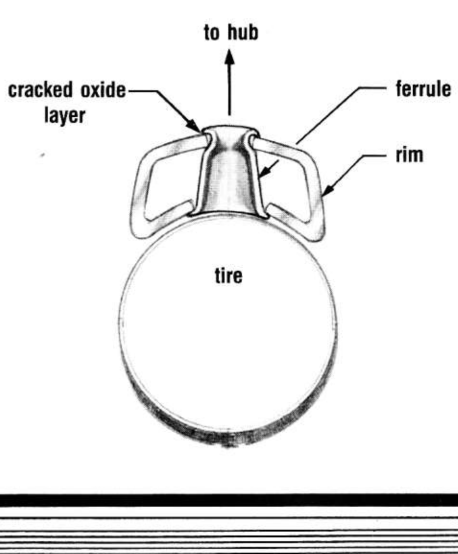


Figure 5: A cross section of the Synthesis rim at the spoke hole showed the oxide layer was cracked where the ferrule contacted the rim (Figure 5a, 500 times magnification). The cracked oxide layer is arrowed in Figure 5b (50 times magnification). Figure 5c is a schematic diagram showing the cross section investigated.

5c



stigate rim failure. This seems a high price to pay for pretty rims.

As an afterthought, I obtained a Mavic GP-4 hard-anodized rim ($58/pair) to see how its hardness compared to the Mavic SSC. Surprisingly, the GP-4 is as hard as the SSC. So, the only difference I can find between these rims is the color of the anodized layer and the decals.

Matrix Rims Are Heat Treated

To my knowledge no European or Japanese rims, hard anodized or otherwise, are heat treated. However, Tru-America Corporation of Marshall, Wisconsin, does make actual heat-treated rims called Matrix™ rims. Three different types of clincher rims are currently available. These rims are made from aluminum alloy 6063 heat treated to a yield strength of 31,000 psi, which is a little stronger than a Fiamme Red Label. Their ductility is better than a Mavic SSC. The cost of these rims is competitive with ordinary clincher rims.

Tubular Matrix™ rims will soon be available. Current prototypes are made with the same 6063, and their price will be competitive.

But if the strength of these rims is going to be comparable to a Red Label, then what is the advantage of heat treating? For similar strengths a heat-treated rim will be more ductile than an ordinary rim. This is a desirable property, because if you hit a pothole you'd rather have the rim dent instead of break. But the significance of ductility is overstated here, because most ordinary rims are only a few percentage points less ductile than heat-treated rims, and ordinary rims perform very well.

Something is amiss here. If the strength and ductility of ordinary rims and heat-treated rims remain comparable, then the reason to heat treat any rim remains in question. Surely, the idea of reducing rim weight while maintaining strength and durability cannot be realized.

There are, however, other aluminum alloys that can be used to make rims. Alloy 6070 is a good example. It has good workability, it can be heat treated to a yield strength of 51,000 psi, and its ductility at this strength is better than that of most ordinary rims. Rims made of this alloy could certainly be lighter and still be as strong as the rims available today.

Mario Emiliani

I would like to thank the following companies for supplying the rims used in this article: Bicycle Parts Pacific; Lee Katz and Co., Inc.; SRC Group, Inc.; and Wheelsmith Fabrications, Inc. Special thanks to Eric Hjertberg of Wheelsmith for his valuable insight into the rim business.

INVENTIONS

The Bent Crank: Chronology of an Idea

Harvey Sachs

Each year, the bicycle industry produces dramatic and radical advances in technology. One of the most startling of these was the P.M.P. "bent" crank, which outdid even the Gear-Tel for originality. Harvey Sachs, best known for his active leadership in East Coast tandem events, predicts what the future holds for P.M.P. in the following special report:

1981: P.M.P., a small Italian firm, bursts on the scene with the revolutionary "bent" crank, featuring a 90-degree bend in the crankarm. The "L-shaped design increases the pedal's propulsion power and lessens energy dispersion on the downstroke," according to the manufacturer's literature.

1981: The British magazine *Cycling* issues a set of P.M.P. cranks to an unnamed first category Surrey roadman for road testing. "Whatever the theories, in practice our roadman tester felt the P.M.P. cranks offered an advantage — and surely that is the true criterion," *Cycling* reported. The roadman himself said, "At low pedaling speeds, dead center seemed to be removed."

1982: P.M.P. cranks are the talk of the New York trade show. Not many orders, but lots of talk . . .

Editor's note: from here, author Sach's chronology dissolves from well-documented factual reporting to crystal-ball speculation.

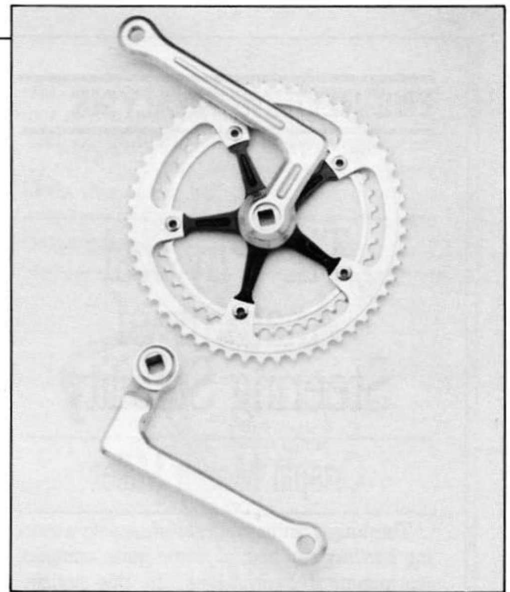
1983: Polish Olympic team purchases 20 pairs (mostly 205-millimeter, equivalent to 170-millimeter "old-style" cranks).

1983: Soviet Olympic team commissions study by East German Sports Academy to determine extent of functional advantage of new bent cranks. To cover bets, Soviet applied mathematician carries out extensive analysis (256 pp of equations) to optimize shape.

1984: Miyata introduces Shimano BX aerodynamic bent cranks with concave pedals to match. Availability is restricted, and interest is intense.

1984: U.S. Olympic team fails to find sponsor for additional cost of either Shimano or P.M.P. cranks; enters Olympics feeling very discouraged.

1984: Polish national team uses P.M.P. cranks only for climbing stages, relying on the Surrey Roadman's report that they "helped me keep a steady rhythm particularly when sitting back in the saddle and climbing hills."



The P.M.P. crankarm has no moving parts — just a longer piece of metal "to allow greater ease on the upstroke."

1985: Bikecology, Lickton's, and Bike Nashbar introduce the components to American amateurs — at $178, plus rings. Delivery time, 6-8 months.

1985: Richard Jow gives equivocal evaluation in *Bicycling* — but uses nice test jig.

1986: Huret joins forces with Maillard to introduce patented recurved (S-shaped) crank for track bikes. Claimed to give equally significant advantage when sprinting or standing. Helicomatic design gives rapid disassembly with a single lightweight wrench (supplied), and recurved design makes it easy to convince the user that the arms are really 180 degrees out of phase.

1988: Polish Olympic team uses straight hollow titanium cranks. Soviet team, on basis of 256 pp. analysis, bolstered by information from East German Sports Institute, introduces the CCCP bent crank — bent to the left instead of the right, of course.

1989: Bikecology sells their only three pairs at warehouse sale for $37 per pair. Bike Nashbar offers remaining three (right only, 43/54, 205 millimeter, Italian thread) for $78.

1992: USCF's famed Elite Athlete Program completes study on the most efficient pedaling motion in the history of cycling; concludes that P.M.P. cranks are the way to go. Purchases the last available P.M.P. cranks at collectors' item prices (rumored to be $500+ per set). Technical Director Ed Burke is ecstatic. Other equipment sponsors (Campagnolo, SunTour, etc.) are perturbed by large cash outlay.

