The Art of Bicycles

Is there is something inherently beautiful and fluid about cycling? Is it the way you move forward easily with each turn of the cranks? The way your bike responds when you stand up to climb? The sense of fulfillment when you ride a relatively long distance in a short amount of time? Or is the bike just a tool to let you travel further and faster under your own power?

What is it about these simple machines that makes people love them so much?

Why would otherwise sane and reasonable seeming people, for instance, not only display their favorite bike brand on their cars, but also embroider it onto their underwear? And I'm not talking about socks. Or on a more committed note, tattoo it onto their legs?

The bike is a minimalist structure to begin with. An exposed frame, and exposed mechanisms for propulsion, steering and braking. Yet with these exposed parts, it is still elegant in its simplicity. Each part is smooth, polished or finished because it is exposed. The manner in which it functions is immediately obvious, because you can see all the parts performing each of their respective functions.

The parts are shaped in relation to the amount of stress that each portion of each part will see, as bike designers and manufacturers are intent on reducing the weight of the overall bicycle, and to not shape them thus would result in unnecessary weight. The frame and wheels of the bike might be compared to the body and legs of a person, and the components must then be the clothes and the jewelry.

The lines of the parts, in order to be low weight and high strength, must be fluid and smooth. Sharp corners create weak areas. Unnecessary protrusions add weight. So excellent mechanical design, and design for performance, can easily go along with beautiful cosmetics.

The earliest bikes, constructed of wood, rubber and steel, are beautiful machines. They represent humanities focus, desire and attempts to expand our physical capabilities, to improve upon nature. To go farther and faster under our own power.

As a child, my bike was the tool for my freedom, as well as a lot of fun in the forest and on the roads and footpaths we would ride. My first bike was a balloon tired Columbia. I learned to ride in my parent's tree farm outside of Cleveland, Texas. The Columbia had big tires and relaxed geometry, but it was not a mountain bike because it was a single speed and did not have a front brake.

From there I graduated up to a 3 speed Huffy when we moved to Newton, Massachusetts. I used to take it fishing along the Charles River.

When my family moved to Palo Alto, California, my parents purchased a Gold Schwinn Varsity for me. I thought that heavy steel frame racing bike was the best bike ever made. My Varsity had chrome fenders and baskets, with ten speeds, a big improvement over my previous 3 speed Huffy coaster brake model. I used it to ride to school, chess club and tennis matches.

I became more seriously interested in bicycles when I attended the University of California at Davis in 1970. The Davis Campus is closed to motor vehicles during school hours and the students and staff transport themselves by bicycle or by foot.

There was a bicycle club within U.C. Davis, including a student run bike shop. I was able to use the special bike tools and purchase parts at low cost. I thought that this was really neat.

The school bike club puts on a bike ride every spring called the Davis Double. It is a 200 mile or 320 km ride including some mountainous terrain. I was intrigued with the idea of riding a bike that far. As kind of a dorm challenge, I decided to participate in the ride. I removed the fenders and baskets from my bike, and practiced the week before by riding about 20 miles, the longest I had ever ridden at one time before. I learned that one of the students in another dorm had a bike called a Masi which cost $300. I was surpassed that a bike could be that expensive and wondered what was different about it.

How could a bike justify that much money? When I eventually saw it, it had a different looking frame, with components labeled Campagnolo. It had a more finished look to it than my bike.

There were 54 riders that year, and we started before dawn. I was really excited. There was a gray haired couple on a tandem without any gear changing mechanisms. They were using a track tandem with a sprocket on each side of the rear wheel. One sprocket was large and the other small. I asked them how they would be able to climb the mountain and complete the ride. They told me that at the bottom of the mountain, they would stop and turned the wheel over to the large rear sprocket. At the top of the mountain, they would stop again and change it back to the small rear sprocket. I later found out the tandem with the 60 year olds was the first bike to finish.

It took me more than 17 hours to complete the ride. I was so tired I slept about 12 hours the next day and could not sit down very well. Fortunately it was a Sunday. At that point I was hooked on cycling.

