The Art and Materials Science of 190-mph Superbikes

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Abstract

The following article is an edited transcript of a talk presented in Symposium X at the 2002 Materials Research Society Fall Meeting in Boston on December 2, 2002. From Bessemer steel used on the first motorized bicycle in 1871 to sintered aluminum ceramic composites and TiN thin-film coatings used on standard production machines today, motorcycles have been at the forefront of the use of high-performance materials. Thanks to developments in materials technology, relatively inexpensive mass-produced motorcycles are now capable of achieving speeds of >190 mph.

Keywords: *advanced materials technology, motorcycles.*

"The Art of the Motorcycle" Museum Exhibition

With over two million visitors at four venues to date, "The Art of the Motorcycle" exhibition, produced by the Solomon R. Guggenheim Museum in New York City, has been by far the museum's most successful exhibition ever. It first opened in 1998; Ultan Guilfoyle, former director of the Guggenheim's Film and Video Production department, and I were the co-curators. In selecting motorcycles for this exhibition, we applied three criteria: aesthetic appeal, social significance, and historical or technological importance. Although all three criteria can be related to materials, here I will focus explicitly on some of the technological aspects of motorcycles that informed our choices of the specific machines for the exhibition. More information on most of the motorcycles discussed here can be found in the exhibition catalog (see Bibliography).

Perhaps the single most significant motorcycle in the exhibition was the 1868–1871 Michaux-Perreaux steam velocipede, made in Paris (Figure 1a). This was the world's first motorcycle; only one was ever made, and yet it somehow survived the Franco-Prussian War and the first and second World Wars. It is now owned by the Musée de l'Ille-de-France in Sceaux, a suburb of Paris. Louis Guillaume Perreaux created this machine by installing his patented steam engine in the first mass-produced pedal bicycle, designed by the Michaux brothers. A steam engine was a logical choice for him to use, having steadily developed from the work of Thomas Savery and Thomas Newcomen in the 17th century to the point where Perreaux was able to make one small enough to use for this purpose. Unfortunately for Perreaux, his machine turned out to be a technological dead-end the moment it was created, since a few years earlier, in 1862, his fellow French countryman Alphonse Beau de Rochas had published the technical description of the four-cycle internal-combustion process. The Michaux-Perreaux engine produces ~1–2 hp, and the overall machine weighs 195 lb (88 kg). We placed this earliest motorcycle at the entrance to the exhibition, next to the 1998 MV Agusta F4 (Figure 1b), which at that time represented the latest achievement in motorcycle design. Significantly, the MV Agusta F4 produces roughly 100 times more horsepower than the Michaux-Perreaux, while weighing only twice as much. As I discuss in this article, it has been the developments in materials technology over the century separating these two machines that made these advances possible.

The Michaux-Perreaux motorcycle had wheels with iron-covered wood rims and a 100-psi steam engine held together with iron rivets. A few years later, the first mass-produced motorcycle, the 1894 Hildebrand & Wolfmüller, incorporated the newly developed drawn-steel tubing and had steel connecting rods directly attached to the rear wheel. In both of these examples, the designers used some of the most advanced materials available at the time the machines were created. To follow subsequent developments in materials technology, it is particularly useful to trace the evolution of racing and sporting motorcycles over the past 100 years, since these machines not only quickly incorporated the latest materials advances, but they also often provided the general public's first exposure to those materials, whether they were aware of it or not.

The fact that for similar classes of objects (high-speed motor vehicles, for example) the costs of mass production reduce to similar numbers of dollars per pound demonstrates why such technology was typically incorporated first in motorcycles rather than in automobiles. Since motorcycles are so light compared with automobiles, their designs are able to incorporate more state-of-the-art materials technology while still maintaining a reasonable total cost. Currently, $11,000 will buy a Suzuki GSX1300R Hayabusa, a motorcycle that is capable of achieving 190 mph directly from the dealer's showroom. In contrast, that same $11,000 will only buy the least expensive four-door sedan on the market—a Hyundai Accent GL—whose top speed is a more modest 110 mph. Performance in an automobile comparable to that of the Suzuki motorcycle certainly is available, but it comes at a price. For $89,000, the Acura/Honda NSX sports car provides the consumer with something approaching Grand Prix racing-level technology in a mass-produced automobile. These prices and relative levels of technology and performance can be better understood by the following comparison: the NSX costs $27/lb and the Suzuki is roughly the same at $23/lb, while the Hyundai costs only $4.80/lb.