2013: MIT engineering professor finds P.M.P. crank in back room of The Bicycle Exchange, and carries out strain tests to see if it really did make a difference.

ENGINEERING ANALYSIS

The Physical Anatomy of Steering Stability

Crispin Mount Miller

The long-standing puzzle of bicycle steering stability can lead to some quite complex mathematical expressions. In this article, though, I'm happy to report that we can offer a simple one; one that can clarify rather than complicate your understanding of steering stability.

Credit for this important clarification goes to Raymond Pipkin of Western Springs, Illinois, who wrote to us in response to the "Balancing and Steering" excerpt (August 1982) we printed from Whitt and Wilson's *Bicycling Science*[1] last year.

(That excerpt described the adventures of British chemist David E. H. Jones as he tried to discover what made a bicycle rideable. After trying several times to build an "unrideable bicycle" by using various odd steering geometrics, Jones eventually turned to computer calculations. With these he identified a mathematical "stability criterion" which he named u, that showed a good correlation with the balancing abilities of his various experimental bicycles.)

Some time after printing that article we received a detailed letter from Pipkin. This letter provides a very satisfying extension of Jones and Whitt and Wilson's work, by specifically pointing out the several forces and torques, or turning moments, that act to turn the steering assembly — and by identifying the variable u as a simple, measurable physical dimension that controls the most important of these torques.

(This means, as Pipkin has let me know, that I had miscalculated when I concluded — in the April '83 letters column — that the units of u were defined arbitrarily.)

In addition, Pipkin takes the trouble to unify his discussion with the one given by Archibald Sharp in his landmark *Bicycles and Tricycles*, published in 1896.[2]

I'll present the significant points of Pipkin's analysis (and some additional insights which I draw from Sharp's book) below. First, though, I'd like to mention why we're so interested in u.

Immediate Physical Interpretation

The magnitude of u, as an abstract number, gives a measure of the tendency of a bike to turn in the direction that it is leaned (and therefore of the bike's ability to respond automatically to an out-of-balance condition). Until Pipkin's analysis, though, u has been only an abstract number, obtained by computer or by an equation complex enough not to offer any intuitive understanding of the forces involved.

It's true (and not surprising, as we'll see) that trail — which is not abstract — is usually a decent approximation of u (within five percent, for typical head angles). But if you think of stability in terms of trail, you may misunderstand the forces involved. Pipkin shows, however, that an exact expression for u is even simpler than the equation for trail, and that this simple expression has "an immediate physical interpretation" which is intuitively useful: u is the length of the lever, or moment arm, through which the ground applies torques to the steering axis. We'll see how this works in a minute.

Pipkin also shows that since there are several important torques affecting steering, u does not fully determine a bicycle's behavior. Although u controls the torques that are probably the most important, it is "at best only a partial criterion of stability," he writes.

Steering Axis to Ground

Describing his procedure, Pipkin writes: "The alternative form for u can be derived by writing the frame height as an explicit function of the steering and lean angles, and taking the double partial derivative [which Jones chose as the definition of u—see box]."

This analysis shows that u is related to trail by a simple proportion determined by the head angle, specifically,

$$u = -t \sin H$$

where t is trail and H is head angle (or, if you're calculating u directly, without calculating trail first,

$$u = y - r \cos H$$

where y is fork rake, r is wheel radius, and H is head angle).

From this expression, Pipkin points out, we can see the simple physical interpretation of u: t sin H (or y - r cos H) is equal to the distance from the steering axis to the tire's point of contact with the ground (see Figure 1a). This distance, then, is the moment arm by which the ground's forces on the front wheel apply torques about the steering axis.

When a bike leans, the vertical supporting force from the ground ceases to lie in the plane of the bike, and becomes oblique to the bike (i.e., the vertical force now has a component that is perpendicular to the new, tilted plane of the bicycle). This component acts as a lateral force on the moment arm. Thus (quoting Pipkin again), "u is physically

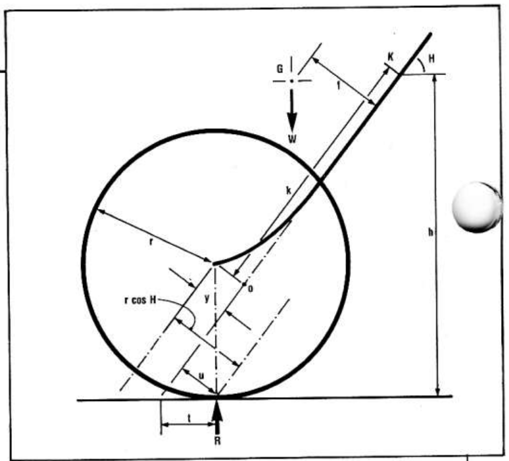


Figure 1a: Dimensions and forces for a bicycle in the vertical plane.
r = wheel radius
y = fork rake
H = head angle
t = trail
u = effective moment arm from ground to steering axis
= r cos H - y
= t sin H
o = point on steering axis nearest wheel axle
K = arbitrary point on steering column
k = distance from o to K
h = height of point K from ground
R = vertical reaction of ground supporting load of front wheel
G = center of gravity of steering assembly (fork, wheel, and handlebar)
f = distance of G from steering axis
W = weight of steering assembly

equivalent to the *turning moment at zero steering angle due to the vertical ground reaction, per unit reaction force and per unit lean angle.*"[3]

And when the bike undergoes a sideways acceleration (as it does in a turn, for example), the force from the ground includes a sideways horizontal component. This also acts on the moment arm.

[1] *Frank Rowland Whitt and David Gordon Wilson,* Bicycling Science *(second edition), MIT Press, Cambridge, Mass., 1982.*

[2] *This remarkable book describes virtually every aspect of bicycle design and construction that existed in 1896, and the thoroughness and accuracy of its analyses put many recent works to shame. The first 140 pages, in fact — almost a third of the book — are a textbook on principles of physics and mechanics, to prepare the reader for the rest of the book. A recently reprinted edition of the book is available from MIT Press.*

[3] *Pipkin actually offers a mathematical proof of this statement, which we have not reproduced here. Interested readers can obtain copies of Pipkin's entire analysis by sending requests, with stamped, self-addressed envelopes, to Pipkin Analysis, c/o Editor,* Bike Tech, *Emmaus, PA 18049.*

Six Torques

The torques created by forces that act on this lever length are obviously very important to the behavior of the bicycle but, as Pipkin says, they aren't the whole story. In particular, the steering assembly generates forces of its own because it has mass and weight.

As a result of these forces and others, there are a total of six torques that act to turn the steering axis, of which I think four have significant magnitudes. (Equations describing these four are given in the box, following the derivation of u.) These four torques come from the following forces (see Figure 1b):

1) The vertically upward support, or "reaction," R, of the ground acting on the wheel at the end of the moment arm u.

2) The vertically downward weight W of the steering assembly, acting at its center of gravity G, which has moment-arm length f from the steering axis.

(These first two forces occur whether or not the bike is moving. The remaining ones occur only when the bike is moving and going through a turn, or through some other sort of steering maneuver which creates lateral accelerations.)

3) The horizontal reaction R_c of the ground acting on the wheel (again on moment arm u). This reaction can arise because the bicycle is undergoing lateral ("centripetal") acceleration in a turn. It can also arise in a similar but smaller-scale occurrence when the steering is accidentally deflected sideways — the wheel will then begin to carry the bicycle sideways (briefly), but this lateral acceleration creates a force and reaction between the wheel and the ground, and the ground's reaction acts on moment arm u to straighten the steering.

4) The horizontal reaction W_c ("centrifugal force") of the steering assembly's mass against the lateral acceleration imposed on it by the path of the bicycle, acting at the same moment arm f as does force W.

(Surprisingly, Sharp, who offers an equation for total steering moment, includes (2) but not (4) in his equation; and Pipkin does not mention (4) either.)