When I transferred to Massachusetts Institute of Technology, there was little cycling activity within the school. Peter Chu and I started the MIT Wheelmen as the school bike club. I purchased a Fuji Finest and began to participate in races. I also operated a student bike shop, supplying bikes and parts to students at wholesale. Many of the businesses that I started working with were the ones who later became my suppliers when I started manufacturing bikes.

I became interested in building aluminum bicycle frames in 1973 while an undergraduate student at MIT. A group of us brought together by Professor Buckley during the January Independent Activities Period thought that aluminum might make a bike frame superior to competition frames made of high strength low alloy steel predominantly used at the time. We started by collecting and analyzing a number of contemporary frames, attempting to determine what the most desirable and important qualities of the frame were. We were trying to figure out what strengths and stiffnesses were most critical, and what the tradeoffs and optimums were between strength, stiffness and weight reduction. We attempted to figure out the major factors that influence ride, handling and overall bike performance.

At that time the aluminum alloy choices were pretty limited. Although some of the tubing stock lists suggested that 7075 and 2024 were available in a small number of sizes, in reality the choices were 6061 and 6063 for use in bicycle frames in the appropriate tubing diameters and wall thicknesses. So our initial frames were made of 6061 seamless drawn tube, the strongest tube material available to us.

The frames most of the students produced were of 1.25-inch diameter, .083 wall straight gauge tubing. This resulted in a frame that was lighter than most steel frames, and stiffer and stronger (with skillful welding) than a typical light weight, high quality steel frame.

Aluminum had been used previously in the Monarch bicycles produced in the US, I think back in the mid 40's. They used hexagonal tubing and cast lugs. The frame was beautifully styled and polished but not competition oriented.

Alan of Italy was making aluminum frames out of standard diameter tubing, 1 inch and 1 1/8 inch, with threaded and bonded lugs. The frames were lightweight but not as rigid as a good competition steel frame. Controlling frame flex under the racing cyclists' exertions appears to be critical criteria of a good competition frameset. By using the same size tubing as conventional steel frames, the appearance of the Alan was similar to a steel frame, but the performance suffered.

Klein was started as an official MIT Innovation center project when I was in graduate school. A professor and 3 of us students put together a business plan and submitted it to the innovation center. Learning from my previous mistakes, I designed a lighter weight and more rigid frame, which took advantage of aluminum's low density. Having a density one third of steel is the single most important feature of aluminum alloys to me. By increasing the tubing diameters to 1.5 inches and reducing the wall thicknesses to .050 to .060 inches, my goals were easily met. We built some prototypes and displayed our first bikes at the International cycle show in New York in February of 1975. They were welded and fully heat treated construction.

Let me talk a little about heat treatment of aluminum alloys. We figured out that the only way to achieve the best properties in a welded aluminum frame was to perform a full T6 solution quench and artificial age on the frame after welding.

Pure aluminum is a very soft metal. It has very little inherent strength. The aluminum atoms share electrons, so it is easy for them to slip over one space at a time. So we strengthen it by adding selected elements. Most of the additions we use dissolve in the aluminum material matrix at high temperatures, around 1000 degrees F. This is called a solid solution. Then when the metal cools down, the impurities crystallize out. Depending on how you control the temperature cycles, and also if there is any cold working involved, you can achieve different distributions, sizes and orientations of the crystals. These small crystals can reinforce or strengthen the base aluminum material. They make it harder for the aluminum to slip a place. Another method of strengthening the aluminum is by alloying elements. Metals like Copper, Magnesium and Lithium have some permanent solubility in the aluminum. These atoms are larger than the aluminum atom, so where one of these atoms is located in the aluminum crystal, the adjacent bonds in the aluminum crystal are strained and tight. As a result, it is harder for the slip planes to form and slide. So this is another method of strengthening aluminum. The alloy system we use incorporates both types of strengthening methods.