Materials Used in the Engine

The challenge of creating motorcycles for racing places high demands on materials. Before World War I, an advanced form of motorcycle racing in the United States developed on wooden board tracks, resulting in machines like the 1914 Cyclone that nicely illustrate the dictum of "form follows function." The smooth, hard finish of the boards resulted in very low rolling resistance, and the steep banking of the oval racecourses eliminated centrifugal force as a problem for keeping the riders from sliding off the track, leaving only

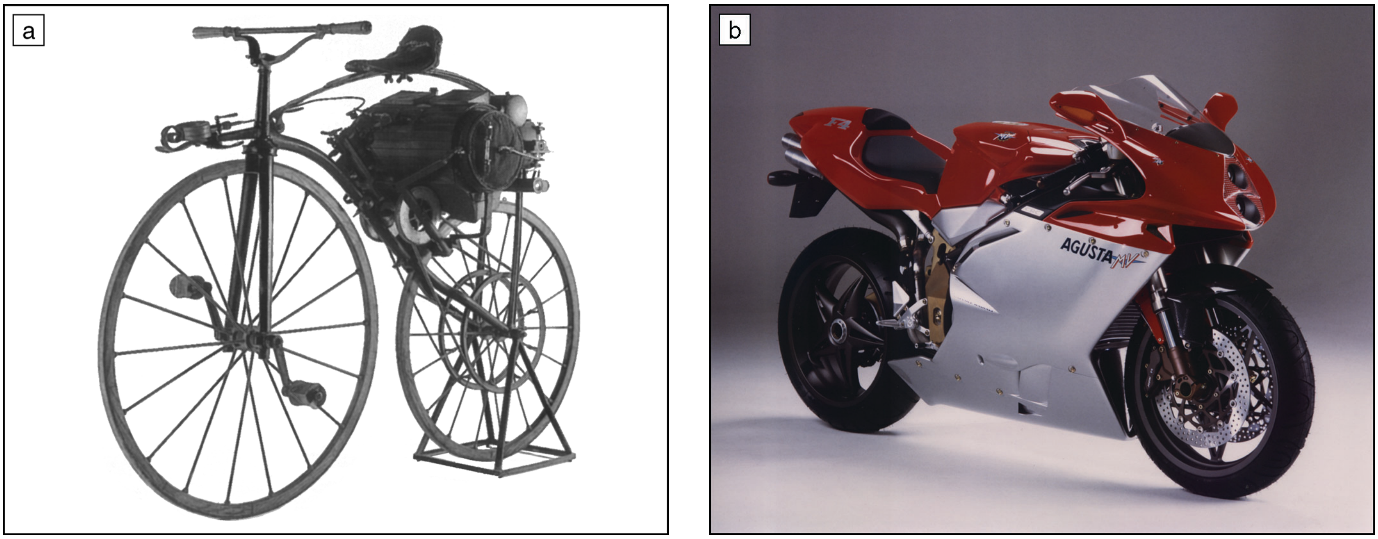

Figure 1. (a) The Michaux-Perreaux steam velocipede (1868–1871). The single-cylinder (22 mm × 80 mm bore × stroke) steam engine in this first motorcycle produces ∼1–2 hp, and the overall machine weighs 195 lb (88 kg). Used in its construction is iron for the frame, iron-covered wood rims with iron spokes for the wheels, and leather belts to transmit power to the rear wheel. (b) The MV Agusta F4 (1998). Its four-cylinder, 750 cc internal-combustion engine with dual overhead camshafts and four radial valves per cylinder produces 126 hp, and the overall machine weighs 397 lb (180 kg), only twice that of the Michaux-Perreaux. Used in its construction are Cr-Mo steel and Al alloy for the frame, Mg alloy for the swinging arm and wheel rims, high-strength steel for the chain drive, carbon-fiber composite for the fenders, plastic for the bodywork, and a Si-based microprocessor for controlling fuel injection. (Photographs courtesy of the Solomon R. Guggenheim Museum and MV Agusta.)

wind resistance as a fundamental limiting factor on speed. Since the only function of these machines was to go as fast as possible around a banked oval track, and since the only purpose of a brake is to slow a motorcycle, the machines were made without brakes in order to save weight. Mufflers were eliminated to save weight as well, and to avoid restricting the power. However, although weight was saved wherever possible on these motorcycles, in order to extract the maximum power, the designers had to concentrate on the engine head.