The remaining two torques, which I consider less important (and which Sharp and Pipkin explicitly leave out of their equations), are:

5) The gyroscopic reaction of the front wheel to the tilting and turning motions of the bicycle. (While this may have some importance on heavy-wheeled bikes, Jones cites calculations which show its magnitude to be small, and — more convincingly — demonstrated no-hands riding on a bike in which this reaction was cancelled. He mounted a "twin" front wheel beside the real one, but just off the ground, and spun it backward as he rode, so that it would exert gyroscopic reactions on the fork that were opposite to any exerted by the forward-rotating wheel.)

6) The torque exerted by tire drag when, due to leaning, the tire touches the ground slightly off-center. The force and the moment arm for this effect are both quite small.

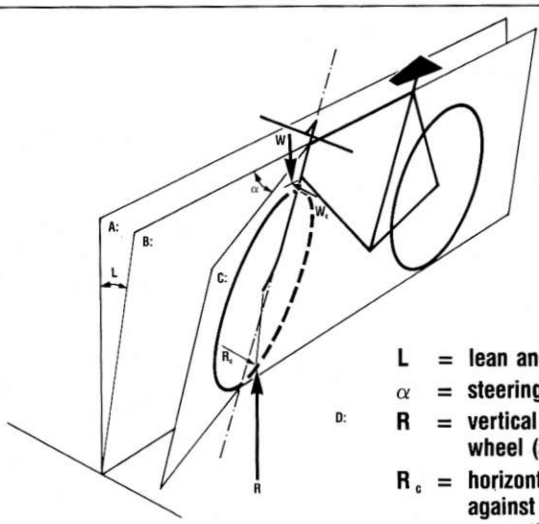


Figure 1b: Dimensions and forces for a bicycle outside the vertical plane.

A: vertical plane

B: plane of bicycle frame

C: plane of front wheel

D: horizontal plane

L = lean angle

α = steering angle

R = vertical reaction of ground against wheel (as in 1a)

R_c = horizontal reaction of ground against wheel due to lateral acceration

W = weight of steering assembly, acting vertically on center of mass G (as in 1a)

W_c = horizontal reaction of steering-assembly mass due to lateral acceleration

Combining Forces

The four principal forces can also be thought of in a slightly different way, which is clearer for some purposes. Since R and R_c act at a common point, and W and W_c also act at a common point, each of these pairs can be combined into a single resultant force—say, R_t and W_t (Figure 2). Not only does this cut in half the number of forces you have to think about, but it may eliminate some entirely.

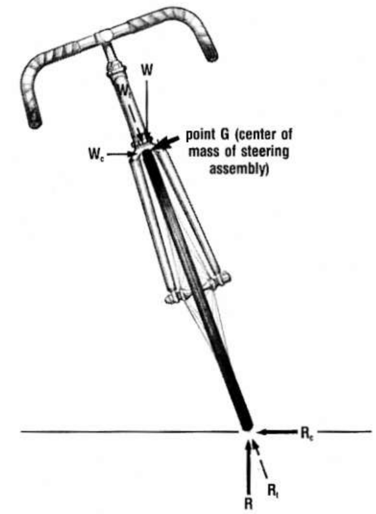


Figure 2: Expressing the sum of horizontal and vertical forces as diagonal resultant forces.

In any smooth turn, R and W create opposite torques, and so do R_c and W_c. The tendency of the bike to oversteer (dive into the turn) or understeer (and then fall sideways into the turn) depends on the relative strength of all these torques. If either of the resultant forces lies within the plane of the wheel, though, that force will exert no torque at all. The desirability of having the force oriented this way, both for control reasons and for structural reasons, is, of course, the whole point of leaning into a turn.

You can evaluate the steering equilibrium of a bike in a turn, then, by figuring out how nearly the two resultant forces lie in the plane of the wheel. I won't analyze the question here, except to say that the resultants can agree pretty well with the wheel plane in wide turns but sometimes don't in sharp turns. (It would make a good computer project, people — but be careful to get your vectors right! Write if you want suggestions.)

Steering Mass

So what steering forces does u not cover, and in what situations are they important? I can think of two cases, and a description of them may help to illustrate how all these factors and torques work as a bike goes through a turn.

To begin with, u clearly doesn't affect the torques created by the steering-assembly mass. How significant are these?

At small steering angles, the steering-mass torques bear a fairly constant relation to the ground-reaction torques, typically being about one-sixth as big on an unloaded bike. (This ratio is given by the ratio between their respective products of "weight by moment-arm length," i.e., the ratio between Ru and Wf — see Figure 1. For instance, the substitution of Wf for Ru is the only difference between Sharp's small-angle equations for torques (1) and (3), or between those for (2) and (4) — see box. For the lightweight, dropped-handlebar bicycles I have measured, Wf is about 18 inch-pounds, whereas I'd estimate Ru — which depends on rider weight — at 110 inch-pounds or more. Note, though, that adding a five-pound handlebar bag will immediately triple Wf.)

Variable Trail

At small steering angles, therefore, the steering-mass torques are unlikely to make much difference unless you've loaded your handlebars or fork. (If you have, then, as any cycle-tourist knows, these torques can take charge of the bicycle.)

At large steering angles, though, particularly if the bike is leaning, the proportionality to ground-reaction torques breaks down and the steering-mass moments can become the principal source of steering torque. The distance f that transmits the steering-mass torques remains constant, but the moment arm for the ground reactions changes!

Note that the distance u is defined (by the equations in the box) at lean and steering angles of zero, and is the effective moment arm only at — or near — these angles. When the steering angle becomes large, the line along which the wheel is tangent to the ground shifts forward around the wheel, so that it no longer forms the same angle H with the steering axis. This shift results in a shorter effective trail, and a moment-arm shorter than u. Figure 3 shows the change in trail and moment arm with change in steering angle for a typical lightweight bicycle.

In fairly tight turns (for instance, with steering angle and lean both just over 20 degrees, corresponding to about a 10-foot turning radius taken at about eight mph), trail actually reaches zero. At this point, then, all the steering torque comes from the upper resultant W_t since the lower force R_t has lost its moment arm and can exert no torque, whether it lies in the plane of the wheel or not. If there's any significant weight in the steering assembly, it will probably make itself felt in this situation as a tendency to oversteer, since the combination of steering angle and head angle will probably make the resultant W_t fall inside the plane of the wheel (that is, if the bicycle is leaned to match the turn, the wheel will be leaned more than that).

In addition, directional stability will be nonexistent in this attitude, since there's no moment arm to straighten the wheel if the steering-assembly weight (or anything else) does deflect it.

Wheel Flop

The other way that steering torque can vary in spite of u is by change in head angle. This effect is a bit more insidious, because it includes a torque from the ground that's actually transmitted through the "u" moment arm.

The overall effect that varies with head angle is the one we've customarily called "wheel flop" torque — the tendency of the wheel, if turned sideways a bit, to turn farther sideways. This torque is proportional to the steering angle (it is zero when the steering is straight) and is one of the effects of ground reaction R and steering-assembly weight W. Both of these forces' torques depend not only on u and lean, but on steering angle and the cosine of head angle (as can be seen from Sharp's small-angle approximations for these torques, M_r and M_w — see box).

This variation not "covered" by u may seem strange, until you consider the purpose for which u was derived. Jones was looking for the factor that made a bicycle correct a fall. He chose u, therefore, to be an indication of the bike's tendency to steer into a lean *from a straight-ahead path*. As a result, u reflects responsiveness to lean, but not to steering angle, since that was assumed to be starting at zero.

For any particular bicycle there is a threshold speed below which you have to restrain the handlebars against wheel flop. Above this speed, the steering-straightening effect (discussed in conjunction with torque (3)) is stronger than the tendency for the steering to flop. Since the straightening effect depends only on u (and speed) but the flopping tendency depends on u and also on head angle (and steering-assembly mass), head angle will affect the relative magnitudes of these competing effects, and therefore head angle will affect the threshold speed.

