Investigating the Modern Use and Fabrication of Metal Matrix Composites and Bonding Adhesives for Bicycles in Mass Transit

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Abstract

This report describes the importance of the bicycle. The properties of metal matrix composites (MMCs) and adhesives used to create new light-weight alternatives to the heavier steel bicycles are discussed. Constituent material and bicycle production processes for MMC and adhesive assembled bicycles are presented. The aluminum (Al) matrix metal A356 with silicon carbide (SiC) reinforcement is chosen to constitute the MMC. These processes are contrasted for mass transit effectiveness. An optimized bicycle design with consideration of physical properties and cost is presented. Current available bicycle products are described, and respective prices for the present and forecast prices for the future are detailed. Analysis of attitudes about bicycles as expressed through federal (United States), state (Texas and Nebraska), and municipal (Austin, Omaha) law are presented and the compatibility of a bicycle mass transit system under these current laws discussed. Bicycles are determined to be full fledged vehicles with all of the rights and responsibilities inherent under the law in that designation. An analysis of the above topics and the feasibility of bicycle mass transit are touched upon with heavy emphasis on the relevance of metal matrix composites and similar emerging materials. MMC bicycles are found to be incompatible with a mass transit system, but low priced steel bicycles are mentioned favorably.

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Introduction

Bicycles Impact Society

The Bicycle is an invention for human scale transportation. Human bicyclists commute short distances faster than human pedestrians. Bicycles do not consume fossil fuels and do not produce pollution. Bicycles are agile and can be adapted to wilderness and urban environments. Bicycles are relatively easy to store and park in homes or at places of business. Bicycling is an excellent form of exercise and promotes environmental awareness and increased contact with people. Bicycles are relatively inexpensive as compared to normal mass transit automobile or train systems, and continue to have a strong popular culture presence, as witnessed by the increase in sales and growth of bicycle companies. Bicycles have impacted society, and will further do so when they are accepted by the mainstream commuting public for all of the above reasons as being a natural and efficient way to get around.

Purpose of Report

This report will describe the importance of the bicycle. The properties of metal matrix composites (MMCs) and adhesives used to create new light-weight alternatives to the heavier steel bicycles will be discussed. Constituent material and bicycle production processes for MMC and adhesive assembled bicycles will be presented. These processes will be contrasted for mass transit effectiveness. An optimized bicycle design with consideration of physical properties and cost will be presented. Current available bicycle products will be described, and respective prices for the present and forecast prices for the future will be detailed. Analysis of attitudes about bicycles as expressed through federal (United States), state (Texas and Nebraska), and municipal (Austin, Omaha) law will be presented and the compatibility of a bicycle mass transit system under these current laws discussed. An analysis of the above topics and the feasibility of bicycle mass transit will be touched upon with heavy emphasis on the relevance of metal matrix composites and similar emerging materials.

The only requirement for understanding the material presented in this report is a willingness to reference the included glossary and illustrations that are included. Engineers and material scientists will be very familiar with the technical terminology relating to material properties and mechanics presented in this report, and the included glossary goes a long way toward explaining the qualitative significance of terms. Some of the included illustrations are rather technical, but a thorough understanding of design technique is not needed because conclusions are thoroughly discussed.

Bicycle Materials

Properties

Designers of metal tubing for bicycle frames rely upon the careful selection of key physical properties of the metals they use. *Metal Matrix Composites* are especially complex and flexible in this regard. MMCs are essentially base metals that have been combined with an alloying metal *fiber*, *whisker*, or *particulate*. A *fiber* is relatively long and has a diameter of about 0.1 mm, which is about the thickness of a human hair. *Fibers* are stronger along their length, and contribute most of their strength to a *composite* in the length direction. A *whisker* is a short, thin version of the *fiber* with a diameter of about 0.01 mm, or a tenth of the thickness of a human hair [Fibre Reinforcement]. *Whiskers* have the directionally dependent strength of *fibers*, but contribute more strength in other directions because they are more dispersed throughout a *matrix*. *Particulate* are tiny particles of metal of no specific shape, and thus no specific shape dependent properties, usually with a diameter of no less than 0.001 mm (1µm – one micrometer). *Particulate* thus makes a composite highly *anisotropic*, or having uniform properties without regard to the direction that *composite* metal is loaded. These complexities allow designers to flexibly determine the composite's properties by choosing the appropriate reinforcement.

Liquids fill their containers, but when they are spilled out over a flat surface liquids spread until *surface energies* between the liquid and the flat surface come to an *equilibrium*. *Wettability* is the ability of a liquid to cover or encapsulate a solid and overcome the *surface energies* associated with equilibrium. One model quantifies wettability with three *vector* energies, where the metal-on-liquid energy works to keep the liquid from spreading. The spherical shape of a drop of liquid creates an angle at the surface, typically named θ (theta). The smaller that θ is, the more that the liquid is spread out over a solid surface. Designers try to get θ to be as small as possible, combining metals in a non – oxygen atmosphere so that oxides which impede bonding do not form [SAE, "The Wettability of …"], so that matrix metal will fully bond to the *reinforcement*. Designers optimize reinforcement and matrix metal combinations using the Sessile Drop method – measuring the *wettability* angle using specially designed cameras [SAE, "The Wettability of SiCp…"].

Interface bond strength is closely dependent upon the *wettability* of *reinforcement*. *Interface bond strength* is the strength of the interatomic bond between the *reinforcement* and the *matrix* metal. *Interface bond strength* is not directly measurable, but it can be qualitatively determined by varying the *wettability* of a composite and testing the composite strength (*UTS* – see below).

Weight percent (wt.%) is the ratio of constituent material weight to total composite material weight. This ratio is simply the fraction of one constituent of a composite. Weight percent is used to prescribe the exact mixture of alloying components in an alloyed metal.

A *volume fraction* is the mathematical fraction of volume of a constituent material of the composite. For instance, for $V_p = 0.20$, 20% of a composite by volume is reinforcement metal. The remaining 80% of the composite is matrix metal. Volume fraction can be used directly to calculate *modulus* and *ultimate tensile strength* (see below). The volume fraction is also an important measurement because the higher the *volume fraction*, the more reinforcement present in a composite metal, and the tendency for clustering of reinforcement increases [SAE, “Thixoforming of Al- based MMC…”]. Clustering increases the possibility for crack formation and fracture of the composite. The larger the volume fraction, the higher its *UTS*, and the higher its *stiffness* [SAE,”The Effect of Thermal Cooling…”]. *UTS* and *stiffness* both increase with increasing reinforcement weight percent (see above for description of weight percent [wt.%]). Beyond 40 wt.% reinforcement, both *UTS* and *stiffness* decrease [SAE, “Thixoforming of Al –based MMC Systems”]. *UTS* and *stiffness* are both quantities that should be maximized when possible, however, so a proper balance between clustering and property maximization is usually made. *Porosity*, measured as a percentage of *porosity* of composite, also increases with a larger *volume fraction*, up to a maximum 50% *volume fraction*. For *volume fractions* greater than 50%, the *porosity* decreases again as the *porosity* due to reinforcement stabilizes and less of the composite is made up of matrix metal. For these reasons I have specifically chosen my composite to have a volume fraction of 30% [SAE, “Fabrication and Properties..”]. This value is widely used in the experiments I have researched, and is closely interrelated to other physical values I have identified and chosen.