While an engine has a number of components serving various essential purposes, all of the power is produced in the combustion chamber of the head. Unfortunately, so is all of the heat. In any internal-combustion engine, only 25% of the energy extracted from the burning fuel ends up as power to the rear wheel, while the other 75% is wasted in the form of heat. The more power generated by an engine, the more heat generated as well. Unless this heat is extracted from the engine, parts will fatigue and fail due to their reduced strength at elevated temperatures. While some of the heat of combustion naturally leaves the head through the exhaust pipe in the form of hot combustion by-products, the rest must be conducted away through the material of the head itself. Here, the materials properties of thermal conductivity and strength at high temperature become key limiting factors.

When the air-cooled BSA “ZB” Gold Star motorcycle engine appeared in 1949, the technology available for casting aluminum limited the size of the cooling fins that transfer heat to the outside air and hence limited the amount of power that could be produced by this engine. Improvements in casting technology over the next seven years resulted in the final “DBD” form of this engine, which had a head with significantly deeper cooling fins than the ZB. During this period, the technology issue facing BSA’s engineers was not that of generating more power, but rather of extracting the additional heat from the engine to prevent component failure in the engine head.

The heads of the earliest motorcycle engines were made primarily of cast iron, which has low thermal conductivity (see Table I). By the 1920s, iron was replaced with either brass or bronze in some racing engines, doubling the thermal conductivity and thereby allowing a useful increase in power generated by the engine. When the technology developed to allow durable iron valve seats to be cast into relatively soft aluminum, thermal conductivity doubled again. As Table I shows, if neither cost nor practicality were issues, diamond would be the optimum choice in this natural progression of increasing thermal conductivity, although silver seems to be a reasonable second choice. Most of the 1947 AJS “Porcupine” racing engine was made of aluminum, for low weight, but the head was cast in silver, for high thermal conductivity. Notches were cut in its cooling fins to maximize the surface area and hence its ability to transfer heat to the air. However, since pure silver is soft, a silver alloy was used to make the material sufficiently hard and durable for use in a racing engine. Unfortunately, by the time sufficient material was alloyed with the silver to attain the required strength, the resultant thermal conductivity had been reduced to that of an aluminum alloy, so the use of silver was quickly abandoned. However, this episode does show that where high-performance motorcycles are concerned, the cost of materials is not a significant factor.

By the 1920s, the excess heat generated by high-performance motorcycle engines was reducing the strength of valves to the point where the heads of the valves were being pulled from the stems by the force exerted by the valve springs. One solution developed at that time was to make the valve stem hollow, then partially fill it with sodium, a low-density material that also has a low melting point and a high boiling point. Under normal operation of the engine, the sodium will alternately hit the hot region of the valve, extract heat

Table I: Thermal Conductivity and Density of Selected Materials.

Material	Thermal Conductivity (W/cm K)	Density (gm/cm^3)	Approx. Weight of Head[a] (lb)
Carbon steel	0.61	7.9	25
Iron	0.80	7.9	25
Brass (60% Cu, 40% Zn)	1.05	8.2	26
Al alloy (0.6% Mg 0.6%, 0.4% Si)	2.00	2.7	9
Aluminum	2.37	2.7	9
Gold	3.15	19.3	61
Copper	3.98	9.0	28
Silver	4.27	10.5	33
Diamond	9.07	2.3	7

[a] Assuming a 500 cc single-cylinder engine.

from it, then hit the cooler end and deposit that heat to be conducted away. Later, in the 1950s, Velocette was one of the first manufacturers to use the Ni-based nonferrous "Nimonic" alloy, developed for jet-engine turbine blades, for exhaust valves in its racing motorcycles.

The steels used for valve springs were a major limitation to the performance of engines, until vacuum melt processes were developed in the 1950s to extract impurities from the steel. If there were no limiting factors—the most significant of which are the amount of air that can be drawn into the combustion chamber and the strength of the connecting rod—the power generated by an engine would increase linearly with rotational speed (rpm). Thus, neglecting all other factors, the faster an engine can be made to turn, the more power can be generated. Unfortunately, through at least the 1950s, valve springs often would fatigue and break when engines were operated for significant periods of time much above 8000 rpm. Different geometrical configurations were developed to reduce or eliminate this problem: four valves per cylinder in the 1937 Rudge Ulster, each with a smaller and therefore more robust coil spring than required for a two-valve head; hairpin-shaped springs in the 1956 Manx Norton; and torsion bars in the 1965 Honda CB450 are several examples. However, once materials scientists developed vacuum-melted high-purity spring steels, the rpm of the engine was no longer limited by valve-spring breakage. For example, the Honda CBR600RR shown in Figure 2 operates at 15,000 rpm without problems with its valve springs.