Aluminum also has a grain structure. The bulk metal is composed of small crystals of aluminum touching each other. The places where the aluminum crystals meet are called the grain boundaries. The aluminum crystals can be typically observed with a laboratory microscope with suitable sample preparation, polishing and etching. The precipitates, the dirt, are typically too small to see in a standard microscope. A special microscope is necessary to easily observe them.

The highest strength and toughest aluminum alloys are typically achieved with very fine evenly dispersed precipitates and very small and directionally oriented aluminum grains, kind of like the grain in wood.

The problem is achieving this structure in a finished bicycle frame. Welding heats the aluminum unevenly. Aluminum grows and shrinks with changes in temperature a lot. Approximately 3 times as much as steel does for the same temperature change. It is one of the few downsides of working with aluminum. One of my early welding jigs fixed the BB and rear dropout rigidly. When welding the parts together, the aluminum chainstay became hot enough that the walls would buckle due to the thermal expansion of the chainstay in length. We solved the problem by making jigs that will accommodate the expansions during welding. When the welding of a frame joint is done, there is a lot of residual stress left in it due to the uneven expansions and contractions during the welding process. These make it hard to achieve a perfect frame alignment and also weaken the frame near the weld.

Also, the high temperature of welding redisolves some of the fine precipitates. At the weld, they are mostly dissolved. A little distance from the weld, the material is heated enough to allow some of the small crystals to dissolve, and some of the larger crystals to grow real large. This approximates the over- aged or even the annealed state.

When we want to form our material easily, we anneal it with a temperature cycle. We heat it up to 875, hold it for 2 hours, then slowly cool it to room temperature over 8 hours. This grows a very few, very large precipitates. These don't reinforce the metal structure very well, so the aluminum alloy is very soft in this condition.

So the heat treat process we use on our finished frames is a solution quench, 1000 degrees for one hour, followed by a rapid 10 second quench to room temperature, followed by careful alignment of the frame and a subsequent artificial age hardening, 8 hours at 350 degrees F. If you just leave the material as quenched, precipitates will form and increase over time. As they do, the material strength and hardness also increase. But this is a very slow process at room temperature. Even after several months, the alloy is not nearly as strong as after the artificial age cycle.

You can improve the strength of the weld by artificially aging the frame after it is welded, but this does not remove the residual stress from welding, nor does it fix the overaged material a little distance from the weld. The residual stress can accelerate the fatigue process, effectively lowering the observed fatigue strength of the frame. As the frame is used and loads are applied to it, the residual stress may relax, changing the frame alignment. If the frame was properly aligned to begin with, this is not desirable. The combination of residual stress and over-aged tubing material near the weld are why many of the frames welded and not fully heat treated have failed a short distance away from the weld.

The innovation center gave our bicycle project a $20,000 grant to see if there was a business there. Each of the partners put up $1,000 and we began to produce, promote and market small batches of aluminum bike frames in the machine shops and our basement office of MIT. After a year and a half, the batch sizes had grown. The two active partners, Jim Williams and myself had bought out the inactive partners. We were hiring students to help machine parts for the frames. We needed a more commercial location.

So I borrowed some money from my parents, purchased some used tools and an old truck, loaded up our jigs and belongings and moved to San Martin, California. My parents let me use some abandoned dehydrator buildings on their former orchard. The free rent was needed, as we were not making and selling very many frames at that point. The racers whom we had targeted as our market were not buying many frames. And the feedback from the recreational riders indicated that they thought the big tubes and lumpy welds were ugly. So we began to work at improving the appearances of our bikes as well as the performance. Just making a technically superior product it seemed was not enough. Science without art did not sell well.

During this period of low income, Jim and I split up. Since I had invested the most, I ended up with the business. I started looking for an engineering job and as a last resort, almost doubled the price of the frames we made from $325 to $575. I was making too little margin on them, and the customers wanted us to spend even more time and effort on the frames, so I figured that raising the price would dry up the orders and would make the decision to close the business easy.

Instead of reducing the demand for the Klein frames, the orders increased markedly. At a premium above the steel frames, somehow the technical advantages of the aluminum frames were more credible to the typical purchaser. I had to hire some help and increase production.

