A brief history and future of materials in the cycling industry

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The evolution of materials in cycling goes along with the design of bikes. Original bikes like those proposed by Da Vinci and Caprotti to those from early 1800's are made from wood and typically whatever was found in the local area. But as the development of materials progressed so have the bikes; with steel, aluminium, magnesium and titanium have all been used through the 1900's and within the last 20 years carbon fibre has become the most heavily developed material of late. As materials in cycling and manufacturing methods have become more advanced what hasn't progressed too much is the overall shape of the conventional bike. The bike has settled on the conventional double triangle design, there are a variety of reasons for this but the ultimate one is the governing body of cycling the UCI have mandated for competition that double triangle design must remain.

Figure 1: Da Vinci and Caprotti concepts from the 1400's and a recreation

So what impact does the frame material have on bike performance? There is an exceptional amount of anecdotal and experimental evidence out there from the weekend racer to the pro peloton to the sport scientist about what makes an ideal bike, how stiff it should be, how comfortable the ride should be and what materials it should be made from. To achieve good bike stiffness (if this indeed is the ultimate bike performance parameter) two things are needed; firstly, the stiffness of the frame material and secondly bike design, both from a geometry of the frame and geometry of the individual tubes. So when comparing a Carbon Fibre Pinarello to Titanium Baum to Aluminium Trek, there is going to be differences in both frame geometry as well as frame material.

Having this situation has pushed designers and engineers much more into the shapes of the tubes, the angles of these triangles and the ride characteristics of the bike. One of the predominate feature of ride characteristics is vibration that is transferred through the frame, the vibration generated from the uneven road surfaces, the stiffer the material the more vibration that is transferred and vice versa. However, if we have a softer material then less vibration is apparent and thus the power transfer from the legs to the pedals and onto the back wheel is less as a general rule. This dilemma has been one of the single most driven design topics around cycling for years, how to make a stiffer bike

Figure 2: Calfee Bamboo material road bike

but increase the levels of comfort. As with the automotive industry there is a constant drive to ensure greater levels of comfort, this in turn leads to reduced fatigue and then onto greater performance, a very good thing if you are completing a three week tour of France! This discussion about bikes is as much about the design of the geometry as to the materials chosen and how that material is used, shaped, moulded or formed.

Originally bikes where made from wood and other natural materials. Leonardo Da Vinci (master) and Gian Giacomo Caprotti (student) proposed a bike design in about 1493, however, it is not quite confirmed as the first bike or an adapted design (figure 1). Several recreations of this design have been developed over the years and by using the materials at the time; wood was predominantly the material of choice. In 1818 the first "Velocipede" or "Draisine" was patented in Germany made from wood with two inline wheels, it had no pedals and was propelled by running then sitting on it. It wasn't until the mid 1800's that pedals became a regular fixture of the bike frame and materials moved from wood onto steel and designs resembling todays shape. In the 1870's was the advent of larger wheels that allowed people to ride faster such examples are the "Penny Farthing".

'To achieve good bike stiffness (if this indeed is the ultimate bike performance parameter) two things are needed; firstly, the stiffness of the frame material and secondly bike design, both from a geometry of the frame and geometry of the individual tubes.'

But natural materials have not stopped there. In recent years there have been many custom and low volume producers that have sought to push the boundaries of not only wood but other materials such as Bamboo. Calfee Design based out of California is taking a different approach, combining Bamboo and other materials to produce a bike frame (figure 2). Bamboo has been reported, once treated, to strengths of up 500 MPa and has better strength properties to aluminium and some low grade steel. Another approach taken from a group of industrial designers and using turn of the previous century wood forming and bending techniques to create a very different shaped, but still semi conventional bike (Figure 3). The Thonet bike mixes not only some older material forming techniques but mixes it with newer composite methods as well.

From grown materials to the metallic the cycling industry has been dominated by steel, it's cheap, abundant and easy to manufacture. Steel has been the choice of bike manufacturers for much of the 20th century. Bikes have been used during both world wars, were the major method of transportation through the great depression and even today in congested and crowded cities such as Tokyo, Mumbai and Paris they are a staple mass movement. As steels have improved over the years so has the

Figure 3: Thonet steamed wood and composite single speeder

cycling industry choice of steels with it being dominated by several key companies out of Europe and USA. These steels generally carry additions of Chromium, Nickel, Molybdenum and Niobium to varying degrees depending on what properties are trying to be achieved. Steel bike are generally split into two categories mass produced, low value bikes. The other side of steel bikes are low volume, custom built and high value specialty items, these generally made mostly by SME's around the world. Australia has a few of these producers namely Llewellyn Custom Bikes based in Queensland and Baum Cycles in Victoria (Figure 4).

'Carbon fibre is definitely the new kid on the block, its rise in the cycling industry started in the late 1980's and has gone on to be the dominate material for low to high end mass produced bikes.'

The materials these SME's work with is important, however, the critical and defining characteristic for these producers is the fit and feel of the bike (see Darren Baum's interview). With the advances in higher strength steels and manufacturing processes tube diameter sizes have managed to increase with wall thickness decreasing to achieve lighter weight frames, again going hand in hand with design and ascetics.

Aluminium has really come on in the latter half of the 20th century mainly due to access for cheaper electrical power and better processing outputs. The lower density of aluminium does make it attractive material but this is generally a trade off to its lower strength, stiffness and fatigue performance compared to materials such as steel and titanium. Common alloys include 6061 and 7005 and are generally found in lower end bike rather than higher performance set-ups. Aluminium did get a poor name for itself, when in the 1980's, a larger bike company used it extensively and it got the nick-name Crank'n'fail due to the poor process control over the butting and welding of tubes together causing a significant amount of frames to fail at critical junction points – this was all but a brief period of time and that company now makes high quality frames used by professionals to amateurs successfully. Due to the poor name aluminium achieved again this material tends to be relegated to mass produced, low value frames and typically over engineered sections to combat poor process control. But there are several cases where aluminium has been used to produce high quality frames, Trek have just released a limited run of aluminium frames with a nice price tag and some custom frame builders also use the material.

'One of the biggest changes is the development of 3D printing and rapid prototyping especially in the area of metallic materials...'