The temperatures needed for processing MMCs are an important factor. As described in the section on welding, applying heat to a metal increases the size of microstructural grains (see Bicycle Production – welds and adhesives). The metal weakens as its grains grow. However, grains do not form until the composite has solidified, and for the composite formation stage of production only the melting temperature of the metals is important. The melting temperature of the aluminum is 660.37 ^{o}C [Fibre Reinforcement]. The melting temperature of the silicon reinforcement is 3273.15^{o}C [Fibre Reinforcement]. The combined melting temperature, useful to know when forging or extruding the composite, is about 580 ^{o} F. In order to avoid markedly affecting the microstructure, handling the composite during processing should never exceed 460 ^{o}F [SAE,”Performance of MMC…”]. This temperature was calculated with the following guideline, and agrees reasonably well with the literature. Composite metal temperatures above 0.8 T_m (melting temperature) cause grain growth in the *microstructure*, temperatures from 0.6 T_m to 0.8 T_m cause the grains to *recrystalize,* and temperatures from 0.4 T_m to 0.6 T_m cause the grains to recover some of their preprocessed shape. Grain growth always occurs in metals at the prescribed temperature ranges above, but *recrystallization* and *recovery* only occur in *strained* metals. The metal composite I am discussing here can be affected at each of these ranges and exhibits each of these phenomena, just like any other metal.

The gaseous pressures involved in processing the composite control the rate of diffusion of the matrix metal into the *reinforcement preform* in the *infiltration* process. Pressure also controls the rate of injection in both pressurized castings and in the *infiltration* process. A pressurized casting (die casting) slows the solidification of the composite, but this is a miniscule effect because the molten metals are practically incompressible and therefore unaffected by increased pressure. For comparison, the infiltration process pressurizes the composite to about 25 megapascals, or over 25 times the pressure of the earth's atmosphere at sea level, to insure proper diffusion. Die castings can require up to 70 megapascals of pressure to insure a proper cast shape. There are substantial monetary savings with a low pressure process.

Four important physical quantities that are used heavily for science and engineering in general and for composites in particular are *ultimate tensile strength*(UTS,σ_u), *modulus of elasticity* (modulus,E), *strain* (ε), and *coefficient of thermal expansion* (CTE,α).

UTS is the measure of the highest stress that a material can withstand before appreciably stretching and deforming, or fracturing. It is a good indicator of a composite metal's overall strength for comparison with other metals. The super high strength of silicon carbide bolsters the aluminum to produce a fairly strong MMC. However, the MMC is still shy of the very high strength of stainless steel (this is of course made up for by the MMC in weight reduction).

Table 1.1:

UTS Values

Component	UTS	Units
MMC	350*	megapascals (meganewtons per meters squared)
adhesive EA9430	15 – 21****	megapascals
typical weld	350	megapascals
aluminum	150**	megapascals
silicon carbide	7700***	megapascals
stainless steel	3000**	megapascals

Values were determined from typical handbook values and typical values in the literature.
* : SAE, “Fabrication…”
** : Fibre Reinforcement pp. 8
*** : Fibre Reinforcement pp. 42
****: Adhesives, Sealants, and Primers pp.404

E is the ratio of material stress to material strain (σ/ε). Modulus is one measure of stiffness of a composite. The combination of the very stiff silicon carbide with the very ductile aluminum produces an MMC slightly less stiff than stainless steel, as seen in the table below.

<u>Table 1.2</u>:

E Values

Component	E (modulus)	Units
MMC	170*	gigapascals (giganewtons per meters squared)
adhesive EA9430	10	gigapascals
typical weld	same as metal	gigapascals
aluminum	71**	gigapascals
silicon carbide	480***	gigapascals
stainless steel	210**	gigapascals

Values were determined from typical handbook values and typical values in the literature.
*   : SAE, "Fabrication…"
** : Fibre Reinforcement pp. 8
***: Fibre Reinforcement pp. 42

Strain is the measure of ductility of a metal. In general, the more that a material is *stressed*, the more that it can be simultaneously deformed. The exact nature of this deformation is different for every material, so that every material has a different *UTS*, modulus, and corresponding allowable strain at its *UTS*.

CTE is the indicator of expansion and contraction of a material due to temperature change. I have taken care to select materials that do not have *CTE*s that are significantly different from one another. A large temperature change might cause the composite to expand or contract to such a degree that nuts, bolts, screws, and components in the breaking and gearing mechanisms could be warped or fractured. Notice that the adhesive below has a substantially lower *CTE* than any metal it would be bonded to. This might cause a problem for the bicycle when it is exposed to extreme thermal and bending stress conditions. However, because the *CTE*s are within a multiple of 10 of each other, this difference is negligible. Also notice how silicon carbide's low *CTE* brings aluminum's high *CTE* down to that of stainless steel as seen below.

Table 1.3:

CTE Values

Component	CTE (Coefficient of Thermal Expansion)	Units
MMC	14*	ppm/^{o}C
adhesive EA9430	1.8****	ppm/^{o}C
typical weld	------------------same as metal------------------	
aluminum	20.9**	ppm/^{o}C
silicon carbide	3.7***	ppm/^{o}C
stainless steel	14.0**	ppm/^{o}C

Values were determined from typical handbook values and typical values in the literature.
*   : SAE, “Fabrication…”
**   : Fibre Reinforcement pp. 8
*** : Fibre Reinforcement pp. 42
****: Adhesives, Sealants, and Primers pp.404

It is also interesting to note the relative specific gravities (weight divided by the “g”, the gravitational constant) of the metals used in the construction of frames. Specific gravity is a measure of a metal’s mass. MMCs are intermediate in SG between aluminum and silicon carbide, and they are much lower than stainless steels, meaning that MMCs are lighter.