Diving into Turns

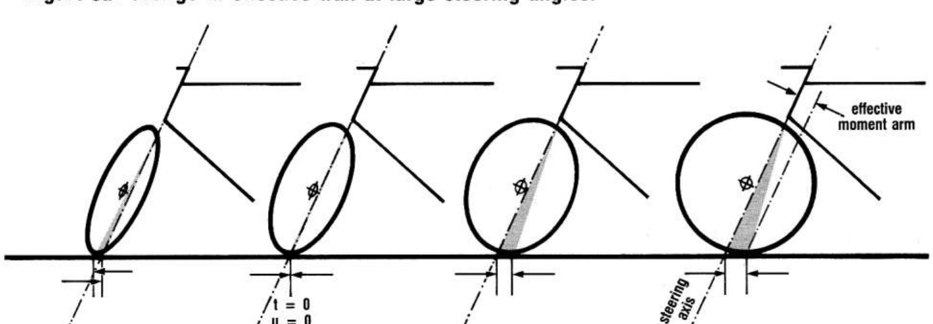
Since the moment arm at the ground gradually decreases with increasing steering angle (as I mentioned in the previous section), at higher steering angles the straightening torque and the "flopping" torque exerted at the ground become less important; but the moment arm torque continues to increase. Thus this situation merges with the one I discussed earlier. An additional point this time, though, is the implication for threshold speed: since the straightening effect "loses ground" as the steering angle increases, the threshold speed to resist flop is higher for turns than it is for going straight. This is one reason bikes with shallow head angles often tend to dive into turns. (Another reason, offered by Pipkin, is that to maintain a given trail or u value, a bike with a shallow head angle has to have a lot of fork rake. This puts the mass of the wheel farther ahead of the steering axis, so that the steering-assembly mass — to which the wheel's mass contributes — exerts a greater flopping torque to begin with.)

Additional Variables

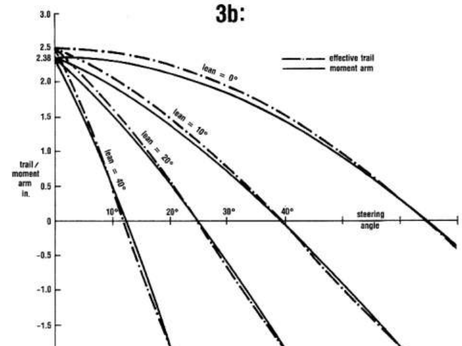
These variations that don't depend on u, then, both concern turns and/or low-speed riding. In the situation for which u was originally selected — riding straight (and fast enough to avoid wheel flop) — I suspect it corresponds to stability quite well.

If this treatment of the subject seems complete, though, that's an illusion. While all this is a reasonably full description of the forces that apply during smooth, even turns, there's more to be sorted out before this can be extended to sudden maneuvers in which

Figure 3a: Change in effective trail at large steering angles.



3b:



the bike is quickly dodging sideways or the mass of the rider is quickly rolling into or out of a lean.

These situations involve rotational accelerations within the bicycle (either of the rider, or the steering assembly, or both), a full understanding of stability — of how a bicycle reacts when its equilibrium gets upset — will have to take account of these additional variables. Such a treatment would probably shed some light on some of the remaining subtleties like wheelbase and bottom bracket height that seem to affect maneuverability and steering response.

I'll keep thinking about these things, and hope to emerge in another few months with something more to say about them (unless one of you beats me to it, or unless I get a lot of fan letters with snores written on them).

Derivation of a Geometric Expression for u

Let the geometry of the steering assembly be as indicated in Figure 1. Then if K is any point on the fork column at an arbitrary distance k from point O, the height h of K for a given combination of lean and steering angle is given by

h = (height to center of hub)
- (vertical component of fork rake)
+ (vertical component of fork length)

or $h = r \sin \Theta - y (\cos \alpha \cos L \cos H - \sin \alpha \sin L) + k \sin H \cos L$

where Θ = (angle between plane of wheel and a horizontal plane)
$= \arccos (\cos \alpha \sin L + \sin \alpha \cos L \cos H)$.

(At $\alpha = 0$, this expression conveniently simplifies to $\Theta = 90° - L$, or $\cot \Theta = \tan L$.)

Taking the partial derivative with respect to α,

$$\frac{\delta h}{\delta \alpha} = r \cot \Theta (\sin \alpha \sin L - \cos \alpha \cos L \cos H) + y (\sin \alpha \cos L \cos H + \cos \alpha \sin L).$$

At $\alpha = 0$, $\sin \alpha = 0$ and $\cos \alpha = 1$, and $\cot \Theta = \tan L$, so the derivative simplifies to

$$\left.\frac{\delta h}{\delta \alpha}\right|_{\alpha=0} = (y - r \cos H) \sin L.$$

But since (from Figure 1)
$y - r \cos H = -t \sin H$,

$$\left.\frac{\delta h}{\delta \alpha}\right|_{\alpha=0} = - t \sin H \sin L.$$

Finally, since $\frac{\delta \sin L}{\delta L} = \cos L$ and, when $L = 0$, $\cos L = 1$,

$$\left.\frac{\delta^2 h}{\delta \alpha \delta L}\right|_{\alpha=0,\ L=0} = y - r \cos H;$$

that is, $u = -t \sin H$.

Values of Steering Torques

(1) M_r due to vertical ground reaction

$$= R \frac{\delta h}{\delta \alpha} \text{ (as in the derivation of u)}$$

$$= R r \cot \Theta (\sin \alpha \sin L - \cos \alpha \cos L \cos H) + y (\sin \alpha \cos L \cos H + \cos \alpha \sin L) \quad \text{(Pipkin)}$$

Approximation for small values of α and L:

$$M_r \approx R t \sin H (L + \alpha \cos H) \quad \text{(Sharp)}$$

(2) M_w due to vertical force from steering-assembly weight

$$= W f (\cos \alpha \sin L + \sin \alpha \cos L \cos H) \quad \text{(Pipkin)}$$

Approximation for small angles:

$$M_w \approx W f (L + \alpha \cos H) \quad \text{(Sharp)}$$

(3) M_{cr} due to lateral reaction of ground (for small and smooth turns angles only)

$$\approx \left(\frac{\frac{R v^2}{g}}{\frac{b}{\alpha \sin H}} \right) (t \sin H)$$

$$\text{or } \frac{R v^2 \ t \ \alpha (\sin H)^2}{g \ b} \quad \text{(Sharp)}$$

where v is speed, b is wheelbase, and g is the value of gravity.

(4) M_{cw} due to lateral reaction of steering assembly's mass (small angles and smooth turns only)

$$\approx \left(\frac{\frac{W v^2}{g}}{\frac{b}{\alpha \sin H}} \right) f$$

$$\text{or } \frac{W v^2 f \alpha \sin H}{g \ b} \quad \text{(Miller)}$$

SHOP TALK

Cutting Oil

Jeff Davis

Recently, I prepared a manual for Campagnolo that included a section on the use of special bicycle tools. I knew that when using cutting, reaming, and tapping tools, a liberal application of cutting oil was imperative. This rule has appeared in many of the professional maintenance manuals I have read, and has been repeated by mechanics and framebuilders I have known. But what is a cutting oil and what does it really do? Why is it important? I found that no one I talked to really knew the answers.

Eventually, I discovered that cutting oil performs several important functions, including:

1) Lubrication
2) Finish improvement
3) Heat control
4) Chip removal
5) Corrosion prevention.

Let's look at these in order.