Titanium has found a good niche in cycling, rated by many cyclists as the best material for bike frames. Titanium either 6-4 or 3-2.5 is typically what is found due to commercial supply; but the strength, stiffness and anti-corrosion properties are most desired when it comes to cycling. Some of the negatives are its cost, machinability and ability to weld. Due to these reasons it remains almost exclusively to low and medium producers who can charge a higher price due to workability issues.

Carbon fibre is definitely the new kid on the block, its rise in the cycling industry started in the late 1980's and has gone on to be

Figure 4: Baum Cycles Steel based "Ristretto"

the dominate material for low to high end mass produced bikes. You can quite easily buy a brand new carbon fibre bike for $2,000 at your local bike shop and in the same breathe you could spend $20,000 on a top of the range carbon fibre bike. The market is dominated by the big brands and two in particular being Giant and Merida based out of Asia. Giant and Merida not only make bikes for themselves but they also use their factories to fabricate frames for many other companies around the world. The other big players come from USA including Trek and Specialized; Europe has the likes of Colnago, Look and Pinarello. Some of these frames are made by the companies in their home country and other models made in factories in Asia. Carbon fibre frames are almost the standard with the metallic materials seen or perceived as either the low end or extremely high end. Frames are generally graded (or priced) depending on the tensile properties of the carbon fibre, with the higher the grade the more expensive the frame; also price can also be dependent on branding and company location e.g. the prestige factor. With carbon fibre frames design of the traditional double triangle has had many variations with each company developing the stiffest bike laterally but with the most vertical compliance possible. There are so many designs just in this space and due to the formability of carbon fibre this is a reality.

If we do a quick comparison of the materials and look at typical properties with respect to density we can see at first glance carbon fibre composite in its uni-directional form is quite good, but as far as practical concerns, multiple layers in various directions are needed; so it's better to look at it in a weave format to get a better

Table 1

Material	Density (g/cm^3)	Elastic modulus-stiffness (GPa)	Specific stiffness (stiffness/ density)	Typical tensile strength (Mpa) (Mpa)	Specific strength (strength / density)
Steel	7.81	210	26.9	250 – 2000	32 - 256
Aluminium	2.73	71	26	100 – 550	37 – 201
Titanium	4.0	114	28.5	170 – 1100	43 – 275
Carbon fibre composite (uni-directional)	1.7	100	55.5	500 – 4000	294 – 2350
Carbon fibre composite (weave)	1.7	50	29.4	500-2000	294-1175

comparison. Specific stiffness is probably the best measure as the elastic modulus is a key feature designer's and engineer's look for, as shown in Table 1 many of the materials that have been discussed are not too dissimilar. This is purely a rough guide to normalise materials against each other.

'Let's not forget that the sports industry is only number two behind the military for uptake of new materials technology and thus has the money to pay for such developments.'

The development of materials and how they are used in the cycling industry is still progressing, we are actively seeing companies develop better types of carbon fibre and mixing it with other materials and additives such as flax for increased comfort or nano particles for increased fracture toughness and resilience. One of the biggest changes is the development of 3D printing and rapid prototyping especially in the area of metallic materials, the thought of printing complex shapes from steel or titanium 10 years ago was merely small scale and almost inaccessible to many companies.

Now with many universities and R&D groups around the world being able to print complex metallic shapes it is a vastly more accessible technology. Let's not forget that the sports industry is only number two behind the military for uptake of new materials technology and thus has the money to pay for such developments. The ability of printing a frame or producing scaffolds to coat with other materials open up new possibilities that replicate the shape of composites but with the stiffness and strength of metals is an interesting concept, suddenly the welds and heat affected zones from the joining process is no longer a big concern. This area of development has already been embraced by small and large cycling companies. The large companies can see it as test bed for ideas and innovation, making new moulds and trialling new shapes. While the smaller custom cycling companies can see it as a point of difference, adding more personalisation to an already personalised piece of equipment; just have a look at the North American Handmade Bike Show each year and the influence on 3D rapid manufacturing techniques are becoming more abundant as the barriers to entry decrease.

A Deakin University engineering student did his final year project on exactly on this topic: what is the best combination of geometry and materials for road cycling? He got a good result, but it ended up as combination of three different companies' designs / materials in a mash up design. It seems no matter how many newly developed materials, new shapes and new concepts come to cycling, people are always going to have a personal preference of one material over the other. The final point is that cycling has as much to do with fashion as it does with function so no matter how well it performs it has to look the goods as well.

Clarity Bike concept suggests transparent future for cycling

Source: Designaffairs

Bicycle design hasn't deviated much from its origins back in the 1800s. A cross frame connecting two wheels to each other works to the point that any attempt to offer something new and innovative – such as the Fliz Bike – is usually derided as being pointless.

However, the materials used to build the humble bike have changed over the years, and will continue to do so all the while there's a demand for lighter, stronger frames. Could a transparent polymer provide the next logical step in the process? German studio Designaffairs thinks so, and it has created a conceptual design which uses a polymer called Trivex for the frame. Trivex is the same material used for the windshields and canopies of helicopters and jet fighters, and it's lightweight while still maintaining tensile strength.

Clarity Bike was born from Designaffairs' focus on using the materials in its library (of over 2,000 samples) in new and/or unusual ways. If this evolved from being a concept to an actual product, then it would be the first bicycle made from Trivex.

The Clarity Bike could be a giant leap forward in bicycle frame engineering and production. The design takes advantage of an advanced polymer which combines high impact resistance, lightweight properties and a gentle flexibility that usually would only be expected on an old Italian steel frame.

The polymer is injection moulded, which allows affordable and precise mass production while enabling unique form factors and a multitude of possible colour combinations. Initially the polymer was used in military applications. Even though the compound has a lower density than polycarbonate & acrylic its advanced performance includes exceptional impact resistance and ultra-lightweight performance. It also offers outstanding chemical resistance and thermal stability as it is virtually unaffected by most organic and inorganic chemicals and withstands very hot and cold temperatures.

Trivex boasts various properties which immediately make it a compelling possibility for use on bikes. It's extremely lightweight, resistant to impacts, and resistant to extreme temperatures. What's more, it can be injection moulded. This opens up the possibility of mass production for the frame, which should lower the costs and therefore the price of the finished product. It also means different form factors and colour schemes would be easily manageable.