Table 1.4:

SG Values

Component	SG (specific gravity)	Units
MMC	2.8*	grams
aluminum	2.7*	grams
silicon carbide	3.2*	grams
stainless steel	7.8*	grams

Values were determined from typical handbook values and typical values in the literature.
* : Fibre Reinforcement, pp. 8

Metals and Composites

I have weighed the properties of the possible combinations for making composite materials and I have chosen the aluminum (Al) matrix metal A356 with silicon carbide (SiC) reinforcement. The aluminum alloy A356 / silicon carbide composite is composed of 0.5 wt.% magnesium and 82.5 wt.% aluminum. The magnesium reduces □, increasing wettability and making the composite stronger [SAE, "Wettability of SiC_p …"]. A356 is ductile, tough, light, and has mid-range values of *UTS* and *E*, as seen in the tables above.

The composite is 17 wt.% silicon carbide. The aluminum is light, nontoxic, easily machined and cast, conducts heat well, stands sixth among metals in ductility {Handbook of Chemistry and Physics, 61st Edition, 1980 –1981, CRC Press, Inc., pp. B-5]. Silicon carbide also conducts heat well, which allows for rapid solidification during composite formation. Silicon carbide is brittle, very hard, has a low density, and has high values of *UTS* and *E*. The composite is light, durable, and able to withstand considerable stresses, making it good for bicycle frame construction.

During the production of composite metals, *intermetallics* can form at the boundary between the matrix and the reinforcement. *Intermetallics* form in metals because the components of a composite or alloy are mixed together in an appropriate proportion for a chemical reaction to occur. A combination of both metals forms into a new molecule, called an *intermetallic*, having new properties different from its constituent molecules. The aluminum and silicon carbide composite that I have chosen forms an *intermetallic*, aluminum carbide (Al_4C_3), at the boundary between SiC and Al as the following chemical equation shows [SAE, "Thixoforming…"]:

$$4Al + 3SiC \Leftrightarrow Al_4C_3 + 3Si$$

The aluminum carbide (Al_4C_3) weakens the *interfacial bond strength*, and therefore weakens the composite metal. *Intermetallic* formation is largely determined by the composite forming process. Both casting and infiltration are susceptible to *intermetallic* formation during solidification because the necessary heat needed for chemical reaction is present. A process called *Thixoforming* forms the composite using solid aluminum and silicon instead of molten composite. Both are heated to about 0.8 T_m and mashed together under low pressure. *Thixoforming* produces less *intermetallic* material at the matrix – reinforcement boundary than casting or infiltration because the composite is not thoroughly melted and therefore is not hot enough for extensive chemical reaction. I have not considered *thixoforming* for bicycle production, however, because *thixoforming* is not widely mentioned in the literature and at present it can only be used to produce simple geometried composites.

Oxide films are thin layers of metal oxides (any metals that have combined chemically with oxygen) that form on the surfaces of susceptible metals. Aluminum exists in nature as a strongly bonded oxide called alumina (Al_2O_3). Alumina formation in an aluminum alloy weakens a composite because the alumina is weakly bonded to the composite in the matrix, and acts as a site for crack formation when the composite is *stressed*. Oxide films develop at the surface and within the matrix of composites. To avoid oxide formation, I have decided to avoid casting the composite. Casting requires stirring equipment to keep the reinforcement uniformly distributed in the molten matrix. Stirring keeps the denser and heavier SiC reinforcement from settling through the less dense Al matrix to the bottom of the cast mold. Settling occurs much more slowly with higher reinforcement *volume fractions* and slower cooling rates [SAE, "Lightweight Magnesium…"].

Settling velocity can be calculated using an equation provided by the literature:

$$V_{settling} = V_o(1 - V_p)^n$$

where

V_o = stoke's velocity = 3.4 millimeters per minute
V_p = volume fraction
n = 4.65

So if $V_p = 0.30$ as in my design, $V_{settling} = 0.647$ millimeters per minute, which is relatively slow compared to a composite of V_p=0.10, which would have a $V_{settling} = 2.08$ millimeters per minute. The lower volume fraction sample would become non – uniform at over twice the rate of my composite design [SAE, "Lightweight Magnesium …"].

In summary, I have chosen a composite having a uniform grain structure, made of A356 matrix and silicon carbide particulate reinforcement with $V_p = 0.30$ and having a relatively high *interface bond strength*. The composite I have chosen has an *UTS* = 350 megapascals, *E* = 170 gigapascals, SG = 2.8 grams and *CTE* = 14.1 ppm/^{o}C, and is bonded together by an adhesive with *UTS* = 20 megapascals, *E* = 10 megapascals, SG =~ 0, and *CTE* = 1.8 ppm/^{o}C. For comparison, a stainless steel bicycle would have an *UTS* = 3000 megapascals, *E* = 210 gigapascals, SG = 7.8, and *CTE* = 14 ppm/^{o}C.

Bicycle Production

Metals such as iron, aluminum, silicon, copper, and magnesium are used in structural applications only after much analysis on constituent *microstructure* and physical property values has been performed. Scientists and engineers can then develop processes for making bicycle frames that optimize these microstructural and physical properties. One of the metallugical processes to have been developed and is now subsequently used in the making of bicycles is *ingot metallurgy* (casting).

Casting

Ingot metallurgy is a metal forming process by which a molten metal is poured into a *cast*. The liquid metal solidifies in the cast and assumes the shape of its container upon hardening. After the hardened metal product has been removed from the cast, metallurgists trim excess material that formed along the mold edges and that filled special tubes entering and exiting the mold, respectively named risers and runners. Risers fill with excess molten metal, and when the molten metal solidifies its volume decreases (this is a physical reality for most liquid to solid transitions). The volume decrease of the excess metal in the riser is called *shrinkage*. The riser absorbs the shrinkage of solidification so that the product of the casting can have a correct total desired shape. Runners fill with excess molten metal and expel trapped gases, typically hydrogen, water vapor or air from the mold. The solid product after risers, runners, and excess mold material have been trimmed is either an *ingot* or a final product.

Solidification of a metal results in two general forms of *microstructure*: *columnar* or *dendritic* grains. Scientists have determined that *dendritic* grains are to be avoided in the making of Metal Matrix Composites because when metals are *stressed*, the *inter-dendritic triple points* (origin points for the three dimensional dendrite arms) are primary locations for the formations of cracks in metals [SAE, “Fatigue Properties of A356…”]. Cracks in the metal *microstructure* cause bicycle frames to eventually fracture, which is never desired. Dendrites are clustered together and concentrate the *stress* imposed upon a metal [SAE, “Fatigue Properties of A356…”]. Locations of concentrated stress are primary locations for crack formations. Scientists prefer the uniform structure and stress bearing capability of columnar grains, which do not concentrate stress and do not in particular act as sites for fracture. Unfortunately, only pure metals, *eutectic* metals, and extrusion processed metals have columnar *microstructures*, so a composite metal must be extruded to create a uniform microstructure.