We worked to further improve the cosmetics of the frames and make them more custom. Improving the visual appeal turned out to be a crucial element in creating a viable business. By 1980, I was building custom frames for over $2000 each.

Many of the cosmetic features on a bike frame are natural. The lightest structure is the one in which the stresses are evenly and smoothly distributed and where there are no sharp corners or edges to create stress risers. For example, I like to see the seat stays blending smoothly into the sides of the top tube at the seat tube. This creates a stiff and strong structure. A structure with smooth clean surfaces works best to maximize stiffness and fatigue life, while helping to minimize weight. Of course, a lot of the cosmetics are in the details. How the tubes are fit together, the dropouts and cable stops. Everything that shows off the workmanship of the finished product.

In 1980 I moved the business to Chehalis, WA where it is currently. I started making production runs of road frames in the early 80’s and mountain bikes in the mid 80’s. These became very popular and completely changed the nature of the business. By the late 80’s we were mostly producing mountain bikes, but the road models have come back significantly since then.

Since we pioneered the large diameter aluminum frame structure, it has become the standard in the industry. I estimate that about 90% of the highest performance competition frames are currently made of large diameter aluminum alloy. The rest are made of Carbon fiber composite, Titanium alloy, and high strength steel alloy. Of the other materials currently in use, I think only the Carbon fiber composite has the potential to produce higher performance with lighter weight than aluminum alloys.

We have used composite materials for selected applications for a number of years, either as reinforcements for the underlying aluminum structure or as the primary structure where appropriate. Fiber composites are most advantageous when used where the loading is primarily in a single direction. We have made used carbon fiber as the primary structure in bicycle handlebars, front forks, and the Mantra front frame for example.

Aluminum frames have recently moved into the medium and lower price categories. Aluminum frame bikes are roughly 50% of the medium to high-end bike market, and growing. Recently, aluminum bikes have begun to be sold in the lower price categories such in mass merchandisers and discount department stores. I don't really see aluminum replacing steel in the lower end, but the cost of making a good aluminum frame continues to decline, and perhaps we will even see aluminum taking over the steel arena in the mass-market bikes.

Aluminum and its alloys are likely to remain more expensive than steel on a cost per pound basis. But with one-third the density, and with appropriate alloy additions, the cost per unit of structural strength may become competitive.

Before I began working on aluminum frames, most of the other component parts of the bike were already made from aluminum, such as the cranks, hubs, deraillers, rims, brakes, seat posts, stems and handlebars. Some items, such as aluminum rims, work so well that they are used even in low cost bicycles. Aluminum extrudes into a precision shape such as a rim section so easily that it is difficult to make a cheaper rim in steel. The reduction in labor cost over rides the higher initial material cost. As labor becomes more and more expensive, the starting material cost will be even less the deciding factor.

The modern racing bike is composed of many components made by many different manufacturers, and is approximately 3/4 by weight made out of high performance aluminum alloys.

Testing:

The Independent Activities Project started back in 1973 with our attempts to test bicycle frames. We looked at frames that had broken from use. We canvassed the members of the MIT and other local bike clubs and our local bike shops for examples. Many of these would be the result of being hit by or running into a car, or riding into a curb or pothole. So it looked like the yield strength around the head tube was important to consider.

On frames that had been used for a long time, there were failures all over which were evidenced as fatigue cracks. We found failures at the seat lug fitting, rear dropout, and near the head tube and BB. These indicated that the repetitive loading on the frame from normal pedaling and riding forces were enough to start and grow cracks in the frame. These cracks were usually at or very near a joint. There were some failures where the steel tubing had rusted through from the inside. Boston puts salt on the roads in the winter, so this was not a big surprise. Occasionally there was a crack further away from the joint in the frame tube where the butting began. As I recall, there were even two cases where a crack started as a result of a defect in the butted steel tubing. By looking at where these failures occurred, the type of failure, the diameter and thickness of the tube material at the point of failure, and looking up the material strength for the type of material used, we could approximate the type and level of loading that caused the failure. This reverse engineered information would later be used to design our aluminum frames.