Caption: Clarity Bike features a frame made from Trivex, a polymer with positive properties

Caption:Clarity Bike with a transparent frame will turn heads

The front of Clarity Bike

However, it will be a long ride getting the Clarity Bike from its present form to one that could safely be used by ordinary people. It may be visually stunning, but the steep geometry of the frame means it would be painful to ride. It's also not clear whether the straight lines are there purely to please the eye or for another, more practical, reason.

Clarity Bike may turn out to be an exercise in aesthetics and nothing more.

The Baum perspective on cycling and materials

Darren Baum trained and worked as a certified aircraft engineer and stainless steel TIG welder before becoming a frame builder. His cycling career began as an A grade rider before a car accident in 1990 sparked a long-term interest in how biomechanics and bike design can be used to increase performance. Darren is now a well regarded bike builder specialising in steel and titanium frames based in Geelong, Victoria.

When designing a bike what is the thought process, looking at the design and characteristics of the bike and what you want to achieve or looking at the available materials and seeing how they would determine the bikes characteristics and design or is it a combination of both?

Biomechanical fit, handling, compliance/ stiffness & style. In that order, it is paramount that a cyclist is comfortable on a bike. It is a custom piece of equipment and there is no need for it not to fit 100% and should be as responsive as possible for each individual.

Materials such as carbon and titanium now make it far easier to get below the 6.8kg UCI mandated minimum weight, where to next in terms of design and material choice but sticking to the UCI rules and regulations?

Meeting the UCI limit is easy, we look at the balance of stiffness between components e.g. fork laterally stiffer than the wheel, wheel is stiffer than bars. A bike should handle a certain way if there is too much compliance in one area and not enough in other areas then this compromises the bike and how it should work.

Additive manufacturing has come on leaps and bounds in the last decade and we are seeing sections of the bike industry embrace this, where do Baum Cycles see this technology heading and is there a place for it in mass/custom manufacturing for cycling?

Figure 1: Titanium frame bike from Baum Cycles

Additive manufacturing has more advantage in custom side with its flexibility of low tooling cost, multiple parts/design in a single run and the higher accepted unit price. It is an area that Baum Cycles is investigating as long as it does not compromise the quality and ride that we strive for.

What industries (eg auto / yachting / textiles) influence your engineers and designers, where do they get the next ideas from, or does it come down to running it by the numbers in terms of FEA, testing and rider feedback?

Influences are coming from the aero parts of the industry, motor racing, yachting, e.g. low torque aero wheels. Aerospace has been a big part of my life so it does influence what I do now. I also have a real interest in car racing so that also influences me.

Figure 2: Finishing titanium to ensure a perfect fitting frame

Figure 3: Cutting titanium tubing

In terms of testing what processes/ tests/standards do you do to ensure frame warranties and long term rider characteristics of the bike?

For testing we work with the pros at Deakin, they are right on our door step and they have some equipment that helps us out in making sure our materials are of the highest quality.

How much influence do the pro-level cyclists have in your design process?

We look at individuals and meet their needs. As stated previously we area about meeting the individual and ensuring that the ride and handling meets their own needs with our bent on frame geometry.

What are the thoughts of a titanium/ carbon or steel/carbon mix like independent fabrications or an exogrid that some companies are working on?

The mix of carbon with titanium and steel in our opinion makes the bike feel like a carbon bike and loses the feel of steel/titanium. It is not something we like to do as we strike for a certain performance characteristics that only steel and titanium can give us.

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The trek bicycle perspective on cycling and materials

Figure 1: Justin Leov of Trek World Racing speeds over rough, steep and rocky terrain on his carbon Trek Session 9.9 bike, proving that carbon fibre is not just a material for lightweight road bikes, but can also handle the rigours of downhill racing.

Trek Bicycle is a global leader in the design and manufacture of bicycles and related products. Trek believes the bicycle can be a simple solution to many of the world's most complex problems, and is committed to breaking down the barriers that prevent people from using bicycles more often for transportation, recreation, and inspiration.

This interview with Jim Colegrove, the Senior Composites Manufacturing Engineer at Trek U.S.A shows that the future is very bright for bicycles indeed. Through the use of powerful design tools, ever improving materials, and implementation of quality repeatable process, the sky seems to be no limit to what Trek can achieve.

When designing a bike what is the thought process, looking at the design and characteristics of the bike and what you want to achieve or looking at the available materials and seeing how they would determine the bikes characteristics and design or is it a combination of both?

Trek uses cross functional teams when designing new product. Members from all the key aspects in our company collaborate so we have a balance in our product offering. Beautiful shapes that are well engineered, and provide great performance for the customer, at a good value. We draw from industrial design, engineering, our

Figure 2: Jim Colegrove, the Senior Composites Manufacturing Engineer at Trek U.S.A

Figure 3: The top-of-the-line Trek bicycle frames are still made by hand in the companies Wisconsin factory.

vast materials background, and processing knowledge to make this happen. We have been producing carbon fiber bikes since 1992 and have gained considerable insight over those years into best practices for bike design and manufacture.

Materials such as carbon and titanium now make it far easier to get below the 6.8kg UCI mandated minimum weight, where to next in terms of design and material choice but sticking to the UCI rules and regulations?

At some point in time we will reach the lower limit of weight for each material of choice. I believe that with most metals the design limit has been reached in the bike industry. Composites is another story, through creative design, enhanced processing , and use of ever higher performance carbon fibers there is still some opportunity to reduce weight. The real trick is to maintain ride performance, improve aerodynamics and ride comfort. We can produce bikes below the UCI limit so now we focus on where we put the weight and how it effects/improves ride performance.We currently work with a very large quiver of different types of carbon fiber to get the performance we want. We use a combination of ply count, ply angles, aerial weight, and performance level (grade) of carbon fibers to make this happen. We use everygrade type of carbon fiber available from standard modulus (33 Msi or 228 GPa) and (620Ksi or 4278 MPa) tensile strength to Intermediate modulus (40 Msi or 278 GPa) and (800 Ksior 5520 MPa) tensile strength, all the way up to Ultra High modulus (78 Msi or 540 GPa) and (580 Ksi or 4020 MPa) tensile strength fibers. These combinations give us the greatest flexibility to tailor each area on the bike to do exactly what we want them to.

Additive manufacturing has come on leaps and bounds in the last decade and we are seeing sections of the bike industry embrace this, where do TREK see this technology heading and is there a place for it in mass manufacturing for cycling?