Two examples of casting used in bicycle frame manufacture are *sand casting* and *die casting*. Sand casting has been used in the making of metals, and bicycles in particular, up until the mid 1970’s [Bridgestone Bicycle Catalogue, pp.48]. Sand casting was favored for custom racing bicycle construction because of the scrupulous care that the process demanded and because the careful handling was reflected in the quality of the created parts. However, the molds in sand casting are destroyed after each use, keeping the costs of sand casting high. Scientists suggest sand casting for production of fewer than 100 parts because of the large amount of labor involved and sand casting’s slow rate of production. *Die casting* has replaced sand casting in the mass production of bicycles because it can handle the thousands of parts produced by a labor-saving automated system. The high initial cost of die casts is made up for in the long run by high volume production and eventual bicycle sales.

Sintering

Powder metallurgy is a metal forming process by which a powdered form of a metal or combination of metals is compacted and heat-treated to become a finished product. The first step in any powder metallurgy process is to place the powder metal into a mold container. The powder is compacted into the crevices of the mold, forming the desired shape. The mold withstands the forces of compaction and quickly allows applied heat to escape, preventing an unbalanced heated condition in the product. Next, the applied heat diffuses the atoms on the boundaries of metal particles, allowing the particles to merge and the powder to solidify once heat is removed. Pressure is often applied through a metal press or from the pressure of a gas to help shape the resultant product. Scientists call this process *sintering*. Sintering is useful in the construction of a *preform* and the *infiltration* process used in creating composite frame tubes.

Infiltration

Infiltration is a composite metal forming process. Scientists and engineers first create a *preform* using a powder metallurgy process like sintering. The designers make their *preform* sufficiently porous so that they are able to diffuse a molten metal into the solid *preform* [SAE, "Fabrication and Prop… Brake Calipers…"]. The diffused metal diffuses into the *preform*, solidifies, and the result after solidifying is a composite metal. I have chosen the infiltration-of-a-sintered-preform method rather than a casting approach for the making of bicycle frame tubes because the casting of a MMC requires expensive *mechanical mixing* equipment to uniformly distribute *particulate* in the molten *matrix*. A designer using the casting instead of the infiltration approach would then die cast the mix to become a bicycle tube. Instead, a designer could first die cast a *particulate preform* (no stirring involved) and place it in a pressurized molding chamber, then inject molten *matrix* metal in to the chamber for diffusion of the metal into the *preform*. The chamber needed for *infiltration* is approximately as expensive as using *mixing equipment* in the casting process, so I have opted for the process that I feel is more accessible to small companies and state or federally funded projects [SAE, Lightweight Magnesium Composites …].

Centrifugal Atomization

The *particulate* used to reinforce an MMC are microscopic: 1 to 25 μm (0.001 – 0.025 millimeters) in diameter. Forming such a fine powder requires special processes. *Particulate* designers can form SiCp powder from successive mechanical rolling operations or by using the Osprey process (spray forming centrifugal atomization). In the Osprey process, designers inject molten alloy into an inert gas stream (at a special proprietary point) that contacts and condenses upon a rotating former. Successive impacts of new condensate on the cooling SiC_p, "splat quenching", eliminates *interdendritic triple points* in its crystal structure. Median particle size is inversely proportional to inlet jet pressure, so that the faster the stream of reinforcement and gas traveling to the former, the smaller the droplets formed [Introduction to Manufacturing Processes, pp.343]. Theoretically the crystals thus formed will fracture upon initial loading in a metal, breaking down to single grains. These single grains are statistically less likely to have imperfections and are therefore stronger and harder than the multi-crystalline particulate [SAE, "Thixoforming"]. Ground or rolled powders are relatively course compared to spray formed powders. I have chosen the spray formed particulate technique to reinforce the bicycle MMC, but because of the expense of using the proprietary Osprey process, I have decided that forming the particulate should done by an outside vendor. A bicycle mass transit department involved in MMC bicycle production would simply purchase the spray formed reinforcement for infiltration from the outside vendor, without spending money developing the relatively new spray forming technology.

Extrusion

Extrusion is a deformation process where a useful part is made from a less useful part. Metal, either molten or solid, is pushed through a cone shaped metal *die* so that a tube of larger diameter is stretched to a tube of smaller diameter, of a size equal to the exit hole of the *die*. I have found that extruding the composite after formation but before processing for product development eliminates *interdendritic triple points*, making the grain structure more columnar and uniform [SAE, "Fatigue Properties of A356…"]. The clusters of *interdendritic triple points* are stretched apart in the extrusion process and spread throughout the aluminum matrix. The grains in the MMC will be stretched or *strained* when the MMC is extruded, therefore *recovery* and *recrystallization* will occur when the MMC is heated. The *extrusion ratio*, or the ratio of *die* inlet diameter to exit diameter, suggested to cause an optimum uniformity in the matrix is 8 [SAE,"Development of Al Powder…"]. This means that the tube before extrusion should have a diameter eight times the diameter to be used. Because extrusion of the tube to this diameter is nearly impossible to accomplish all at once, the extrusion is accomplished via several runs through several dies until the designer arrives upon an appropriate diameter for the tube. This is an essential step in the making of bicycle tubes.

Forging

Forging is similar to the blacksmith practice of hammering a piece of metal on an anvil. Engineers impact a metal with precise force and in calculated locations so as to form the shape of a finished product, to tailor the physical properties of a product, or to alter the shape or properties of a product so that the metal can be further processed. Designers often *forge* the tubing in bicycle frames to increase the stiffness at the end of the tube where excessive *stress* can concentrate. They can forge the portion of the *top tube* nearest to the *steering column* and the portion of the *chain stay tube* nearest to the *front gears* so that the sides are pushed in slightly, increasing turning stiffness. They can also forge the portion of the *top tube* nearest to the *seat tube* so that the top and bottom tube walls are pushed in slightly, increasing rider weight stiffness [GT Bicycles 1999 Catalogue]. Forging always takes place after the metal to be worked has completed the casting or infiltration process. Forging can also be done while simultaneously heating the metal, and then the forging process is called *hot forging*. The elongation of grains in the metal is countered by the heat addition, so a strong, uniform structure is maintained even as the metal's shape is changed.