We also tried to devise some stiffness tests that would correlate to how well the frame would perform in a hill climb or sprint. We clamped some sticks to the seat and down tube, with markers on the ends. As the frame was ridden and the frame tubes flexed, the markers would trace how far the frame flexed, kind of like a ground tremor recorder. We had a good sprinter use the bike for a while, and recorded how far the frame flexed under his peak sprints. We also observed how the frame flexed when we loaded the pedals in a static situation.

From these measurements we devised two stiffness tests and a long-term fatigue test. It looked the major frame deflections were in torsion between the head tube and the BB, and in a combination of bending and torsion between the head tube and the rear dropouts as the BB was loaded.

I kept hearing racers talk about their frames going dead or losing stiffness after a season of use. So we performed the 2 stiffness tests on a frame, then set the frame up with an eccentric cam and a motor to repeatedly deflect it to the maximum deflection recorded by Bill Bridge while sprinting. We ran the fatigue test for over 1 million repetitions, then removed the frame and retested the frame stiffness. There were no cracks visible, and the stiffness did not change after the fatigue test.

We did not solve the question of whether brazed steel frames lose stiffness with normal use, but felt confident that our aluminum frames would not.

We currently make road frames around 2.5 lbs. and mountain bike frames around 3 lbs. With better alloys and metal forming processes, I think we will see another .5 lb. coming off of our frame weights, with no decrease in strength. So far, as we have taken weight out of our frames, the strength levels have gone up. This has occurred because of better understanding of the frame structure and loads, the manufacturing process and its effect on the strength, and improved methods of metal fabrication that allow us to more optimize the material placement in the frame.

Dear Steve:

I would like to respond to your opening statement in the Steel article.

I think the "Aluminum Time Bomb Theory" demonstrates the lack of materials knowledge in the bike industry. It should be common knowledge that most modern aircraft use aluminum exclusively for their primary structures (internal frames and bulkheads) and 95% or better of their exterior surfaces, including load bearing skins. The aircraft industry has been using these alloys for several decades. I have recently been a passenger on some planes that I estimate were made no later than the 60's. So aluminum alloys have certainly proved their long term durability and high performance in the aircraft industry. The occasional failure that has occurred has typically been due to a design or manufacturing defect or improper maintenance.

The aircraft companies have picked aluminum because it offers the best combination of material properties and processing capability in order to create high performance, lightweight, robust aircraft. Prior to the widespread use of aluminum alloys in airframes, I believe that Chrome Moly Steel was used in many cases for structural members and coated fabric was used for skins.

Aircraft see high levels of shock and vibration. They are subjected to high G loads, both positive and negative in severe turbulence and positive when landing. The most severe repetitive G loads occur on aircraft carriers. The planes are accelerated and decelerated at high G's by mechanical linkage with the carrier.

The example given of repeatedly bending a small piece of metal is not relevant to the durability or reliability of a bicycle frame. When you permanently deform the material as in the example you are yielding it. This is not what fatigue strength or fatigue life refers to or is about. It has no relation to fatigue strength. Some of the highest fatigue strength materials I have used are carbon fiber and boron fiber. They will not take a significant permanent set, breaking instead at a high force level. So these extremely high fatigue strength fibers would rate near zero by the repeated bending test.

The example is comparing the material property to withstand reversing yield conditions. On a bike, this would be like crashing the bike, smashing the head tube back and buckling the top and down tubes. Then straightening the tubes back (to the degree possible) and repeating the cycle. While this might be useful in a few circumstances, I would rather my frame did not yield so easily in the first place. The optimum material for this reversing yield property might be a low carbon (low yield strength) or mild steel alloy which has not proven to be a good choice for high performance bike frames.