Trek has been using rapid prototype machines to make all manner of bike pieces and parts for about 4 years now. The Objet machine we use is primarily for 3D mock-ups so we can get a true eye on what the product will look like. There are several different material choices the machine offers from a rigid plastic to an elastomeric "rubber". The options can be comingled to yield multiple durometer parts. We also use these prototypes for initial assembly and functional review. Trek has been looking at equipment that can make true structural parts that would be ride-able. Currently the process is relatively slow and expensive to make parts out of aluminum or titanium. We will continue to monitor developments in this area for future applications on bikes and components.

What industries (eg auto / yachting / textiles) influence your engineers and designers, where do they get the next ideas such as the damping characteristics of the Domane or the layup pattern in the Madone, or does it come down to running it by the numbers in terms of FEA, testing and rider feedback?

Trek keeps its eye on all major industries to see trends and leverage opportunities. Our ID team loves the automotive and motorcycle industries. Most of the technology for Domane, ABP, carbon armor, etc. are all from in-house thinking, brainstorms, and our search for solutions to bicycle specific issues. Trek uses all currently available analytical tools like FEA, CFD, and laminate optimization to converge on the best solutions. We do analysis in the virtual world, manufacture the options that show the most promise and then correlate lab bench testing and ride testing feedback provided by our professional athletes and test riders to improve our products as well as refine how we use the analytical tools for development. This multi-functional approach gives us a broad view and guarantees the greatest possible results. We also use windtunnels,

Figure 4: The Trek Madone 7.9, featuring a hi-modulous carbon fibre frame complemented by Bontrager carbon fibre handlebars, stem, seatpost, saddles and wheels.

motion capture software, high speed cameras, pressure mapping, strain gages, and accelerometers with high speed data acquisition systems to more fully understand what bike and rider experience in the multitude of environments (Downhill MTB to aerodynamic time trials) we create product for.

In terms of testing what processes/ tests/standards do you do to ensure frame warranties and long term rider characteristics of the bike?

Trek tests all it products to various industry standards like ASTM, CEN, CPSC, JIS, DIN, ISO, basically all major country and global standards for compliance. We also have a group of "Trek" test standards that are unique to our company. These apply loads to frame, fork, or other component to higher loads, or slightly different application of loading. These have been developed by Trek over the years and show us modes of failure that in our opinion more closely replicate real world riding and the resulting failures we see from the field.

How much influence do the pro-level cyclists have in your design process?

Trek works very closely with our pro riders. They are key to continuous improvement and are the best feedback for us. They push the product to the highest points and put maximum miles on in the shortest periods of time. The use and abuse the pro's put our products thru is invaluable information for us in developing the next generation of bikes. They help us, drive us, in many cases force us to take it to the next level.

What are the thoughts of a ti/carbon or steel/carbon mix like independent fabrications or an exogrid that some companies are working on

Trek had several "multi-material bikes in the past. The blended properties worked very well and the unique look was a great selling point. However in many cases the cost to produce along with the performance and ride feel differences that were at best subtle lead us to abandon these types of products. Trek has always worked diligently to use the appropriate material in the appropriate locations to handle the job at hand. We co-mold and/or secondarily bond parts to make the best all-around parts. We use carbon to carbon, carbon to aluminum in the majority of applications.

Figure 5: Trek Madone 7.9 frame, featuring a host of Trek exclusive technologies.

Figure 6: A carbon fibre frame component is removed from it's mould.

Figure 7: Trek was one of the pioneers of the use of carbon fibre in the manufacturer of bicycles, as well as the computer software to design and test them.

What in your opinion is the next big thing in materials and design for the cycling industry?

I believe that Nano Carbon fiber and tubes holds tremendous promise. Unfortunately we have not seen the fantastic properties translate in to the macro world we live in. The possibilities are out there and the performance enhancements and weight reductions so compelling that it will only be a matter of time before bikes will realize the almost unbelievable properties of these materials. I am hopeful that other materials like unobtainium and youcantdoium[;o)] will make their way on to bikes of the future.

Carbon composites used in bicycles

By Raoul Luescher

Carbon fibre is being used extensively in cycling these days, not just for the elite racers but also for everyday recreational riders.

What is carbon composite and why is it good for bicycles?

Carbon composite is a blend of carbon fibres with a polymer matrix. The fibre gives very high tensile strength and most importantly stiffness, the polymer matrix bonds the fibres to each other so each fibre can transfer load to the next fibre.

With composite materials an engineer can design specific mechanical properties to handle a particular load scenario. Want a bike that is torsionally stiff for good power transfer but vertically compliant for comfort? Carbon composite can do it, and do it for less weight.

As shown in table 1 the specific properties are very impressive, combine this with the ability to tune the ride characteristics and to readily create different shapes and the advantages are clear to see.

Its all about the fibre

There are many different types of carbon fibre as well as other fibres such as aramid, ceramics and of course glass fibres.

The most commonly used grades of carbon used in cycling are known as standard modulus or high strength, a typical example is Toray T700, Hexcel AS4 or Mitsubishi TR50S. Other fibres grades are also sometimes used in specific applications, these are referred to as intermediate modulus and high modulus. Examples of intermediate modulus is Toray T800, Hexcel IM7 or Mitsubishi MR40. Examples of high modulus fibres are Toray M60, or Mitsubishi HS40.

Material	Tensile Strength (MPa)	Young's Modulus (GPa)	Mass density (g/cm^3)	Specific Tensile Strength ($Gpa/g/cm^3$)
High Tensile Steel	1300	210	7.87	0.17
7005 Aluminium Alloy	390	70	2.7	0.15
T700 Carbon Fibre / Epoxy	3400	160	1.4	2.4

Table 1 – Properties comparison with metals commonly used in bicycle frame manufacture.

Designation	Tensile Strength (MPa)	Tensile Modulus (Gpa)	Elongation (%)	Density (g/cm^3)
T300	3530	230	1.5	1.76
T400HB	4410	250	1.8	1.8
T700SC	4900	230	2.1	1.8
T800HB	5490	294	1.9	1.81
T1000GB	6370	294	2.2	1.8
M35JB	4510	343	1.3	1.75
M40JB	4400	377	1.2	1.75
M46JB	4200	436	1	1.84
M50JB	4120	475	0.9	1.88
M55J	4020	540	0.8	1.91
M60JB	3820	588	0.7	1.93

Table 2 – Carbon fibre properties. (Courtesy of Toray)

Why is "modulus" important?

