Advancements in Materials Used in Bicycle Frames

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Abstract

Bicycle frames have gone from wood to steel to advanced alloys to composites in the last century and a half. Bikes themselves have gone from mere curiosities to serious modes of transportation in developing countries and a major form of sports & recreation in developed ones. While the automotive and aerospace industry helped to stifle advancements in the last century on bicycles by stealing the focus away from them, the advancements made in those fields are now helping to fuel a renaissance in the bicycle industry. As costs of materials used in advanced aerospace applications come down materials have gone from the most basic to the most advanced. Likewise, mass production techniques derived for the automotive industry have helped bring the cost down. However, many of the original materials and production processes used today remain unchanged from over a hundred years ago.

Introduction

The history of materials and processes used in manufacturing bicycle frames is one that has come full circle. The precursor to the modern bicycles was invented 1817 by Baron von Drais de Sauerbrun of Germany. The vehicle he invented was powered by pushing on the ground with one's feet. He called his invention the draisienne, or hobbyhorse. The first pedal bicycle, known as the velocipede, was invented in 1863 by Pierre Lallement and manufactured in Paris. The velocipede had pedals attached directly to the front wheel and speed was limited by the diameter of the front wheel. The innovation of spoked wheels led to larger diameter wheels and therefore greater speeds. A method of maintaining uniform tension on the spokes by James Starley and William Hillman of England in 1871 led to bikes known as high wheelers. These bikes are recognizable to most people by their comically oversized front wheel. It was the addition of a chain drive connecting a crank with pedals below the rider to a sprocket mounted on the rear wheel and rubber pneumatic tires in the latter part of the 19^{th} century that really allowed bicycling to become popular [8]. One of the first, and most popular, bicycles to incorporate all of these technologies was the Rover Safety Bicycle. Introduced in 1885 by J.K. Starley of England, the Safety Bicycle, followed by John Dunlop's patented pneumatic tire in 1890, marked the final major development in the innovation of the bicycle form for almost a hundred years [12]. The stage was set for fierce competition between manufacturers for technological innovation and brand loyalty.

The most interesting aspect of the history of the bicycle is that all the above innovations actually helped lead to its decline. By the early 20th century automobiles were changing the American landscape and reshaping society. Everything from the spoked wheel, pneumatic tire, to the manufacturing processes for machining gears and assembling frames as well as paved streets all happened because of the bicycling craze. It was precisely these innovations that allowed for cars to become so cheap and so reliable so quickly, since all the critical infrastructure was in place. In fact, the next great transportation revolution - airplanes, was in many ways the children of the bicycle industry. The Wright brothers, who built and flew the first successful airplane, as well as a slew of early inventors, builders, and pilots (steering an early plane was akin to steering a bicycle by leaning into turns) all got their start in the bicycle industry [12]. This is where history comes full circle. While America was fixated with automobiles for the last 80 years, innovations in bicycles came to a near halt. But with the soaring prices of fuel, an obesity epidemic, as well as thrill seekers and competition junkies constantly looking for new outlets, bicycle have made a roaring comeback. The irony is that innovations in manufacturing processes and materials for the automotive and aerospace industries is what paved the way for lighter, faster, stronger, and cheaper bikes. The very industries that nearly destroyed the bicycle industry helped to revitalize it. It seemed to be a fitting payback.

Description of the Product

Functional Requirements

Learning to ride a bike has become a right of passage for a child in America today. It is kids, or rather the parents that purchase a child their first bike, who comprise a large part of the bicycle industry's consumer base. The major functional requirement's of a kid's bike is that it be affordable and resistant to corrosion from outdoor elements (i.e. water from rain and riding through puddles).

The other major group of consumers is the sports enthusiasts market. While bicycle racing kept biking alive through much of the 20th century the advent of off-road bikes, or mountain bikes, has played a pivotal role in the re-emergence of bicycling popularity. Racing bicycles major concern is weight. The lighter a bike is, the less energy a cyclist has to use to propel the bike. However, strength must not be sacrificed. Cost is still a concern for these bikes, but less so that for a kid's bike. The real emphasis is on performance. For mountain bikes used off road and under extreme conditions (like downhill on ski slopes in the summer months) the frame must endure extreme stresses.