The statement "Alu has a shorter fatigue life than steel." also demonstrates shortage of material

knowledge and understanding. Sure, a high strength steel alloy will exhibit a longer fatigue life at a high fully reversing load level than a high strength aluminum alloy. These numbers always reflect performance for a unit volume. But it also weighs 3 times as much for the same volume. If the mass of the bike is unimportant, then I guess steel is the better material. If density is factored in, aluminum is actually stronger.
Failure of a structure due to repeated stress cycles has two main components. They are crack initiation and crack propagation. The obvious thing to design for is to prevent crack initiation. In theory, if no cracks can start, then we don't need to worry about fracture toughness, or crack propagation. But this does not work in real life. I think that all metal bike frames have millions of small cracks. It is inherent in their metal structure. Most metals are made up of very small metal crystals or grains stuck together. There are inherently a lot of flaws in the micro structure. The concentration of cracks is higher where the metal has been welded or brazed, such as at the joints. I believe this is true for steel, aluminum and titanium alloys. A tough material will allow the bike to perform adequately for a long time with a crack in it that is below a certain crack size. The tougher the material, the larger the allowable crack. Below this critical size, the crack will grow so slowly that it will not become a problem.

Crack initiation behavior is measured by fatigue tests.

Fatigue behavior of a given material is not at all well defined by any single number. Fatigue behavior for a material is more accurately portrayed by a series of curves. The behavior (and number of cycles it can withstand) will vary considerably depending on whether the load is only applied in one direction, both directions, or is applied in addition to a static or constant load. For each type of loading condition described above, the material will exhibit a range of fatigue cycles to failure depending on the load level applied. The most commonly used test is the fully reversed load without static load. It is a simple test to perform.

The fatigue life increases as the stress level is reduced. Common steel alloys and common aluminum alloys have differently shaped curves.

The curve for steel under fully reversed loading is approximately a constant downward slope (plotted on a logarithmic cycle's scale) until about one million cycles, where the curve abruptly becomes horizontal. It has a well-defined corner in it. This is called the endurance limit for steel.

The curve for aluminum does not have this sharp corner. The curve continues to decrease very slowly well past one million cycles and becomes horizontal at five hundred million cycles. So the fatigue limit for aluminum alloys is typically measured at 500 x 10^6 cycles, where the curve is no longer decreasing. This is way more high stress cycles than a bicycle will ever see.

I should also add that there is typically a lot of scatter in fatigue data. Often a thick band showing the range of cycles that the material withstood may represent the curves.

The shape of the curves sort of gives aluminum an advantage in the fatigue mode. I think the real high stress cycles that a bike sees are more likely to be around 10,000 cycles during its expected lifetime (about 20 years). As aluminum's published data is typically measured at 500 million cycles, it is considerably stronger at lower cycles. Steel is also stronger at lower cycles, but since it was measured at one million cycles, the strength improvement at 10,000 is probably not as great as in the aluminum.

This has all been theory and laboratory testing. The reality of aluminum frames has been a little rockier. As aluminum frames are becoming available at a wide range of price points, so does the quality vary widely. I would much rather ride a medium quality steel frame than a poorly designed and manufactured aluminum frame. In other words, the material is not nearly as important as the design, engineering and construction.

Why do I like designing and building aluminum frames?

Aluminum is a great material to work with.

Light weight: It is called “light alloy” because of its low density. One cubic inch weighs one tenth of a pound. One cubic inch of steel weighs three tenths of a pound. So I can use twice the volume of metal that a good steel frame uses and the steel frame will still weigh 50% more than my aluminum frame.

We are currently making road and Mt bike production frames in the weight range of 2.5 to 3 lbs. for a bare frame. These are robust frames designed and intended for hard competition use.

Great ride. The low density and high formability of the material allows me to tailor the stiffness of each part of the frame through tubing and joint design. And the lighter weight positively affects the ride quality. When I ride a high quality steel frame (which is not very often) it usually feels a little clunky and slightly harsh by comparison.