Modulus refers to the stiffness value of a material, it is not the strength. Stiffness is the rate of deflection, strength is the load that can be resisted. The higher modulus fibres have greater stiffness than standard modulus fibre, they can be more than twice as stiff as shown in Table 2.

Bike frames generally are limited by stiffness, so by using higher modulus fibre less is needed to meet the design requirements, thus a lighter bike is the

Figure 1: Typical woven prepreg fabric.

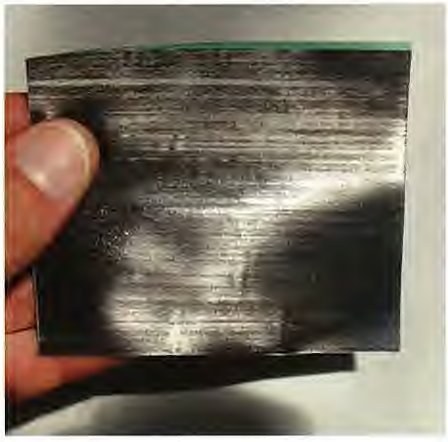

Figure 2: Typical Unidirectional prepreg.

result. However high modulus fibre has less elongation and may have lower strength so using less of it makes a less damage tolerant part than standard modulus. High modulus fibre is also very expensive, these factors can limit its use in bicycles. Sometimes blends of different fibres are used at various locations on a frame. This starts to get complex so the designer really has to design each layer and how it interacts with other plies within the frame for this to be successful.

Fabric Types

There are two basic forms used, multidirectional or woven fabric, (Figure 1) and unidirectional sheet, (Figure 2). Wherever you see the carbon "weave" you are looking at a multidirectional fabric. This is made by weaving bundles of carbon filaments called tows. These tows are commonly made up of 3000, 6000 or 12000 individual carbon filaments, this is referred to as 3k, 6k 12k etc. There are also many different styles of weave to give different properties and looks. Unidirectional has the fibres running in one direction only and doesn't have the typical woven look.

Some advantages of woven fabrics are drapability which makes it easier to place in complex shapes, it is more damage resistant and it looks good. Disadvantages include slightly lower mechanical properties, it is more expensive and it is slightly heavier.

Often an outer layer of woven is used with unidirectional material under this layer. This blends the better protection and look of a woven fabric with the better weight, strength and price of unidirectional.

Fibre Direction

Individual filaments are only strong along their length. This means a unidirectional material is only strong in one direction, woven bi-directional material is strong in two directions.

This is where the design engineering comes in, by placing layers at different angles, the designer can select the properties required. This is the reason carbon frames can be stiff in torsion for good power transmission and yet also have some vertical compliance to make them comfortable. This is a major difference between composites and metals. A metal tube will have the same strength and stiffness in all directions, a tube maker can change the wall thickness and diameter of the tube but not the material properties in different planes.

Hence the direction that the fibre is placed in a structure is very important to the final outcome and must be controlled during manufacture. Unidirectional material gives the designer good control of what each layer of fibre is doing to optimise the part,.

The Matrix

The matrix resin is used to encapsulate the fibres and bond each fibre to the fibres around it. This allows each fibre to transfer load to the next fibre and thus create a rigid product. It is the fibre that has the high tensile strength and stiffness, the resin properties are very low compared to the fibre.

In most cases various types of epoxy resins are used for bicycle parts. There is a wide variety of epoxy resins available with different properties and cure cycles. Some resins are "toughened", with additives to limit crack growth. Resin selection is dependant on the environment that you want it to perform in, compared with a composite aircraft, bicycles have got it pretty easy with much less variation in temperature and other environmental factors. Other considerations include the cure cycle time to reduce production costs.

'There are many different ways to manufacture a bike frame. It can be made in one piece, often termed monocoque, or it can be made in pieces and the individual pieces assembled.'

The carbon fibre fabric will often come supplied with a premixed resin impregnated in to it at a consistent ratio. This fabric, commonly called :Pre-Preg" needs to be stored in a freezer until ready to use as the resin will slowly cure at room temperature. It is then fully cured under pressure at an elevated temperature usually above 80 C up to about 180 C. The advantages are many, especially with handling and quality.

Processing fibres into bicycles

To create a bicycle frame or part from raw fibres and resin requires specific tooling and processes. The fibres need to be positioned in a mould or around a form that will give it the shape required. Once the fibres are in the mould pressure is required to compact the fibres to be as close as possible to each other so they can transfer load through the part. The pressure also reduces any trapped air pockets and excess resin matrix from the composite. The resin matrix is then cured and the part is created.

Bladder moulding is the most common manufacturing process for hollow tubular bicycle products. This process uses a plastic or rubber bag inflated to high pressure inside the hollow carbon section pressing the fibre against a mould. This forces the carbon into the shape of the mould and provides a finished exterior surface. It is possible to manufacture all kinds of different shapes with this method, including closed shapes such as rims and crank arms (Figure 3) where often the thin plastic membrane is left inside the final.

Figure 3: Bladder molded carbon crank arm cross section, note the thin plastic bladder remains in the part.

History has shown that although one piece frames can have a performance advantage if made well, there are manufacturing problems in volume production, also the limitation in sizes available due to many different moulds being required is a major drawback.

Repair of damage to these bicycles is becoming common, methods developed from the aerospace industry also allow bicycle frames to be repaired safely without any heat treatment issues associated with the welding of metal frames.

Today most of the carbon bike frames are assembled from smaller sub assemblies (Figure 4). Parts are made and cured separately and then the individual parts are assembled with adhesive or wrapped with more composite layers to create the full frame. This has many advantages in terms of production. It is much easier to control the manufacturing process of a single tube or component than a complete bike. This provides a higher level of quality control when compared with one piece frames. If a problem is found in one section, it can be discarded and a new one made. So the production and quality advantages with this method have made it popular with bicycle builders.

Each frame needs to meet quality standards to ensure safety and a consistent standard of performance for the rider. To do this each step of the manufacturing process needs to be controlled to achieve consistent results, this can be difficult and expensive.

Figure 4: Typical sub assembly part and mould.