Iron is an excellent material to use for the cylinder of an engine. With the right amount of carbon in it, the material is self-lubricating, so the piston rings do not abrade, while sealing in the hot gases. The problem with iron, however, is that it is very heavy. A lighter material like aluminum would be preferable, except that it has far less abrasion resistance than steel. In one recent development, aluminum has been impregnated with a ceramic graphite composite to combine the weight advantages of the aluminum with the tribological properties of the composite. In the Nikasil process, patented by the Honda Motor Co. in 1998, SiC in a Ni matrix is bonded to a lightweight aluminum cylinder.

A good material to use for the crankcase of a racing engine is magnesium, due to its low density. Because Mg does not resist corrosion well, it is usually anodized or painted to protect it. Although Mg has a lower density than aluminum and thus its use reduces the weight of the motorcycle, Mg is more expensive than Al and it is much more difficult to work with because it burns at 454°C in air. However, these practical difficulties are offset by its weight advantage, and as a result, Mg alloys have been used in many racing engines, such as the crankcase of the 1962 Matchless G50.

Materials Issues

To understand the selection of materials for constructing racing motorcycles, it is useful to look at tensile strength, or the specific strength, which is the tensile strength normalized to the density of the material. As Table II shows, strength and cost typically scale together.

The governing bodies that sanction races typically specify limits on both the maximum displacement of the engines as well as the minimum total weight of the machines. However, the minimum weight limit does not eliminate the use of the highest technology in materials, because the location of the weight also matters greatly. For maximum maneuverability, a motorcycle must have as low a center of gravity as possible; to prevent the torque applied to the rear wheel from elevating the front wheel and thereby constraining the rider from applying even more power, the center of gravity should also be as far forward as possible. The higher specific strength of the materials now available provides designers with more parameters to position the center of gravity for best performance without increasing the overall weight of the machines.

Substituting aluminum for cast iron in a part doubles or triples its strength while reducing the weight by one-third, but it does so at a fivefold increase in cost. While

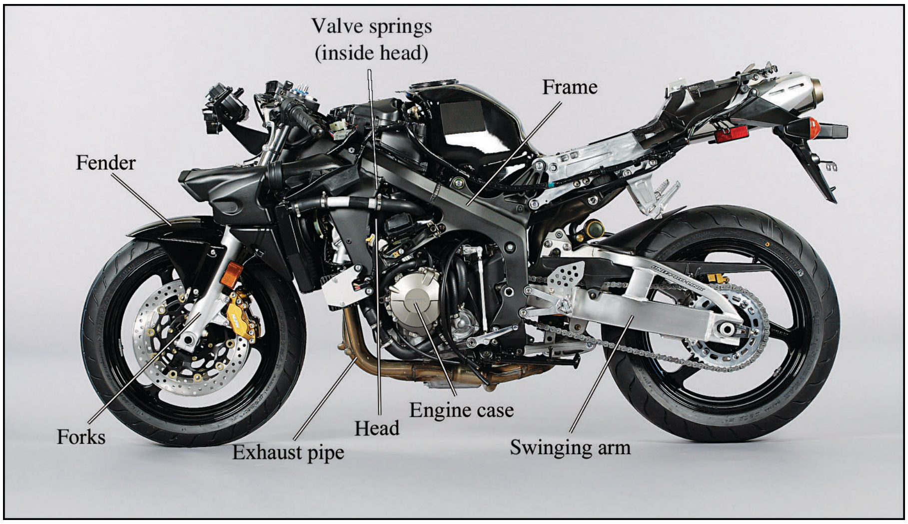

Figure 2. The 2003 Honda CBR600RR with its fairing (front and side bodywork) removed, showing most of the major components discussed in this article. (Courtesy of American Honda Motor Co. Inc.)

Table II: Tensile Strength of Selected Materials Used in Motorcycle Construction.