Welds and Adhesives

Welding is a joining process that forms interatomic bonds between metals. Designers apply intense heat to the adjacent surfaces of a metal to be joined, raising the metals to their melting point, and merging the surfaces together. Welding is a *heat treatment* of the metal. The grains nearest the weld expand because metal atoms from smaller grains diffuse toward larger grains. Physics and chemistry explain this diffusion by saying that the larger grains have a smaller surface energy and due to entropy the lower energy states are usually attained after chemical or physical reactions. Enlarged grains around the weld weaken the metal, but the *microstructure* inside the weld is relatively strong and similar to the standard *cast microstructure*. When a welded metal is *stressed* sufficiently to cause fracture, the fracture will occur outside of the strong weld structure, and in the weakened and softened workpiece. Therefore, a welded metal can be unreliable, especially if alloying element grains enlarge more than the base metal. Metal Matrix Composites are subject to over enlargement of alloying grain structures, and so designers of MMCs turn to other joining methods.

Adhesives do not change the metal microstructure. Adhesives bond adjacent surfaces interatomically without the addition of heat. Adhesive strengths are sufficient for the relatively low structural loads of bicycles. Adhesives are usually stored as two unreactive parts (*epoxy monomer* and a *hardening agent*). The two parts are combined and remain a liquid for a limited time before they harden and bond to whatever surfaces they are designed for. I have decided on using a metal bonding adhesive such as the one chosen by Trek Bicycle Company – EA9430, an epoxy having good low-bond strengths, and high peel (resistance to peeling) and shear (resistance to bending and twisting) strengths [Adhesives Age, pp. 56]. In addition, adhesives require less labor (welding proficiency) and frame assembly is typically faster [Adhesives Age, pp.56]. The surface of the tubes to be joined will need to be properly prepared before applying adhesive to ensure excellent bonding. This preparation is discussed in the section on frame assembly methods below.

Methods and Techniques

I have evaluated the casting and deformation processes and the welding and adhesive joining processes above, and I have determined a bicycle frame manufacturing technique suitable for the implementation of affordable bicycle mass transit. Where appropriate I restate previous conclusions to better describe my plan.

First, designers acquire SiCp from an outside vendor or a designer spray forms the SiCp using the proprietary Osprey process.

Inlet Pressure:	variable	megapascals
SiC_p Particulate Size:	10	micrometers
Cooling Rates	1000 to 1000000	^{o}C/second
Rotating Former Speed	15000	revolutions per minute

Next, designers *sinter* a *SiC_p preform* of chosen V_p into a tube of appropriate diameter with excess material trimmed away.

Table 2.1:

Preform Parameters

Preform Parameter	**Value**
Compaction Pressure:	100 megapascals
Sintering Temperature:	2291.15 ^{o}C to 2945.15 ^{o}C ($0.7T_m$ to $0.9T_m$)
V_p :	0.30

Suggested Tube Circumferences

Top Tube:	4	inches
Seat Tube:	3.625	inches
Down Tube:	4.375	inches
Rear Fork Tube:	2.25	inches
Front Fork Tube:	3.625	inches (handle bar end of tube) /
	2.75	inches (wheel end of tube)
Head Tube (lug):	5.875	inches

Tube sizes are determined from typical bicycle frames. Sintering temperature and pressure are determined from “schey”

The designers next place the *preform* in a pressurized molding chamber.

Then bicycle designers inject molten *matrix* metal into the chamber. The *matrix* metal diffuses into the *preform* [SAE,”Characterization …”]

Infiltration Steps:

1) Overheat Aluminum to 750 ^oC to insure complete melting.
2) Preheat the mold and preform to 500 ^oC to reduce needed compaction pressure.
3) Place preform into mold, and pour aluminum melt over the preform.
4) Pressurize the chamber to 25 megapascals (low pressure) for 60 seconds.

Bicycle designers allow the infiltrated *preform* to cool.

Cooling Time: 5 to 10 seconds (100 – 1000 Kelvin/second)

Bicycle designers forge the tubes to maximize turning and weight bearing stiffnesses.

Designers then perform any *machining* processes needed for wheel-to-frame joints or for additional bolts in the frame (To avoid the relatively difficult machining of very hard MMC, holes for bolts or screws can be formed in the preform stage instead, before infiltration. The metal matrix coats the holes and is easily threaded)[SAE,"The Effect of Thermal Cooling…"].

Table 2.2:

Thread Pullout Force

Material	**Thread Description**	**Pullout Load** (Kilonewtons)
aluminum alloy (359- T6)	threaded into matrix	88
Vp=0.30/SiC/Al MMC	threaded into matrix	93

The increase in "pullout load", or the force required to remove a commonly tightened screw from a thread, for the all-matrix aluminum alloy is markedly less than that for the MMC [SAE," The Effect of Thermal Cooling…"]

Bicycle designers need to then prepare the tube joint surfaces for the application of adhesive, removing dirt or grease and etching the surface with acids to create a larger surface area for bonding [Adhesives, Sealants and Primers, pp. A-9] .

Surface Treatment Steps:

1) Immerse surface for 20 +/- 2 minutes @ 150oF in a solution of
    - (a) distilled or deionized water
    - (b) sulfuric acid (etchant)
    - (c) sodium dichromate
2) Then rinse thoroughly with one or a combination of
    - (a) overflow rinse – immerse surface in one or two tanks of distilled or deionized water; the final tank having a pH of between 5 and 8.5
    - (b) spray rinse – thoroughly spray water of pH between 5 and 8.5 to rinse surface

Bicycle designers combine epoxy and hardening agent to form an adhesive and apply the adhesive to prepared bicycle frame tube ends. They assemble the frame, allowing the adhesive to cure according to the rated time, at which time the frame is securely joined and can be further processed.

Selected Cure Time for Adhesive EA9430: 50 minutes at 77°C

Bicycle Legislation

There are numerous laws and regulations on the federal, state, and local levels governing the operation of bicycles. This body of laws has been recently reviewed and updated in Texas to reflect the growing number of riders and their growing rights and responsibilities on the road. In order to better understand the bicycle's place in society, to inform riders of their rights and responsibilities, and to demonstrate the importance of bicycles, I have compiled some important bicycle operation rules. Also, because each of the fifty states has a different set of laws that have subtle differences but are essentially the same, I will focus on the laws in Austin, Texas, and Omaha, Nebraska, two cities that I have lived in for substantial amounts of time. The two regions are easily contrasted as legislatively progressive and apathetic toward bicycles, respectively.