When coming down off a jump or running into a hard object as often happens in extreme competition, the frame must be able to withstand a force from the wheels with minimal flexing. If the bike frame were to flex, it could throw the balance of the rider off because the bike would feel spongy beneath them. This type of stress induced on a frame is considered an in-plane bending moment (see Figure 1). In climbing hills, there is an out-of-plane bending moment acting on the frame [11]. When climbing a hill a typical rider uses the strength of their arms to move the bike back and forth so they can throw their weight on the pedals to climb faster and with less strain on the leg muscles.

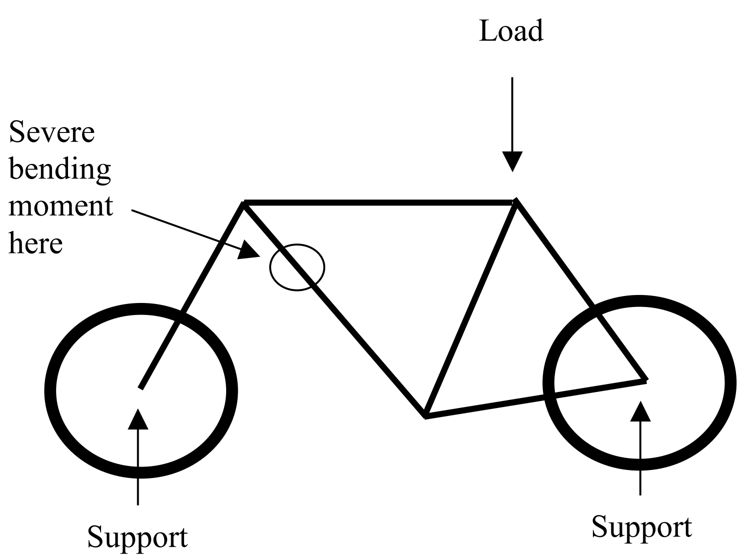

Figure 1: Forces acting on a typical bicycle frame

Design Criteria

The triangular frame was nearly perfected by the late 19th century and still has yet to be improved on. The advancements have come in the way of materials and processing. Although, some stress (as shown in Figure 1) has been reduced in extreme riding conditions by the addition of shock absorbers just like those used in cars. The triangular design is ideal for a bike. Because the front wheel of the bike extends out and is not connected with two supports like the rear wheel (because it has to turn) a severe bending moment occurs in the lower member of the front triangle. This must be accounted for in the design and usually this part of the frame, along with the horizontal top bar, are the thickest and sturdiest part of the frame. Triangulation allows for the forces acting on the bike to be dispersed through the frame so that all the members are primarily in tension or compression instead of buckling (excluding the previously mentioned member). This is a design just like a Warren-truss that is used to support a bridge and is ideal since bending is a more severe form of stress than tension or compression [11].

Required Properties for new materials

For a kid's bike, or an affordable bike used primarily for transportation purposes, corrosion resistance and stiffness must be achieved at a minimum cost. Aesthetics are also a concern since no kid wants a bike that isn't attractive.

For a high performance bike, strength to weight ratios are of critical importance. Any new material must be as strong as steel but should be lighter. A high modulus of elasticity is critical for stiffness for the reasons mentioned above. However, some vibration dampening is desirable because too stiff of a frame will send every shock and bump into the rider via the seat and handlebars. High fatigue strength is desired since the frame experiences some bending and the material should not become fatigued over long periods of time or it could fail down the road under otherwise normal conditions. High yield strength is also needed to handle the compressive and tensile loads of an average adult who may be coming down off as high as a 4-meter drop or greater! For this reasons, the yield strength must always remain in the elastic region. Serviceability is a concern on many bike components since the rider must make repairs on site, even in the middle of a race. However the frame itself, if broken, is not widely expected to be serviceable on site.