Material	Specific Strength (N m/kg)	Max. Working Temperature (°C)	Relative Cost (cast iron = 1)
Cast iron	52	300	1
Stainless steel (18% Cr, 8% Ni)	98	600	8
Tempered steel (0.5% C)	119	550	5
Aluminum alloys	70–155	180	5
Magnesium alloys	105–125	*	*
Nimonic 115 (Ni alloy)	134	900	*
Titanium alloy (6% Al, 4% V)	280	500	25
Maraging steel	299	*	*
Carbon-fiber-reinforced resin	1140	~200	30

Note: Specific strength = tensile strength/density.
* Data not provided.

Figure 3. A composite low-friction synthetic polymer, deposited on a bronze substrate for rigidity, provides the load-bearing surface of a 45-mm-diameter bushing. (Courtesy of American Honda Motor Co. Inc.)

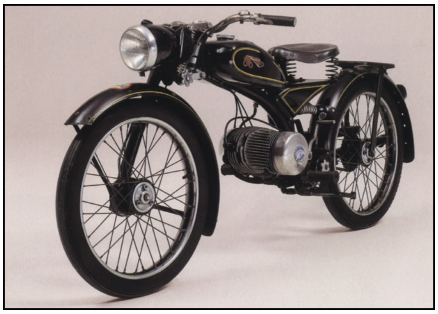

Figure 4. The 1949 Imme R110, designed to economize on the use of materials by incorporating such innovations as single-sided front and rear suspensions, the latter serving double duty as the exhaust pipe. (Courtesy of the Solomon R. Guggenheim Museum.)

there is no cost advantage to making this substitution, the savings in weight is clearly a performance advantage. Carbon-fiber-reinforced resins also exhibit much higher specific strength than standard structural metals, but at a much higher cost. The entire front fork assembly as well as the wheel rims of the 1995 Britten were made with carbon-fiber composite to gain that weight advantage over the competing materials, which would have been steel or aluminum. This sort of weight-saving substitution can be, and is, carried to extremes. A plastic front fender on a motorcycle weighs only a few ounces, so the weight saved by replacing it with one made of carbon fiber is tiny. Even though the cost increases greatly when carbon fiber is used for such a purpose, a significant number of buyers are willing to pay that cost for even a trivial performance increase. As a result, carbon-fiber components are to be found on many of today's production motorcycles.

The 1932 MGC featured a fuel tank made from cast aluminum. Taking advantage of the relatively thick and strong aluminum casting, the designer, Marcel Guiguet, was able to form a fuel tank that also served as the main structural backbone of the frame. Unfortunately, the tungsten–inert gas (TIG) welding process, which prevents the formation of aluminum oxide, had not been developed at that time, so Guiguet had to resort to crude aluminum struts bolted to the tank to connect it to the rear portion of the frame. Today, thanks to finite element analysis, a designer can optimize the design of every curve and segment of a complex frame and then use robotic welding to form the individual components into an overall frame of whatever complexity is needed.

The forks of a motorcycle have to compress and extend to absorb the irregularities of the road. To absorb even the smallest irregularities requires the surfaces in contact with the bushings in the forks to have the lowest possible coefficient of friction. One approach to accomplishing this has been to deposit a titanium nitride film on the polished steel of the fork legs. The expense of the process to deposit this material is irrelevant in terms of the increase in performance. For roughly $30,000, the 180-mph 2003 Ducati 999R has TiN-coated fork legs, a magnesium headlight assembly, and the entire fairing—the bodywork surrounding the front and sides of the motorcycle—is made of a carbon-fiber composite. Since the bushings in the forks also contribute to the friction, a recent development from Honda is a composite synthetic polymer/metal (Syntallic) bushing designed so that the coefficients of both static and dynamic friction are as close to zero as possible (Figure 3).

The 2001 Honda "New American Sports" concept motorcycle was designed with a single-sided front fork and rear suspension. This asymmetric design requires a very high-strength material for support. The front fork is made from a carbon-fiber composite and the leg is TiN-coated. This is not the first time such a single-sided front suspension has been used, although in an earlier example, the designer was more interested in saving material than in achieving high performance.

In the late 1940s, industrial production in Germany was still recovering from the war, and engineering materials were in short supply. In this economic climate, Norbet Riedl designed the 1949 Imme R110 with a single-sided front suspension (Figure 4).