A range of non destructive inspection methods such as ultrasound and radiography may also be used to assist with quality assurance, these methods are common in aerospace production however are often considered too costly for higher volume production.

What is the future for composite bicycles?

The materials, processes and the engineering of bicycles will continue to evolve. A production carbon road racing frame has gone from a weight of 1200g a few years ago to around 800g for the latest models. The ride quality and handling also continue to improve.

Repair of damage to these bicycles is becoming common, methods developed from the aerospace industry also allow bicycle frames to be repaired safely without any heat treatment issues associated with the welding of metal frames. This makes composite frames readily repairable as long as the full extent of the damage is known. Specialist equipment such as portable ultrasound scans can be used to determine the damage.

Recycling of carbon composite however remains a challenge for the future.

Raoul Luescher

Raoul has worked with composite materials for over 20 years. He has been employed by Boeing Aerospace, contracted to Defence and the Australian Institute of Sport. As the director of Luescher Teknik, Raoul consults on the design, manufacture and quality on a range of composite material applications primarily in the sporting field but also to the defence, mining and automotive industries.

He was the lead designer for the iconic Australian Malvern Star range of carbon bicycles, and has consulted to other manufacturers of cycling products. He is passionate about advanced materials and sports performance.

The birth, development and success of Lightweight Wheels

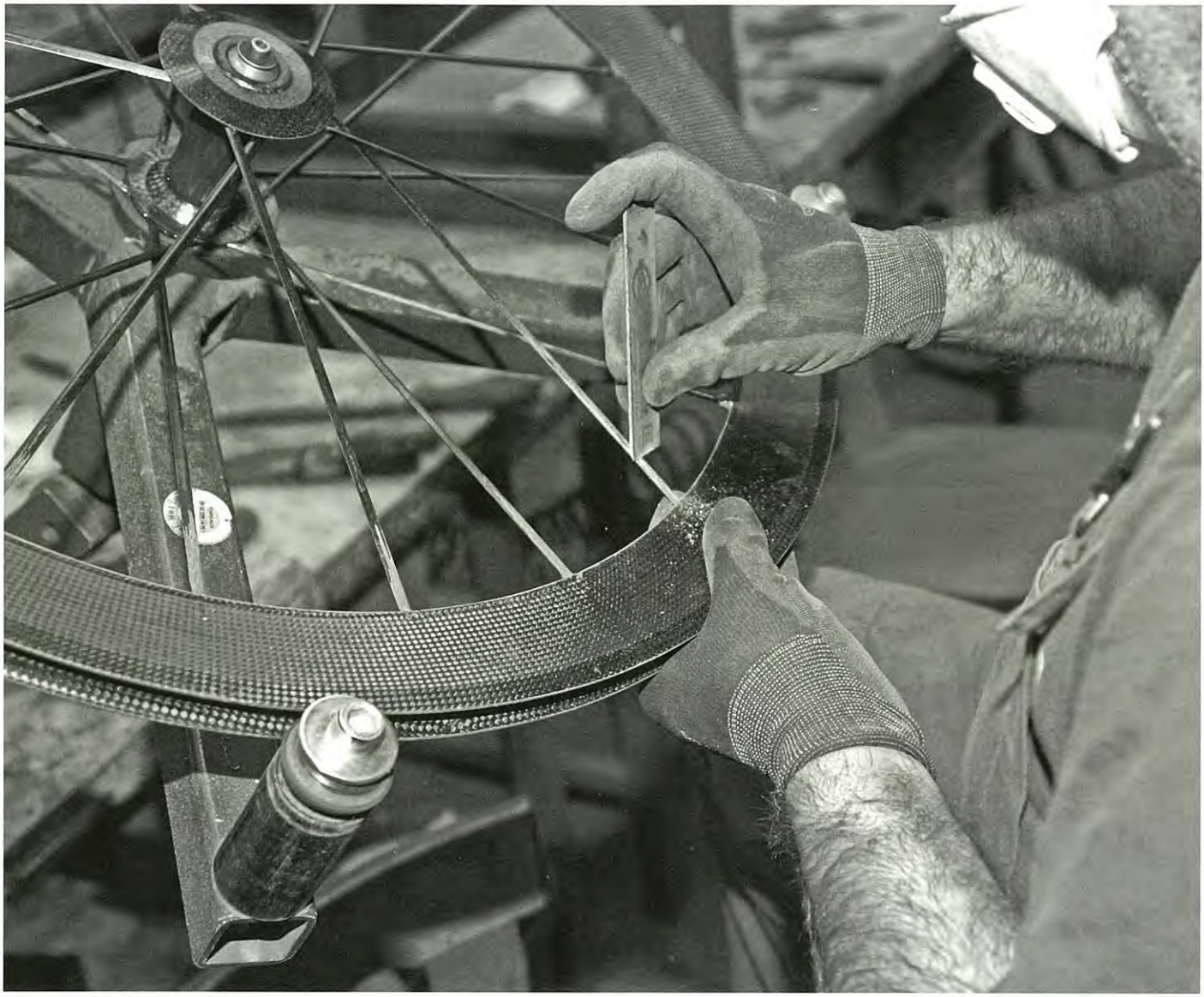

Figure 1: Finishing process of a 80% ready Lightweight MEILENSTEIN

"We can do it". This was the answer Heinz Obermayer gave one night in a bar to somebody that tried to annoy him, answering that Heinz and his partner could maybe do some wheel covers for sulky trailers used in horse races, but won´t be able to create something suitable for road bikes. In fact this answer, given in the late 80's can be taken as the moment of birth for Lightweight wheels.

And this answer is also something that stands exemplary for all the projects and ethos the whole company group the Lightweight brand belongs to and is involved with today.

Back in the day, Heinz Obermayer and his partner Rudolf Dierl went back to their private work shop - an old garage - considering what could be needed in a road bike wheel. Both were working engineers in the R&D department of a well know German car manufacturing company. In their free time they worked with fiber technology offering body kits for cars, sulky wheels and other items. Having no clue what makes a road bike wheel so special to other wheels, they started researching, spoke with riders, shop owners and learned about weight, stiffness, measurements and the fact that a rear wheel has to be asymmetric.