Milling, reaming, and tapping remove metal from the bicycle frame in the form of chips, carved away by the cutting tool. To separate and pull away, each chip must deform severely. This requirement creates heavy pressures where the chip slides over the surface of the tool, and these pressures tend to make chips adhere (actually weld) to the tool momentarily before breaking away. Tool wear is the cumulative result of these repeated adhesions and tears, but it can be significantly reduced by lubrication. Cutting oil enables the chip to slide over the tool more freely, thus reducing wear.*

Finish Improvement

A related aspect of the lubrication process is the corresponding finish improvement that results when cutting oil is used. By acting as a barrier between tool and metal, cutting oils reduce adhesion. Adhesions are easily recognized as tool chatter. Less chattering means a smoother finish. An obvious example of this is a hacksaw cut: without oil, the cut is much rougher, and chattering is more pronounced.

**For a long time, it was assumed that a cutting oil formed a film between the actual cutting edge and the working metal. But such a function would require a cohesion (film strength) far beyond the ability of most oils—the pressure at the cutting edge can exceed 10,000 psi. Moreover, the tool's cutting edge must contact the working metal directly for the cutting to take place. The place where cutting oil functions as a lubricant, therefore, is along the more-or-less flat surfaces of the tool a short distance behind the edge.*

Heat Control

Heat control is a critical service of cutting oils. Cutting operations create heat by the friction of the chip on the tool, and by the internal heat generated by the chip as it deforms. Oil controls heat both by reducing friction and by carrying away the heat that is generated. Heat control is important because the temperature of the tool and the metal affect cutting speed: the higher the temperature, the slower the cut. (As a general rule, the faster the cut, the smoother the finish.) Clearly, this is a more important consideration in high-speed cutting operations than in the hand operations used to prepare bicycle frames.

Chip Removal

Cutting oils also facilitate chip removal, preventing clogging and dulling of the tool, and allowing the tool user to see what he is doing. In high-speed work, oil is forced into the interface with a pump; chips are removed through hydraulic pressure. Happily, bicycle work requires no such added complications; gravity carries the oil and chips away from the cut.

Corrosion Inhibitor

Finally, oil acts as a corrosion inhibitor. This can be an important contribution, inasmuch as any protective finish, such as paint, plating, or anodization, will have been removed before or during the cut. After preparation, a frame may sit for some time, awaiting installation of the headset, bottom bracket, and so on. The residual cutting oil may be the only barrier between the frame and rust or oxidation.

There are four general categories of cutting oils:

1) "Neat" or "straight" cutting oils, consisting of petroleum products only.

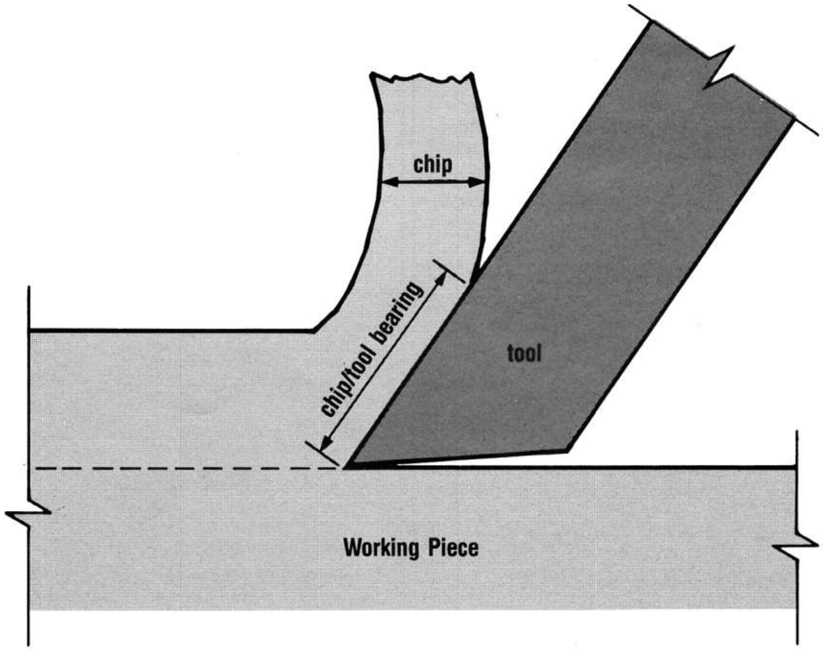
2) Cutting oils that are a mixture of petroleum and vegetable or animal oils. These oils will generally contain an antibiotic to prevent the oil from being attacked by airborne molds or bacteria.

3) Cutting oils that have chemical additives such as sulfur or chlorine.

4) Cutting oils that are a mixture of the second and third types.

Cutting oils are generally labeled primarily by type of use, and don't always specify their composition in very much detail. Still, a general knowledge of cutting oils' compositions and respective applications can give you a better understanding of which tasks can use the same oils and which ones are likely to need different oils.

Bicycle frames, for the most part, are constructed with steel, although there are some exotics made of aluminum, titanium, or composites. Steel frames require the use of sulfur-bearing oils. The high anti-weld properties of these oils make them ideal for today's tough steel alloys. For steels with a carbon content below 0.35 percent, such as Reynolds 531 and Columbus SL, the sulfur content should be fairly high (around one percent). (This can be difficult to check directly, since oils are frequently not labeled for sulfur content. However, any all-petroleum-based low-speed cutting oil can be assumed to be a high-sulfur type suitable for low-carbon steels. Frequently these come in small cans, since they are typically used for small jobs done by hand.) Oils for this use should have no added animal or vegetable oils; these can adversely affect the quality of the cut.



Viscosity

Steels with carbon content above 0.40 percent should have a lower sulfur content and can include animal or vegetable oils. Regardless of the carbon content of the steel, the oils should not be too low in viscosity since hand cutting is slow and good oil-to-tool adhesion is important. A typical viscosity appropriate to hand-cutting operations is 150 Saybolt Universal Seconds ("SSU"). (Extremely thin cutting oils are best used for high-speed immersion bath operations, such as those found in a machine shop.)

Since oil does not absorb the heat of machine-cutting operations very well, some cutting oils are used mixed with water. (The temperature is then held at or below the temperature of boiling water.) Oils for hand cutting do not need water, however.

Aluminum has different qualities from steel and as such requires a different cutting oil. It is recommended that the oil have a 15–20 percent mixture of refined fatty oils. This gives the high lubricity needed when cutting metals such as aluminum or magnesium. Again, the viscosity should be high enough to maintain good oil-to-tool adhesion during the cut, and there is no need to add water to the oil.

In a perfect world, cutting oil would be precisely formulated for a specific task, and large scale users do in fact enjoy this luxury. Because of the cost involved, this ideal is beyond the reach of the bicycle shop. Nevertheless, it is still important that the bicycle technician pay attention to his choice of cutting oils and to the quality of the work they do. This is the only way to ensure the long life of cutting tools. Remember these points:

1) Use a cutting oil that fulfills your requirements as dictated by the metal and the cutting speed.

2) Use lots of oil; an $8 can of oil is much cheaper than a $300 set of taps. It is impossible to hurt the tool by using too much oil.

3) Always inspect your cutters for wear.

4) Keep the tools sharp. Dull tools make sloppy cuts and wear out faster than sharp ones. Never force the tool. If it binds, stop and find out why.

5) If the cutting oil starts to grow a mold, get rid of it—the mold will give the oil unknown and possibly undesirable properties. This mold could also irritate your skin.

In an emergency when the appropriate cutting oil is unavailable, you can use SAE 30 motor oil. The tools will wear faster, but not as fast as if you used a chain lubricant or no lubricant at all. If motor oil must be substituted, use lots of it—more than you use if it were cutting oil—and proceed very carefully.