While the fork leg of the Imme was significantly heavier than that of an individual leg of a standard set of forks, the fact that only one was required reduced the overall amount of material needed for the front suspension. Riedl's clever use of materials extended to other components. The exhaust pipe of the Imme was made from much thicker steel than normally would be used for this component, but by doing so it was able to simultaneously serve as a single-sided rear-suspension leg. We can speculate that Riedl got the idea for his front suspension from the design of the single-strut landing gear of the Messerschmitt Me109, the most widely used fighter plane flown by the German Air Force during World War II. Aircraft design, especially that of fighter aircraft, has many of the same requirements as motorcycle design: the highest quality materials, at the lightest weight, with the highest performance. The design is further enhanced whenever an individual component can serve more than one function. Other examples could be cited, such as the rotary engine of the 1922 Megola, or the styling of the 1957 Aermacchi Chimera, where aircraft technology directly led to developments in motorcycle technology.

Magnetic properties of materials play an essential role in ignition systems. Until the early 1960s, most high-performance motorcycles used magnetos for their ignition systems, since this device eliminates the weight and potential unreliability of a battery. A magneto generates the high voltage for a spark plug by simply spinning a coil of wire in a magnetic field. (Although this statement is true in principle, to actually understand the operation of a magneto in detail would require a lengthy treatise.) Since the larger the magnetic field, the smaller the coil needed to generate a given voltage, and thus the smaller and lighter the total magneto, it is quite advantageous to use magnets that have the highest available energy product (magnetic field B times magnetic intensity H). As a result, during the first half of the 20th century, when magnetos were essential components in racing motorcycles, these electrical devices were at the forefront of the use of the latest magnetic materials. Magnetos moved through steels of tungsten, chromium, cobalt, and then nickel, then quickly made the transition to Alnico shortly after it was developed in the 1930s. The anisotropic grain structure in this family of aluminum-nickel-cobalt alloys gives it particularly favorable magnetic properties. Subsequent improvements in varieties of Alnico continued to be incorporated until the early 1960s, when the magneto itself ceased to be used in the latest racing motorcycles.

The same principle of rotating a coil of wire through a magnetic field is used to generate electrical power for auxiliary functions like lights. Today's sporting motorcycles are expected to supply over 500 W of electrical power, five times that of a similar-weight machine of only 30 years ago, and improved magnetic materials have helped make this possible without an unacceptable increase in the weight of the electrical system.

Antilock brakes have certain advantages for some motorcycles, but the additional weight of the system is a significantly more serious problem than it is for a much heavier automobile. However, small sensors based on high-performance giant-magnetoresistance materials for determining wheel speed are now commercially available, and antilock braking systems are being incorporated in an ever-wider number of motorcycle models. For some years, magnetic sensors have been common items on racing motorcycles, used in data-acquisition systems that monitor suspension travel in order to rapidly determine for each racetrack the optimum spring rates and compression and rebound settings for the shock absorbers.

A Materials Story of Social Significance

Industrialized Countries versus Developing Nations

In this article, I have mostly addressed some of the highest levels of materials technology available, as used in racing and sporting motorcycles. In industrialized countries, a typical consumer wants a motorcycle with the highest possible horsepower and the lightest weight, along with a stylish appearance and innovations like antilock brakes. To meet these goals, typical construction materials may include high-Si-content forged-Al pistons, pressure-cast Al engine heads, Ti for valves and rods, alloy steels for other engine parts, Mg for engine and frame components, and carbon-fiber composites for the body parts. However, in large parts of the world, motorcycles have a very different function, where they often provide the only means of personal transportation. In a developing country, motorcycles must be inexpensive, easy to maintain, and able to operate on low-octane fuel. Thus, the materials for their construction are cast iron for cylinders, gravity-cast Al for engine heads, low-grade steels for engine parts, and cold-drawn-steel tubing for the frame.

In the future, new materials and fabrication technologies will play a major role in the motorcycles of both industrialized and developing nations. In the former case, higher-strength composite materials would allow designers to produce smoother, rounder, more organic shapes, such as seen in the Yamaha Morpho concept motorcycle of the early 1990s. To the extent that such materials could replace relatively expensive metals like stainless steel, they also could help provide more people in developing nations with the benefits of personal transportation. On this subject, it is appropriate to end with a quote from the eminent physicist Freeman Dyson: "The technologies that raise the fewest ethical problems are those that work on a human scale, brightening the lives of individual people. For my father 90 years ago, technology was a motorcycle." For a significant fraction of the world's population, these words still apply today.

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