Starting with a disk wheel for track racers, both understood immediately that this

Figure 2: Lightweight and CarboFiberTec headquarter in Friedrichshafen, Germany.

wouldn't be the end of the story. Driven by the idea of the best wheel in the market they had to start from scratch, inventing not only the full carbon wheel itself but also, all the tools to make it. As a result of all this work and sleepless nights in an old tractor garage, using a lorry heater and an old oven for the heating processes, the first Lightweight wheels were born. In a time when a road bike frame itself was mostly made of alloy with a weight of nearly 2kg, these wheels had a set weight of a little bit more than 1.000g, offering a stiffness that hadn't been realised with any other previous materials. These wheels were simply unreal, not to speak that the pro riders couldn't wait to get their hands on them. As history has it, Johan Museeuw rode Lightweights to victory at the World Championships in 1996, Jan Ullrich took the yellow jersey of Tour de France in 1997 on Lightweight wheels and many other great victories in pro cycling have occurred on these full carbon fiber wheels to present date.

Also in the 80's Erhard Wissler made his way in the business world. Like Heinz Obermayer, he also hadn't been on a bike since his childhood, knowing nothing about the business. Erhard Wissler became the owner of a company producing products for precision farming. His interest was always to find materials and methods to improve his production processes and products.

'Driven by the idea of the best wheel in the market they had to start from scratch, inventing not only the full carbon wheel itself but also, all the tools to make it. As a result of all this work and sleepless nights in an old tractor garage, using a lorry heater and an old oven for the heating processes, the first Lightweight wheels were born.'

He came into the world of carbon fiber through a business opportunity in the late 80's. One of the new owners of Dornier aircraft company, the very first company that ever used carbon fiber technology in planes worldwide, decided surprisingly enough that carbon fiber technology was a dead end, closing that department of Donier and making a whole group of the most experienced carbon fiber engineers redundant. Erhard Wissler couldn't believe his luck! For him carbon fiber technology was clearly the future, so he went down to Friedrichshafen and collected all these guys. A new company started with eight engineers developing products for the precision farming and aircraft business.

Some years later, Erhard Wissler got an offer from a group of solicitors who were liquidating the assets of another carbon technology company. Within this, there were some left over items Erhard assumed to be worthless ; a number of bicycle frame moulds. Nevertheless he took the all the items and left those moulds sitting in storage. "I had no experience in that business. The only thing I knew about bicycles at the time was that you could buy a bike for 200 Deutschmarks in the supermarket," he explains. So he continued working in the aerospace business. Then the events of September 11, 2001 shook the world and with the all the other factors, the aircraft industry faced a dramatic decrease.

This prompted Erhard Wissler to have a second look at those leftover molds. His initial aim was to simply give his employees something to keep them busy. Knowing nothing about bikes, Erhard went to Eurobike bicycle show for research and saw the potential in the bike market. He decided to return the very next year as an exhibitor showing the world what his

Figure 3: Lightweight wheels are made by hand!

experienced carbon fiber engineers could do in this field with that frame he already owned the moulds of. He did return, displaying the frame, but didn't get the response he expected. No one cared about the frame, but everybody went crazy for the wheels. "Just by chance we put some Lightweights on the display model, just for the show. We had borrowed them from a German bicycling editor because we couldn't buy a set. At this time the wait list for these wheels was nearly one year. But all the visitors entering our booth only looked at the wheels - no one even took notice of our frame. I really thought that these guys where somehow crazy," he explains his first experience in the cycling industry.

Erhard Wissler kept this in mind and again sometime later he heard a story about these two old guys near Munich still producing the carbon fiber wheels and that they made everybody pay for them! Even a guy named Lance Armstrong was sent home without wheels when he was not willing to spend his money. In the end the US boy got his wheels, after handing out some cash, and rode them to multiple Tour de France victories. Erhard Wissler thought about a kind of joint venture, picked up the phone and called Heinz Obermayer. "You can either buy the company or go away", was the answer. An appointment was set. Because Heinz and his partners recognised the business Erhard Wissler was in they didn't want to meet in their "factory", so a neutral meeting point in a dark Italian restaurant was the first time the both parties met. The business discussion was started by a rather rough announcement Rudolf Dierl made: "Remember, we can negotiate everything - but not the price!"

"To begin with they had a resin that was past the usable date by far," Erhard Wissler explains. "Normally resin is liquid but this one had gone completely solid. So they had to warm it up to make it liquid again. It was used because they got it for free. After we set up the production here we ran out of that old stuff one day and replaced it by new high performance resin with less viscosity..."

After everything was settled, contract signed and money transferred Erhard Wissler and his engineers got the first chance to step into the old Lightweight head quarters - still a small garage with the lorry heater and all the handmade tools and wheels. As every carbon fiber structure has its specific heating circle with exact heating up and cooling down timeline the engineers where more than shocked when they saw how the hub shells were "cooked" in an oven and the rims were

Figure 4: Finishing process - Lightweight MEILENSTEIN nearly ready to get the artwork done.

hardened out under some UV-light. So they asked Heinz about the specific heating circle. "Oh, just turn the lorry heater to 2.5 and leave it for about two hours". The same kind of vague answers came when they asked about the tolerances: "Well, you have to do it by feeling".

So over a period of almost one and a half years, they started to figure out that "feeling" and transfer this into the German engineers world of exact measurements, figures, graphs, temperatures and time circles. In the end they thought that once they had all the technical details for the production of the wheels the hard part was over. Not quite. "To begin with they had a resin that was past the usable date by far," Erhard Wissler explains. "Normally resin is liquid but this one had gone completely solid. So they had to warm it up to make it liquid again. It was used because they got it for free. After we set up the production here we ran out of that old stuff one day and replaced it by new high performance resin with less viscosity. And the problem started. The new wheels gained over 50g extra weight. We didn't know what happened until we recognized that this new resin went way deeper into the carbon fiber structure. More resin means more weight."

Since then there were multiple issues to be fixed. The engineers got used to all of this and they are still learning. Even today everything is handmade and it takes a long process of hand craft to build one of these wheels. Depending on the model it needs 16 to 20 hours to produce a Lightweight wheel. However today with more employees working the output numbers have been raised.

'Erhard Wissler believes that innovation comes from people making specific demands for a product that often can't be reached. Most of the time, pro riders are perfect for this job in the cycling industry.'