The Traffic Laws Commentary published by the Department of Transportation in 1977 has important information regarding federal, state, and city legislation. The federal vehicle regulations are called the "Uniform Vehicle Code", or UVC. The body of law written as a template for state and city governments to follow is called the "Model Traffic Ordinance", or MTO. The two are similar, except that the UVC handles interstate travel and the MTO handles intrastate travel. The UVC is regulatable law and must be obeyed by bicyclists. The MTO is not regulatable law, in that it is only a guideline for states to deviate from at their discretion, and often do.

The bicycle is defined to be any tandem wheeled vehicle with wheels (at least two) at least 20" apart (size mentioned to avoid regulating child bicycles), powered by a human through the use of gears and belts or chains [The Traffic Laws Commentary, pp.10]. This is essentially the same definition in federal, state, and local laws. However, until recently the bicycle was not technically considered to be a "vehicle" as defined under any law. States and localities have control over this definition, and to date Texas but not Nebraska has reviewed and updated its laws to designate a bicycle as a vehicle.

Other definitions needed for bicycle travel are important. The stretch of road upon which vehicles can travel is called the "roadway". When shoulders, dividers, and bike lanes are included within the roadway, the stretch of road so described is named a "highway", and includes "the entire width between the boundary lines of every way publicly maintained" [The Traffic Laws Commentary, pp.12]. The states define their roadways and highways differently. However, both Texas and Nebraska law conform substantially to this concept set forth by the UVC.

UVC 11-101/11-102/11-103 state that "every person riding a bicycle shall be subject to the same rules applicable to the driver of a vehicle." [The Traffic Laws Commentary, pp.15] Although the UVC explicitly states that a bicycle is not a vehicle, bicyclists must still abide by the rules of the UVC. Texas law recently changed the definition of the bicycle to be a vehicle in 1990, so that bicyclists are subject to the same "rights and responsibilities" as motorists [A Bicycle Master Plan for Texas, pp.102]. This subtle change places bicycling among the serious modes of transportation. These rules also state that violations of the bicycle federal, state, and local traffic codes are misdemeanors, and that bicyclists, just like motorists, must obey commands made to them by firemen and police officers.

Other interesting facts abound for bicyclists. Bicyclists become pedestrians when walking their bicycle and have the right of way to bicyclists on sidewalks or shoulders of highways [The Traffic Laws Commentary, pp. 50]. “Wherever a usable path for bicycles has been provided adjacent to a roadway, bicycle riders shall use such a path and shall not use the roadway.” [The Traffic Laws Commentary, pp. 86] The sidewalk is not included as an adjacent path, so when no bike path is present, bicycle riders may use the roadway. Bicycle riders may also ride on the shoulder of the highway, but because bicycles are vehicles they are not required to do so. The only time that bicyclists may not ride on the sidewalk is when the local constable has posted signs forbidding it, which is often done in busy business districts. Otherwise, states and localities are not legally justified in forbidding bicycle travel, as on state highways or busy inter-city streets [The Traffic Laws Commentary, pp. 92]. UVC law states that if riding at night, bicyclists must have a light that illuminates at least 500 feet in front and both Nebraska and Texas state laws conform to this standard. However, although Austin law is also conforming, Omaha municipal law has no such standard [The Traffic Laws Commentary, pp.109]! UVC law states that bicycles must have red reflectors of approved type that are visible 100 to 600 feet away on both the front and rear. Texas and Nebraska laws leave out the phrase “of approved type” and Austin law just requires some “reflecting device”. Omaha just requires a “reflector” [The Traffic Laws Commentary, pp. 110].
UVC also requires that bicycles have a working bell! Texas, Nebraska, Austin, and Omaha laws overlook this provision [The Traffic Laws Commentary, pp. 112]. Another regulation covers brakes – UVC says that bicycles “must have brakes that work on clean, dry pavement" [The Traffic Laws Commentary, pp. 112]. Texas and Nebraska laws cover this, but Austin and Omaha laws do not.

Registration, licensing, requiring insurance, and requiring inspection are not required of bicyclists under the UVC. However, Austin law requires bicycles to be registered with the local authorities by registered bicycle dealers upon first sale. Austin has a City Manager whose department oversees the registration of bicycles. Omaha does not handle this responsibility. Neither Austin nor Omaha require licensing, insurance, or inspections for bicycling, although Austin does provide for bicycle inspections and an identification plate for theft prevention [The Traffic Laws Commentary, pp.130].

Although the responsibilities of bicyclists are numerous, bicyclists also have rights safeguarding them against unlawful police enforcement of traffic law. Bicyclists may lock their bicycles on street meters without paying for the privilege, as long as the bicycle does not impede parking, or vehicular or pedestrian traffic [The Traffic Laws Commentary, pp. 107]. Local authorities may not impound the bicycle of a person who has committed a traffic violation using the bicycle without a court hearing [The Traffic Laws Commentary, pp. 160]. Finally, UVC states that governments may not take away driver's license points from a person under any circumstances for violating traffic laws using a bicycle [hearing [The Traffic Laws Commentary, pp. 170]. Knowing what rights a person has while riding makes the person a better bicyclist.

In 1990 the Texas State Department of Highways and Public Transportation (SDHPT) came under the scrutiny of the Sunset Review Commission [A Bicycle Master Plan for Texas, pp. 95]. The Sunset Review was formed by the legislature to review state agencies and make recommendations for change. After several public hearings in Houston, Austin, and Dallas, citizen bicycling organizations and environmental groups petitioned for the formation of a formal representative body in the government of Texas to oversee the concerns of bicyclists [Commission [A Bicycle Master Plan for Texas, pp. 98]. The commission favored the movement and included the following provisions in their highway bill: 1) A Bicycle Coordinator was instated within the SDHPT, 2) bans and restrictions on bicycles to use the highways of the state were forbidden, 3) a "bicycle master plan" was created to guide bicycle policy in the future, and 4) bicycles were formally designated as "vehicles". However, a Bicycle Advisory Committee that was sought by the petitioners was only created for a temporary time to construct the guidelines for the state master plan, and was dissolved upon completion of the plan [A

Bicycle Master Plan for Texas, pp. 99]. These progressive moves by the state legislature greatly enhanced the bicycle's position as a growing means of mass transportation.

Besides the regulatory laws that exist to support bicycles, there are federal funds available to states and cities from federal treasuries. The Surface Transportation Act of 1954 (STAA) allocates $4 million to states that petition the federal government for funds going toward state organized bicycle funds, out of a total $45 million a year [A Bicycle Master Plan for Texas, pp. 46]. The National Highway Traffic Safety Administration (NHTSA) also has stated that it will make monies available to states in the future for bicycle programs emphasizing safety [A Bicycle Master Plan for Texas, pp. 50]. Even the federal Department of Transportation (DOT) has changed its attitude about bicycles since 1990, with the creation of the federal Bicycle Coordinator in the Federal Highway Administration (FHWA), which promises to bring more money to the states and localities.