Another Three-Speed Parts Quirk

Sheldon Brown and John S. Allen

For more than eighty years, the Sturmey-Archer three-speed hub has had the well-deserved reputation of being the lowest-maintenance, most reliable bicycle gearing system available. To maintain this reliability, it has always been considered good practice to use only genuine Sturmey-Archer replacement parts. For instance, replacement axle nuts are available from a number of manufacturers around the world. Almost all of these imitations are made of mild steel, so they will strip much more readily than the genuine Sturmey-Archers, which are hardened, and made of unusually high-quality steel.

It is easy to tell genuine Sturmey-Archer parts from imitations, because the real ones have the letters "SA" stamped into them.

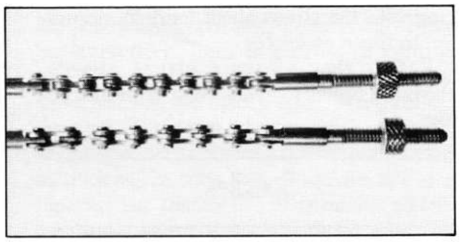
Unfortunately, however, the quality of some genuine Sturmey-Archer parts has been downgraded in an effort to save manufacturing costs, and this is beginning to present service problems.

A particular case in point is the part that Sturmey-Archer calls an "indicator spindle" — the small part with a length of chain that connects the end of the control cable to the sliding clutch inside the hub.

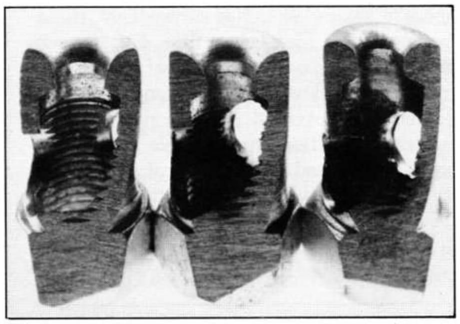
Critical Curvature

The old-style indicator chains have a pitch of about .161-inch, while the new ones use longer links with a pitch of .221-inch. This allows the part to be made with only 3½ links, instead of the previous 4½ links. The old-style chain was made with the inner (single) plate twice as thick as each of the side plates in each link. The new-style chain uses the same thickness for both the inner and outer plates.

The new chains are flimsier, due to the longer, thinner, inner links. Nevertheless, they can give satisfactory service, as long as they are used with either genuine Sturmey-Archer axle nuts or good copies. The problem is that many of the replacement axle nuts are not good copies! Some of the widely distributed right-side axle nuts have a much sharper curvature to the lip that the chain runs against than the real thing. These have worked okay with the old short link chains, but the long narrow inner links of the new style chains can get hung up so that it may not be possible to get all three gears!



(Top) Old-style short link chain. (Bottom) New-style long link chain.



(Left) Genuine Sturmey-Archer. (Center) Good imitation. (Right) Poor imitation. Note the difference in curvature of the poor imitation.

Latent Mismatch

The easy answer to this problem is to say "Well, you should use genuine Sturmey-Archer axle nuts!" This ignores the reality of the situation. There are many thousands of bicycles on the road right now with old-style indicator chains that are working perfectly well with these inferior nuts. When owners of these bicycles come into your shop to replace a lost or damaged indicator chain (far and away the most frequently replaced three-speed hub part) they will not be happy if you sell them one that turns out not to work with the axle nut that they have been using for years.

The best way to prevent this problem is to avoid stocking inferior parts, whether they come from Sturmey-Archer or any other source. Short-link indicator chains are still available from other manufacturers, so these are the safest type to buy. When buying right axle nuts, either buy genuine Sturmey-Archer, or take a good look at the curvature inside the outer end.

Let us hope that Sturmey-Archer will soon realize that this particular bit of corner cutting was a mistake, and return to their older, higher standards!

According to John Temple of T.I. Sturmey-Archer of America, the Sturmey-Archer factory says that the indicator chain links were lengthened to improve the shifting motion of the chain (when it is used with the genuine Sturmey-Archer nut). They acknowledge that the new chain may be incompatible with some makes of nuts, but do not feel that this compatibility should be Sturmey-Archer's responsibility.

DESIGN CRITERIA

Stress Raisers in Bicycles

Gary Klein

Stress raisers lurk in many bicycle parts. They can snap pedals and crack frames. They weaken a part to a mere fraction of its apparent strength and can drastically shorten its life. What are they? They are shapes — surface features of the part itself that concentrate force into small areas when a load is applied. In these areas the stress (force per unit area) can be several times the stress in nearby areas of the part. If failure occurs in normal use it will almost always occur or at least begin at a stress raiser.

Typical stress-raising shapes are notches, grooves, shoulders, and holes — anything that causes a sudden decrease *or increase* in the cross-section carrying the load. The severity of the stress increase is strongly correlated with the sharpness of the concave curvature, but it also depends on other dimensional proportions and on the elastic and plastic properties of the material used. Fatigue[1] is the mode of failure that stress raisers most strongly affect — normal use is exactly where they cause trouble.

How do stress raisers concentrate the loading force? Not just by uniformly crowding it into a smaller cross-section — the effect can be much worse than that. They do crowd the force by a bottleneck effect, but the crowding is uneven; if a part narrows abruptly, the load carried in the truncated portion must quickly shift sideways into some remaining portion, and it all lands on the nearest adjacent part. Large forces in this small area create high stresses.

In this article I'll briefly discuss a few parts of the bicycle to illustrate how design affects the stress raiser. The examples will be pedal spindles, crank spindles, hub axles, and two frame joints. These are by no means the only areas where stress raisers are a problem, but I chose them as illustrations.

Strain Lines

The contour lines in the drawings follow regions of equal strain (stretch or compression) in the material, and the increments between lines are constant. Each set of parallel contours represents a series of zones of progressively higher strain, generally increasing

[1]*Fatigue is failure caused by many repetitions of a stress lower than the material's yield stress.*

from inside to outside; strains in different places (or stresses, which vary correspondingly) can be compared by comparing the number of lines separating each area of interest from an unstressed area.

The exact magnitude of stress at a sharp-bottomed recess is difficult to determine because the minute detail at the bottom can make a difference, and because the behavior of the particular metal becomes a large factor, modifying the value that geometry alone would predict. The contours shown here are estimates based on photoelasticity studies[2] of similar shapes.

One can also deduce some idea of magnitudes from the East Rochester pedals in the example shown. Based on the material and on how long the pedals last, I estimate that the spindles fail from fatigue at a stress of 50,000 psi. Theoretical stress without the stress-raising shoulder would be about 12,000 psi at the upper and lower surfaces for a 400-pound sprinting force applied 2 inches out the spindle; thus the stress raiser magnifies the stress about fourfold, according to these estimates.

Rather than measure stress raisers, though, I prefer to avoid them by proper design.

Spindles

Pedal spindles: The East Rochester pedal (no longer made) has a severe stress raiser designed into it at the shoulder where the inboard bearing sits. Not surprisingly, these pedals have a high failure rate. I have seen several broken ones and know of at least one resulting accident. Ancient Campagnolo relieved the potential stress raiser with a smooth transition from spindle to bearing cone surface and a reduced shaft section between bearing and crank. The rate of fatigue failure on these is very low. Pedal shafts typically fail during a sprint when the greatest stress is applied. Unfortunately, this is the worst time for sudden spindle failure, since it often results in a bad spill and possible injury.