High strength: It is possible to achieve significantly higher strength properties in the aluminum structure per weight than I could in steel.
*Part of this comes frame the basic material properties.
*Part of this comes from the increased design freedom that the lower density material offers. For example, where I need a part of a given shape, such as a cable stop or a dropout, the aluminum part will weigh one third of the steel. A pair of Attitude rear dropouts weighs 60 grams. How does this improve strength? By removing mass from some of the shaped parts, it allows me to put the material where it is needed for strength purposes instead.
*Part of the higher strength occurs because we fully heat treat the frames after welding. We solution quench and artificially age harden them up to full strength T6 condition. While it is conceivable that welded alloy steel frames could be hardened and tempered to improve their strength, I am not aware of any production frames using this technique.
*The largest contributor to high strength is engineering and design. The low density and high formability of aluminum allows me to use increased wall thickness, complex shapes and larger sections where I want to achieve high strength properties in the overall structure.

High toughness: Some of the highest strength aluminum alloys, particularly in the 7000 series, have low toughness, or resistance to crack propagation. We use alloy systems specially selected for high toughness.

High power train efficiency: Here I use the low density to create shapes and sections that resist the bottom bracket and rear wheel from twisting under the riders pedaling strokes. Thus more of the cyclists energy goes into forward motion.

Corrosion Resistant: Inherent corrosion resistance much better than steel or magnesium alloys.

Easy to build custom frames and prototypes with.

I should add that I also use Carbon and Boron fiber in some of our products. For some applications, the high property fiber materials are superior to metal.

2. What advantages does a rider get from a good alu frame? And do you think alu becomes better of worse than the alternatives for particular functions?

Aluminum features:
Great ride feel: Better than steel and Titanium, competitive with lightweight Carbon.
Light weight: Lighter than steel and Titanium, competitive with Carbon.
Power Train Efficiency: Better than steel, Titanium or Carbon.
Fatigue strength: Better than steel, competitive with carbon and Titanium.
Impact strength: Better than carbon or Titanium, competitive with steel.
Yield strength: Better than steel or Titanium, competitive with carbon.
Corrosion resistance: Better than steel, competitive with carbon, below Titanium.

For functions, I would go with aluminum on road and off road, suspension and hardtail.
For some types of frame designs, such as monocoques, I think carbon has an advantage.

3. What is the future of alu frames, generally and from a personal perspective?

Generally, we will see more aluminum frames from developing countries at lower price points. As aluminum takes more care to build a good frame with, I have some concerns about the potential quality and reliability of some of those products. Because of the new sources, I think aluminum will take some market away from Chrome Moly frames, but is not likely to go so low in cost as to affect carbon steel.

At the medium and higher quality end, I see aluminum frames incorporating better alloys and manufacturing techniques. I see the durability improving and the frame weights reducing further. I think top quality frames will approach 2 lbs. and suspension frames 4 lbs. As a result of these improvements, I think the high-end aluminum market is going to grow substantially. As the suspension bikes become lighter, and function better, the market for them will get very hot.

I am not in the steel or Titanium business, but unless they are working on some quantum leap technology in their materials, I see a dim future for them in high-end frame products. The materials are too dense. They are not going to go away, but they will not be where the major action is, either.

Carbon and other high property fiber reinforced materials, however, have tremendous potential. I expect aluminum and Carbon to become the key contestants for the highest performance bike frames.

I might point out the history of the tennis racket. For many years they have been made of wood, which is what I learned on. Then there were Chrome Moly steel rackets, then aluminum rackets. Then fiber composite rackets. Modern rackets are resin bonded fiber composite for high end, and aluminum for medium and low end.

The tennis racket is a simpler structure which lends itself better to composite construction than the bike frame, but as manufacturing techniques improve over the next decade, I expect fiber composite bike frames to become more developed, successfully competing with and replacing high end aluminum frames. Competition aluminum frames will continue to evolve and improve through introduction of higher property aluminum alloys and improved metal working techniques.

Aluminum bikes over the next decade will be produced at lower and lower costs, replacing steel bikes in the lower end, high volume end of the market.

Klein will continue to use both composite and high property aluminum structures, picking whichever type of material has the most advantage for a particular application. Eventually I think we will see ceramics at the highest level of competition products.

Many bike design people will look at a bike and say, "Where can I take a little more weight off?"