It is clear that bicycling is a major concern of governments, citizen action groups, and commuters across the state of Texas and across the United States. With 60 percent of U.S. commutes made under five miles [A Bicycle Master Plan for Texas, pp. 15], $24 Billion a year lost to employee time lost and tardiness due to traffic congestion [A Bicycle Master Plan for Texas, pp. 16], and supportive legislation, short distance bicycle commuting will make the air cleaner (reducing automobile carbon monoxide emissions), the streets less crowded, and the commuters healthier and happier.

Mass Transit Analysis

I have determined that the extensive processing involved for the construction of MMCs is too involved to think that MMC bicycles could become a suitable material for use in mass transit bicycles funded by any government. Therefore my theory, based upon the processes that I have described previously, is that steel bicycles, already cheaply produced and widely distributed throughout the nation, will be used in a bicycle mass transit system. As newer materials are developed for bicycle manufacture, the prices of less advanced materials, like stainless steel and molybdenum/chromium bicycles will be driven down. The newer materials will be priced at the old prices, and the older steel bicycle prices will continue to fall. This drop in prices will allow mass transit authorities to afford to buy new or buy and repair used bicycles (as is done by the non-profit organization Yellow Bike Project in Austin Texas) to be used free of charge by a concerned mobile citizenry.

Evidence of a drop in prices is seen as the difference in listed prices between the 1998 and 1999 bicycle catalog price guides of the GT bicycle company.

GT Catalog, 1998		**GT Catalog, 1999**	
steel, molybdenum, chromium	*Aluminum (MMC)*	*steel, molybdenum, chromium*	*Aluminum (MMC)*
palomar ($249)	backwoods ($689)	palomar ($241)	backwoods ($652)
outpost trail ($282)	ricochet ($599)	outpost trail ($282)	ricochet ($815)
outpost ($329)	avalanche ($899)	---	outpost ($324), avalanche ($1087)
timberline ($399)		timberline ($460)	
aggressor ($429)			aggressor ($387)
rebound ($549)			rebound ($523)
tequesta ($499)			

For example, in 1998 the “outpost” had a suggested retail price of $329, and was made of the less expensive molybdenum/chromium alloy. In 1999 the “outpost” was redesigned and has an aluminum frame, with a suggested retail price of $324. Although the price changed very little, the material used in its construction is of a superior quality, and my theory of dropping prices is affirmed. The “aggressor” had a similar change - $429 in 1998 to $327 in 1999. Also worth noting is that although some bicycles, for example the “avalanche”, increased substantially in price, several other factors, like improved brakes, improved shocks, and changed geometry, affected this change. Therefore my theory is still valid. However, more data on bicycle prices is suggested for a thorough study of this phenomenon, and these data should not be taken as a factual trend in present bicycle sales.

Conclusions

I have found that scientists and engineers can develop processes for making bicycle frames that optimize microstructural and physical properties. I have opted for the process that I feel is more accessible to small companies and state or federally funded projects – infiltration of a centrifugally atomized and sintered silicon carbide preform with aluminum matrix metal.

I have decided that forming the particulate should done by an outside vendor. A bicycle mass transit department involved in MMC bicycle production would simply purchase the spray formed reinforcement for infiltration from the outside vendor.

I have found that extruding the composite after formation but before processing for product development eliminates *interdendritic triple points*, making the grain structure more columnar and uniform (an essential step in the making of MMCs).

A welded metal can be unreliable, especially if alloying element grains enlarge more than the base metal, so I have decided on using a metal bonding adhesive such as the one chosen by Trek Bicycle Company – EA9430, an epoxy having good low-bond strengths, and high peel (resistance to peeling) and shear (resistance to bending and twisting) strengths [Adhesives Age, pp. 56].

I have determined a bicycle frame manufacturing technique suitable for the implementation of affordable bicycle mass transit, and the important values quantifying this bicycle are listed in the methods and techniques subsection of the Bicycle Production section.

I have determined that the extensive processing involved for the construction of MMCs is too involved to think that MMC bicycles could become a suitable material for use in mass transit bicycles funded by any government. Therefore my theory, based upon the processes that I have described previously, is that steel bicycles, already cheaply produced and widely distributed throughout the nation, will be used in a bicycle mass transit system.

These conclusions are the results of my research, but further research and consolidation of information of bicycle sales and bicycle mass transit organizations (the “Yellow Bicycle Project”) and bicycle clubs and organizations (UT cycling) would be beneficial.

Glossary

anisotropic : properties of the metal depend upon the direction that the metal is tested. (ie: higher strength in the length direction than in the width direction)pp.100

casting : melting a metal charge in a furnace, pouring the melt into a previously prepared mold, extraction of heat from the melt and solidification, removal and treatment of the part. pp. 99

coefficient of thermal expansion (CTE) : a measure of the tendency of materials to expand or contract in the presence of a thermal gradient or change. pp.373

columnar grains : elongated solidified grain groupings in a metal that grow in the direction of heat extraction and are very anisotropic. Pp.121

dendritic grains : undercooling of a liquid of lean composition of one component of alloy forms dendrites. The tree-like branches grow in the direction of heat extraction, but run out of the lean component and branch out arms from its sides at 90^o. The lean component dendrites bunch together to act as stress raisers and fracture sites. pp. 123

die : tool used to plastically or permanently deform a metal; the die face is the part of the tool that is in physical contact with the deformed metal. pp. 210

die casting : the mold cavity is filled under moderate to high pressures, forcing the metal into intricate details of the cavity. pp. 170

epoxy monomer : a single unit of a polymer (made of thousands of repeating monomers) plastic; epoxies are pastes that need high pressure for spray application. “Two part” epoxies are stable pastes until they react with a hardening agent, when they “cure” or solidify. pp. 407

equilibrium : a state where energies, forces, atoms, and temperatures are in balance and there is no impetus for change.