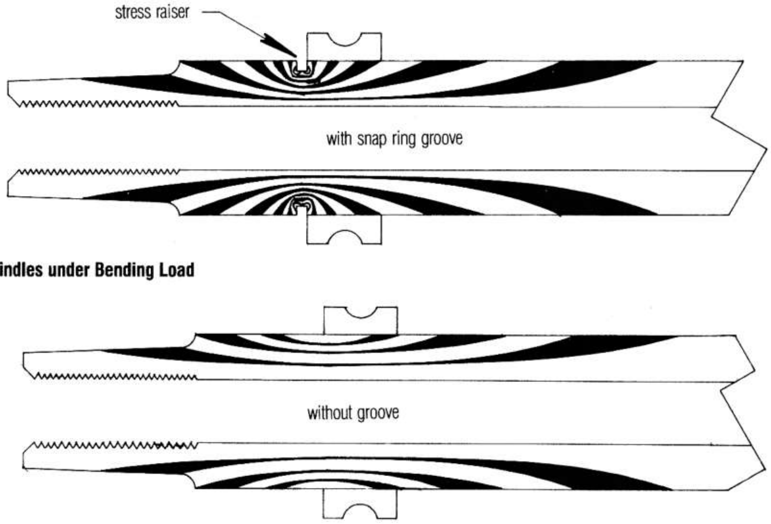
Bottom bracket spindle: These also need to be carefully designed. A spindle with snap ring grooves is not likely to be as strong as a straight shaft even the *smaller diameter* of the snap ring groove. This is particularly true if the snap ring is in the most highly stressed portion of the shaft. Again the stress raisers (the two sharp corners at the bottom of the groove) are amplifying the stress many times at those points. Cracks can form there and propagate through the shaft.[3] Rounding the bottom of the groove can improve the durability dramatically. Of course, the least stressed design is still the full-size shaft with no grooves.

Axles

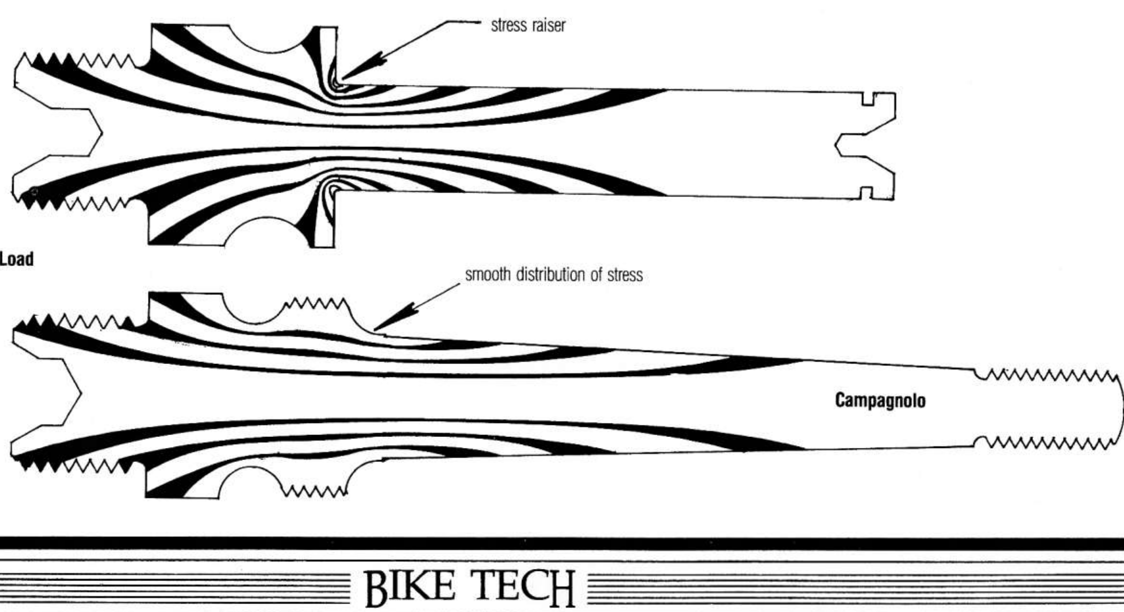
Hub axles: These are available in many styles and configurations, but they can be classified into three basic types:

1. 10-mm hollow threaded axle (most quick-release road hubs)
2. 10-mm solid threaded axle (fixed-gear hubs)
3. 1/2-inch hollow tube (sealed-bearing-type hubs)

For the 140-pound rider they typically all work fine. Heavy riders tend to bend or break the 10-mm hollow threaded axles. These riders can develop chain tension of half-a-ton in a sprint. During a sprint in a high



Bottom Bracket Spindles under Bending Load



Pedal Spindles under Bending Load

[2] *Photoelasticity is a technique that makes such contours visible by using clear plastic models and stressing them while viewing them in polarized light.*

[3] *I haven't actually seen a failure of this kind, but I think the design asks for trouble.*

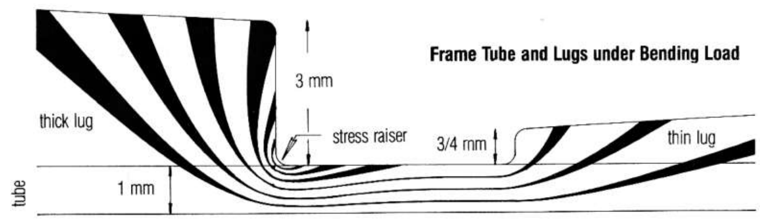
gear, extra leverage is developed on the right-hand bearing of the hub; the chain position is much farther outboard than the bearing. This leverage applies a large forward force on the axle where it carries the right-hand bearing. The 10-mm solid axle probably could take this bending load if it were not threaded; but the threads remove needed material, and the base of each thread acts as a stress raiser. The third type of axle with one plain hollow tube and sealed precision bearings seems to be the best solution for the strong, heavy rider. The larger shaft gives more rigidity and strength with less weight, and there are no threads to create stress raisers.

Frame Lugs

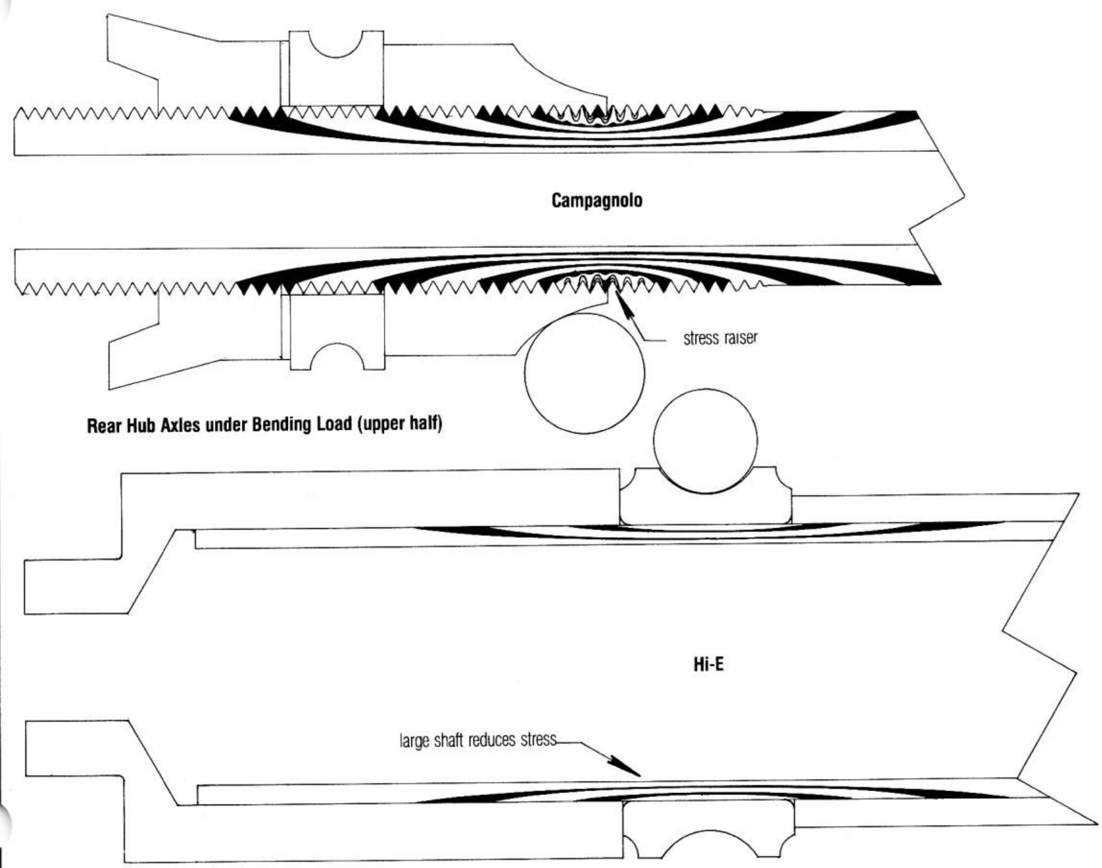
Frame lugs: A common type of frame failure occurs on the down tube at the lower head tube lug. The design and shape of the lug points are important; if the point of the lug is too thick, there is a stress concentration in the down tube. When the tube flexes in normal use, the tip of the lug, being stiffer, does not. The down tube can crack or buckle at this spot. Poor practice is a lug point twice as thick as the tube wall. Good practice is a tapered lug thickness, distributing stress evenly through the lug and down tube. To flex with the tube, the lug tip should be no thicker than the tube wall, which is typically 1 mm in the butted section near the lug.