Out of the old garage factory and the farming world the Wissler Group today contains a number of different companies, all are specialists and market leaders in their field of fiber technology. For the cycling world CarbonSports, owner of Lightweight brand, cooperates deeply with CarboFiberTec, the think tank regarding carbon technology for the whole group. Besides building probably the best wheels on the planet, the Wissler Group has a very strong leg in aeronautics industry and other businesses. They are also building the satellite body of Galileo-3 project for ESA. A body nearly completely made of carbon fiber with a precision of 5 micron (or 0,005mm) that has to withstand forces up to 20G, being able to measure the surface temperature of our planet from more than 400km above within 0.2 Kelvin tolerance. As well as this, still today parts for planes are on the list, for example the structure of the Guggenheim-Lab, a special super precise carbon fiber pencils, robot-arms and many other items.

"Satellite construction might be the highest discipline in carbon fiber technology but the most difficult part we have ever developed is our Lightweight MEILENSTEIN Clincher wheel," Erhard Wissler says. "It's the single thing we have ever created

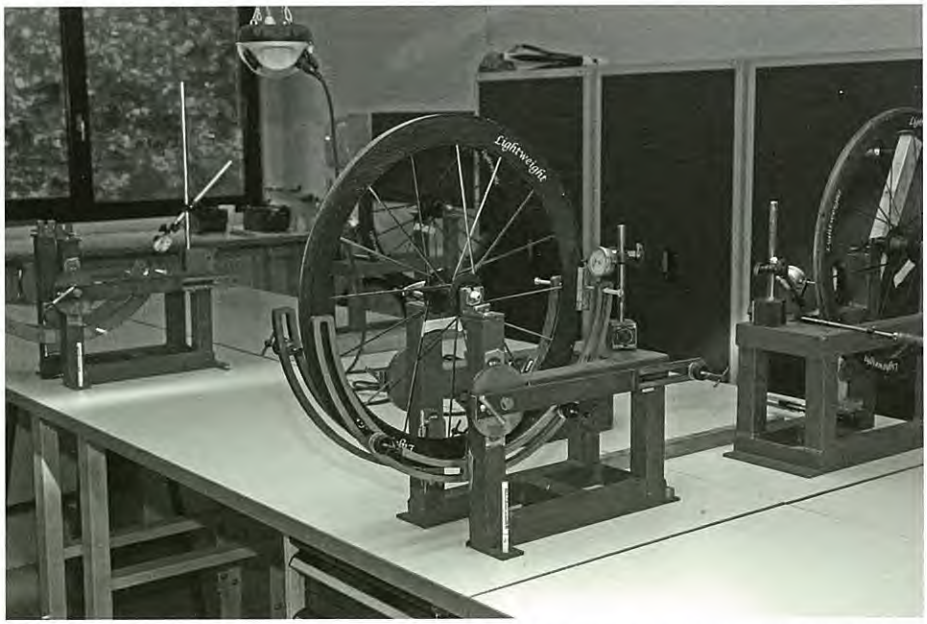

Figure 5: Lightweight MEILENSTEIN in the workstand - a short look into the service department - even here all tools built specially for Lightweight wheels.

Figure 6: The award winning Speedwheel - Lightweight FERNWEG

Figure 7: Layup-work

which needed the most attention. We got a new layup with real high end fiber and resin combination and a unique production process specially developed for the Clincher only. Some days the engineers come to my office telling me that they would need a new compressor. They jacked the wheels up to a tire pressure of 290psi and it still didn't blow up. So they didn't know what to do."

Erhard Wissler believes that innovation comes from people making specific demands for a product that often can't be reached. Most of the time, pro riders are perfect for this job in the cycling industry. Erhard will remember for the rest of his life when Jan Ullrich came to him asking for a super light uphill only wheel to be used in some uphill time trial races. Heinz Obermayer, who is still with the company today and something like a task force for some special items, built this special uphill only set of wheels without a real braking surface to make it super light. When handing them out to Jan Ullrich, both Heinz and Erhard clearly pointed out to be super careful and never use it going downhill. Some weeks later Erhard Wissler nearly faced a heart attack when he watched a race on TV and saw Jan Ullrich down hilling that wheels with a crazy speed. Ullrich gave them back, totally damaged, delaminated nearly to complete failure. That was the last time they ever handed out prototypes to pros!

"Satellite construction might be the highest discipline in carbon fiber technology but the most difficult part we have ever developed is our Lightweight MEILENSTEIN Clincher wheel."

With the latest generation of the MEILENSTEIN, a wheel that hasn't changed it's look over all the years and can be taken as THE Lightweight wheel, now this little German based company reached again a new level. Using all the knowledge

Figure 8: Tools - just a few needed to work on the hub internals and other items

about carbon fiber technology and having access to some kinds of carbon fiber and resins that are normally strictly reserved for special needs in the aeronautic industry this wheel shows an incredible combination of light weight and stiffness. Combining this with the best braking performance of a full carbon fiber wheel under every condition by far. The MEILENSTEIN tubular and MEILENSTEIN C (clincher version) today faces some good company with other wheels in the Lightweight product line. So the FERNWEG (tubular and clincher) as well as the AUTOBAHN and AUTOBAHN disk wheel cover the needs of speed maniacs like time trial racers and triathlon athletes. Both speed combinations proved their performance not only in endless wind tunnel and test ride sessions and races, but also by winning the latest aero wheel comparison test of German Tour-Magazin, the hardest testing magazine in the world. The GIPFELSTURM is the answer for all riders demanding a full carbon fiber wheel with lower rim profile, adding some comfort aspects to their Lightweight ride with no crosswind effects. The MEILENSTEIN OBERMAYER is a special dedication to all the people out there looking for a super performance and extra light wheel.

"My target is to be unique and more competent than our competitors and to do things with which they are struggling. I do not like to discuss about 5p per piece by squeezing prices and all that sort of thing. Maybe could do it if we would move some parts of our production to the far east, but this is not our way. We are proud to live and work here in Germany. These people make me proud, this job makes me proud. Lightweight is special to us - to me!" Erhard Wissler summarizes - and he still loves to answer to all the demands and requests of customers asking for some solutions in carbon fiber technology that seem to be impossible: "We can do it".

'After all these developments in the company and all the improvements of Lightweight wheels over the years, one thing still remains the same and will forever. The fact that these wheels are 100% built by hand in Germany, giving work and income to more than 50 families today.'