eutectic : the composition of an alloy such that the solidification temperature is lower than either constituent metals’ solidification temperatures, and the composition of an alloy that has the most evenly distributed grain structure. pp. 107

extrusion ratio : ratio of initial cross-sectional area or diameter to final cross-sectional area or diameter. pp. 251

fiber : wire of variable length and diameter of about 0.01 mm used to reinforce a ductile metal matrix. pp. 430

forging : a workpiece is deformed plastically or permanently. pp. 210

heat treatment : distribution of the phases and the morphology or size of the eutectic grains depends on the cooling history. Different heat treatments vary the concentration of phases and grain sizes. pp. 136

hot forging : forging a metal at an elevated temperature to cause recovery and possibly recrystallization in the metal, counteracting the elongation of grains caused by forging. This technique keeps grains uniform and strong. pp. 211

infiltration : a composite forming process where a preform is placed in a pressurized chamber with matrix metal and allowed to diffuse into the preform and solidify. pp. 151

ingot metallurgy : metals cast of circular, octagonal, or round-cornered square cross-sections and later melted and casted as finished product. pp. 151

interdendritic triple point : point of origination of side branching arms on the main dendrite branch. pp. 123

interface bond strength : the qualitative strength between reinforcement and matrix. This strength value is responsible for the ability of the matrix to transfer imposed load to the reinforcement across the interface. pp. 429

intermetallic : phase formed in an alloy at specific compositions with distinct properties, often being brittle, hard, and of a high melting point. pp. 109

isotropic : properties of a metal are the same in all directions. pp. 100

machining : a process that generates the shape of a workpiece from a solid metal by removing excess material in the form of chips. pp. 441

matrix : bulk metal crystal lattice filled with reinforcement. Metal matrices are ductile and tough; reinforcements are hard and very strong. pp. 374

metal matrix composite : an alloy of two metals. The matrix metal is the ductile “solvent” that is mixed with hard and strong reinforcement “solute” to produce a combined metal of superior overall quality. pp. 343

microstructure : the organization of the crystal lattice of a metal on a microscopic level (ie: 1 micrometer or μm is 0.000001 meters) pp. 124

mixing equipment : blending turbines used to mix up the reinforcement in a metal matrix composite. pp. 560

particulate : tiny particles of metal of no particular shape or shape dependant properties with a diameter of no less than 0.0001 mm. pp. 330

porosity : gaps, or gas or solid inclusions in a MMC that deleteriously affect the properties of the metal. Porosity is measured in percent of the volume of the metal. pp. 123

preform : a sintered part in the infiltration process which is made sufficiently porous so pressurized matrix metal will diffuse in and completely wet, bond, and combine to produce a MMC. pp. 151

recovery : a metal’s temperature is raised from 0.3 Tm to 0.5 Tm. The heat gives the metal atoms increased mobility and atomic dislocations are rearranged. Some of the original softness of a strained material is restored and ductility Returns without necessarily affecting strength. pp. 190

recrystallization : a strained material raised to a temperature above 0.5 Tm, where the metal grains are replaced by internally produced crystals, redistributing the elongated grains as uniform grains. The metal is softened and free of dislocations. pp. 191

reinforcement : a brittle, tough, hard, and strong, usually intermetallic metal that is mixed into a ductile metal to strengthen it. Reinforcement comes in the following three shapes of ascending length and size : particulate, whiskers, and fibers. pp. 330

sand casting : a casting process that uses common, inexpensive silica (sand) as its mold material. This is the best method for prototyping and is suggested for processing 1 – 100 parts. pp. 162

shrinkage : the shrinking of most metals and composites upon solidification that appears as a cavity at the top surface of a cast product. This is generally a defect to be removed from the final product. Risers are tubes attached to a cast that fill with excess metal and contain the shrinkage cavity for removal. Runners are tubes that fill with exiting metal and allow gas porosity and inclusions to be removed. pp. 121

sintering : particles are mixed thoroughly, compacted to be brought into close proximity, while imparting a desired part configuration, heated to melt and diffuse particles together, so that a permanent bond is established and a part is made. pp. 330

stiffness : a measure of the resistance of a solid to bend under a force. One measure of stiffness is the modulus, E.

strain : the length that a metal elongates when a certain stress or force is imposed upon a metal.

stress : the force per unit area imposed upon a metal. 101 kilopascals is equivalent to the pressure imposed on the surface of the earth by the atmosphere at sea level. A megapascal is one thousand times this amount. pp. 39

surface energy : any metallic interface, even a grain boundary in a pure metal, is a site of many unsatisfied, broken interatomic bonds that add up to this excess energy (also called interfacial energy). pp. 114

thixoforming : warming a part and simultaneously deforming it so that particulate can be worked into a metal and uniformly distributed to produce a MMC. The advantages of thixoforming are that a dendritic grain structure is avoided, and less heating is required than conventional methods. pp. 574

ultimate tensile strength : the highest stress that a metal is capable of enduring. However, the metal can still endure more straining or elongation before fracture, but excessive thinning occurs that lowers the required stress needed for exceeding strain. pp. 40

volume fraction : a mathematical fraction of volume of a constituent material of a composite. V = 0.20 means that 20% of the composite is reinforcement, and the remaining amount is matrix metal. pp. 330

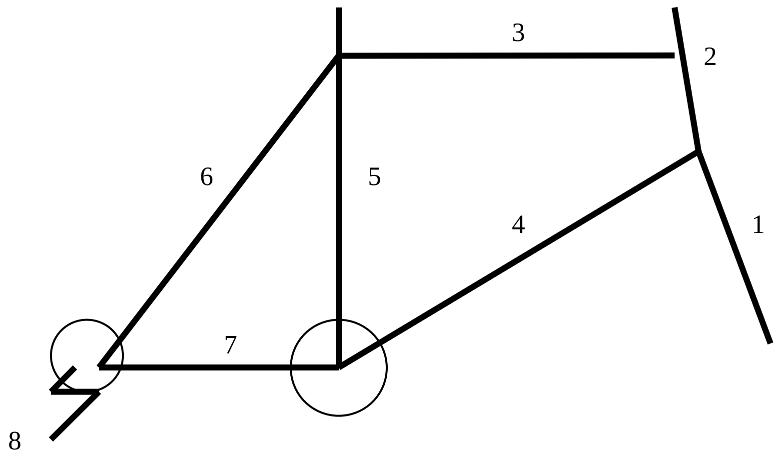
vector : a value of any quantity expressed as a magnitude and direction. (ie: an arrow pointing north, 5 feet long, is the vector quantity expressing how Bill walked 5 feet north while completing an orienteering course) pp. 30

weight fraction : ratio of constituent material weight to total composite material weight. pp. 30

wettability : ability of a liquid to cover or encapsulate a solid and overcome the surface energies associated with equilibrium. pp. 114

Bicycle Frame Terminology

front fork (1)
head tube / lug (2)
top tube (3)
down tube (4)
seat tube (5)
rear fork (6)
chain stay tube (7)
derailleurs (8)



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