On some early prototypes of the Klein frames, we had problems with stress raisers in the seat clamp assembly. We had underestimated the fatigue stress there. The seat clamp slot was made with a slitting type of mill, leaving sharp corners in the bottom of the groove. To make matters worse, the wall thickness of the seat tube was turned down at this end to reduce tension on the Campagnolo seat binder bolt. In the thinned tube, the sharp corners developed cracks that would slowly work their way around the seat clamp. Present design, with which we have had no problem, uses a longer slot with a 1/4-inch diameter stress-relief hole at the base. A 6-mm high-strength bolt clamps the seat reliably, eliminating the need for turning down the tube wall. The stress raisers are greatly reduced.

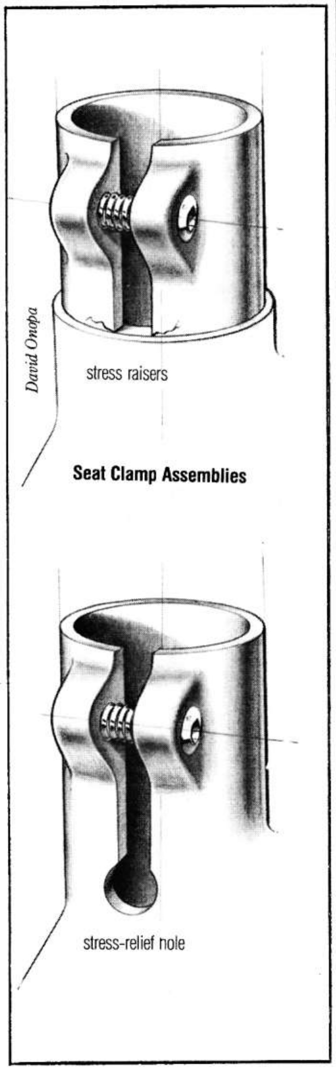
Bicycle parts are typically designed to be just heavy enough for the stress anticipated. Stress raisers, by concentrating that stress in small areas, can drastically reduce the durability and allow early failure, with possible accident and human injury. Designers and manufacturers obviously should be aware of stress raisers and should try to avoid them or compensate for them; and most components on the market today are adequate for average use or even rigorous use by a lighter cyclist. But every rider, and especially the stronger, heavier rider, should examine his or her own equipment, preferably before buying it, to check its suitability for the intended use.



Frame Tube and Lugs under Bending Load



Rear Hub Axles under Bending Load (upper half)



Seat Clamp Assemblies

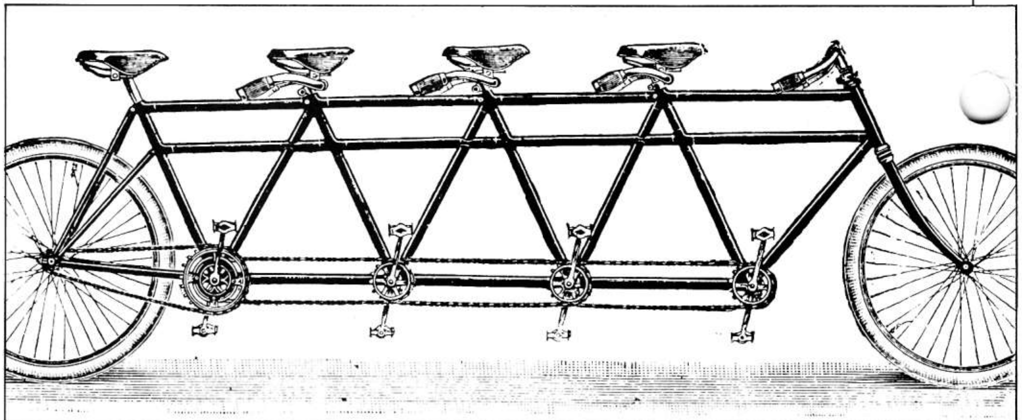
BOOK REVIEW

Fahrradkultur: Early Bikes From a New Perspective

David Gordon Wilson

Fahrradkultur 1: Der Höhepunkt um 1900

(The World of Bicycling at its Zenith in 1900): by Hans-Erhard Lessing. (Rowohlt Taschenbuch, Hamburg, Oct. 1982.)



This delightful book can be enjoyed by all bicyclists. The profuse and detailed illustrations from the main body of the book, which is a reprint of *Das Radfahren und Seine Hygiene* (roughly "bicycling and health") of 1900, by Schiefferdecker, professor of anatomy at Bonn, do not need an understanding of German to be appreciated. Details of construction of tires, chains, shaft drives, strange linkages, brakes, and so forth are presented the more clearly because the author was not an engineer. Accordingly, some details that might have been edited out by a fastidious engineer are preserved for our enlightenment and enjoyment.

Budding inventors would do well to look through these pages as a start to a patent search: I found several devices illustrated here that have been re-invented recently, sometimes with less careful attention to detail. Here, for instance, is a cyclist's foot pump: I was thinking of designing one myself until I saw that it had already been done. There are some atrocious brakes and some very good ones. The book is not comprehensive, despite its almost 600 pages: there is almost nothing on change-gear systems, except those for shaft-drive bicycles which were produced briefly at that time by almost every manufacturer.

As one would expect from an author who was a medical doctor of anatomy, there is a great deal on the construction of human beings and saddles. (There is even a quite decent photograph of a nude man riding a bicycle to illustrate a point about saddle construction). Pedaling action and rudimentary ergonomics get some attention. The author freely gives considerable advice to women in choosing their voluminous under- and over-garments, including tight corsets and a disabling system of wrapping the calves known, when I was a British Army cadet, as "Puttees." The reprint part of the book closes with a professor of law (Schumacher) writing on "the rights of bicyclists."

Hans-Erhard Lessing, professor of physics and physical chemistry at Ulm, author of *Radfahren in Der Stadt* ("Bicycling in cities") and *Das Fahrradbuch* ("The bicycling book"), puts the historical book in perspective with a 25-page introduction covering the bicycle industry of those early days, individual patterns of travel, the emancipation of women, the influence on and of the churches, and the status of technology. Apart from the legal section on bicyclists' rights, the main book and Lessing's introduction are far from insular, there being continual references to and examples of U.S. and U.K. practice.

I heartily recommend it for education and enjoyment.

Let Us Hear

We'd like *Bike Tech* to serve as an information exchange — a specific place where bicycle investigators can follow each other's discoveries. We think an active network served by a focused newsletter can stimulate the field of bicycle science considerably.

To serve this function we need to hear from people who've discovered things. We know some of you already; in fact some of you wrote articles in this issue. But there's always room for more — if you have done research, or plan to do some, that you want to share with the bicycle technical community, please get in touch.