Materials Used in the Manufacture of the Frames

The first bikes were made of wood. Often bamboo or hickory [13] were used since these woods have a long grain and therefore can handle stress better than one with a shorter grain or a softer wood. These wood bikes were usually reinforced at the joints with primitive steel. Advancements in mass production of steel led to making it more affordable. For this reason, kids bikes and those used for cheap transportation are still made of rolled steel tubes. Since steel is so plentiful and cheap, it is hard to find an affordable replacement when weight is not the most critical factor. Rolled steel tubing allows for extra stiffness and lighter weight than solid steel. High performance bikes, on the other hand, are increasingly making use of advanced materials that are coming down in price from their original application for aerospace. With an even greater emphasis on increased strength to weight ratios and very little emphasis on cost, intensive research has been performed in the last several decades for the military and commercial airline industries to find materials that could outperform steel.

The first major breakthrough in frame materials was known in the industry as cromoly. Cromoly is either a chromium-molybdenum or manganese-molybdenum steel alloy. This alloy is stronger than steel and thus less material can be used for a lighter bike. It is also easily formed and brazed for cheap processing [7].

One of the more affordable materials that can outperform steel is aluminum and its alloys. Aluminum alloy 6061 is commonly used in bike frames because of its age hardening capabilities. One way bike builders achieve high-strength aluminum frames is with thin walled large diameter tubing. Even though more material must be used to achieve comparable strength to steel, the result is still lighter.

The future of bike frames is in more advanced alloys and composites. Titanium and even cast magnesium are becoming more viable options as the cost of production continues to come down. The same is true with fiber-reinforced composites. With a carbon fiber embedded in a polymer matrix, the tensile load is carried in the carbon fiber which is very strong in tension but brittle in bending, while the bending is carried in the polymer (usually nylon) matrix. Another advantage to carbon fiber frames is that they can be made from one piece, eliminating the need of joining the pieces that is one of the biggest considerations in frame design.

Manufacturing of the Frames

Cheap bikes employ many advancements made in the automotive industry. Mass production of bike frames allows the cost to be kept extremely low while maintaining a high level of quality robotic welding and assembly line production are used at many large scale facilities all over the world. High performance bikes, on the other hand, often use old style batch processing. Batch processing was used early on because such rapid advancements were being made in bike technology that large scale tooling was not a feasible investment. This also allowed for the manufacturer to be more flexible to consumer demand. These same reasons drive the industry today.

Cold-drawn steel tubes are still manufactured on a large scale, but they can then be purchased and assembled at a separate, smaller location. Seamless tube aluminum is also becoming increasingly popular [14].

Methods of joining frame pieces is of the greatest importance along with achieving consistent physical properties in the material itself. Brazing and welding are the most commonly employed methods of frame assembly. Early frames were brazed, often with an investment cast joint to hold the tubes in place and give greater thickness to the material, otherwise tempering in the steel is reduced from the heating process [8]. While brazing is still used, it has been largely replaced by tungsten inert gas welding (TIG). TIG welding works well on most metals. Because of the heating of the material during brazing and welding, the tubing is often thicker at the ends where joints occur. Thicker material decreases the heat affected zone (HAZ). This is especially crucial for aluminum that usually has very thin walls on the tubing and extreme heating can reduce the age hardening. For tungsten, care must be taken in not only applying inert gas to the area being welded but also the inside of the tube since tungsten is so reactive [12]. Another issue with joining of the frames by brazing or welding is that the only way to inspect the quality of the weld (i.e. penetration) is to cut it in half. This obviously destroys the joint and thus quality control and skilled welders are a must.

Gluing has become a viable option for joining frames. This requires a joint piece, usually cast, stamped in two halves, or formed from sheet metal to hold the tubes together and giver more surface area for the glue to adhere. Gluing solves a lot of the problems of overheating the metal, but is not widely used since it is still difficult to get a glue joint that can withstand the shock that a welded one can and not crack.

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