



# Frame Materials

**Version 2.1**

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**I**n the quest of building the ultimate HPV, the frame material becomes an important issue. For building the Thunderbolt and Spitfire, I have narrowed the materials down to four metals, Carbon steel, CroMo, Aluminum and Titanium. Each of these materials has its strong and weak points, as I shall attempt to point out in this chapter. I've also included a small essay on carbon composites, as this material is quickly gaining acceptance in the bicycle industry.

Throughout this chapter, I use the terms 'Tensile Yield' and 'Tensile Ultimate' to describe the strength attributes of the alloys mentioned. In laymen terms, Tensile Yield (commonly referred to as Yield strength) is the applied pressure value measured in PSI where the metal starts to bend or deform. Tensile ultimate (or just plain Tensile Strength) is the applied pressure value measured in PSI where the metal may expect to fail.

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## Carbon Steels

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**T**he most popular material for bicycle frames is carbon steel as it is inexpensive and can be welded or bonded by a number of processes making it ideal for mass production and for the home frame builder. Several grades of carbon steel exist. The grades I am familiar with are 1010, 1018, 1020, and 1028. The last two digits represent the carbon content of the steel as a 10th of a percent. Therefore, 1028 has .28% carbon, which is slightly less than 4130 CroMo. The more percentage of carbon added, the harder and stronger the steel. However, too much carbon causes the steel to become brittle. Therefore, .4% carbon is about the maximum you shall see for frame building.

For frame building, I would prefer to use 1028 if available. It offers a tensile strength of 87,000 PSI and yield strength of 72,000 PSI, which is almost as



hard as normalized Cro-Mo. However, plain old 2-inch muffler pipe might work fine if the wall thickness is suitable.

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## **Chromium Molybdenum (CroMo, 4130)**

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I do not have extensive knowledge or a lot of experience frame building with CroMo. I do understand that it is extremely tough and strong making it an ideal choice for frame building. The strength to weight ratio of fully heat-treated 4130 (most common) CroMo exceeds that of 6061-T6 aluminum. However, the lower strength 'normalized' grade of 4130 CroMo is what is widely used for bicycle frames, as it is less brittle. The best attribute of CroMo is its inexpensive cost relative to other performance materials.

Because of the alloys used for 4130 CroMo, the material must be welded using a TIG or MIG process, although it can also be brazed. The major alloys used for making CroMo are Chrome and Molybdenum. Also known as 'light alloy' steel, only 3% of alloy material is added to give this material its super strength. The designation '4130' refers to the alloy and carbon content. The '41' represents the alloy type and quantity and the '30' represents the carbon content as a 10th of a percent. Regardless of the alloy content, this metal TIG welds easily and produces great results with little effort.

As with Aluminum, 4130 CroMo has different temper conditions. Likewise, the temper levels affect the strength and characteristics of this alloy steel. As mentioned, the WQ&T 4130 is extremely strong, perhaps to a fault. For bicycle frame applications, the weaker normalized temper is used to maintain Cro-Mo's fine balance of longevity and strength (E.g., less prone to breaking). In summary, tempering restores some of the ductility that may be lost after the hardening heat treatment and quench. Alloy 4130 is tempered at between 750 F and 1050 F, depending upon the strength level desired. The lower the tempering temperature the greater the strength. This normalized temper upsets the strength to weight ratio in favor of aluminum.

<b>Temper</b>	<b>Tensile strength Ultimate(PSI)</b>	<b>Yield Strength (PSI)</b>
<b>Annealed</b>	<b>80,000</b>	<b>50,000</b>
<b>Normalized</b>	<b>90,000</b>	<b>70,000</b>
<b>WQ&amp;T</b>	<b>128,000</b>	<b>113,000</b>

For all-out performance, 4130 CroMo falls short to 6061-T6 aluminum. Many bike aficionados claim that a steel frame will always outlive an aluminum frame and is more forgiving.

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## **Aluminum (6061, 7005 and 7075)**

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Aluminum is quickly gaining ground as the material of choice for bicycles such as Trek, Cannondale, Klien and other top brands. New technologies have emerged recently that have lowered the cost of aluminum fabrication making it a strong contender to CroMo. The proverbial 6061-T6-grade aluminum is now the industry standard for quality aluminum frame composition. This is in part because this type of aluminum can be easily welded and is relatively strong. Lately, the bicycle industry has leaned towards the 7005 series of aluminum for low to medium cost frames, as this type of aluminum does not require a post heat treatment, hence lowering the cost considerably.

Aluminum is extremely easy to work and machine making frame fabrication painless. Depending on the diameter and wall thickness, aluminum tubing can be easily formed using a standard conduit bender without use of a mandrel. Since aluminum is relatively soft, it can be filed, drilled and sanded with ease.

The cost of aluminum is higher than most frame building materials. Aluminum is derived in two ways: either from ore or from recycled scrap. Due to its low melting point of 660°C (steel: 1535 °C), processing or recycling of aluminum is relatively easy. On the other hand, extraction from ore is another story. It requires that bauxite be turned into an aluminum oxide, and then converted into aluminum using electrolysis. It takes four tons of bauxite to produce one ton of aluminum. The complete process consumes almost 75 KW/hours of energy to produce a single pound of aluminum.

Home builders may find aluminum fabrication challenging as it requires a TIG or MIG process and is more difficult to weld than CroMo or carbon steel using the same process. Additionally, the 6061-T6 series aluminum loses half its total strength when welded. Consequently, a post heat treatment process is required to regain its full T6 strength. The 7005 series aluminum retains enough of its original strength (it is much stronger than 6061 to begin with) that a post heat treat is not always required.



The 6061 series of aluminum is alloyed with magnesium & silicon. However, these are only the majority of alloying elements, as other elements are included such as copper, zinc, manganese and titanium. A total of 4% of alloying elements comprise the 6061 specification. The 6061 series is divided into grades or designations that refer to the post temper process. The most common grades are T0, T4, and T6. The grades, processes and strengths are depicted below:

### 6061 Series Aluminum

<b>Temper</b>	<b>Process</b>	<b>Tensile Ultimate.(PSI)</b>	<b>Yield(PSI)</b>
<b>T0 or O</b>	<b>fully annealed aluminum</b>	<b>11,600</b>	<b>8,000</b>
<b>T4</b>	<b>Solution heat treated and naturally aged</b>	<b>35,000</b>	<b>21,000</b>
<b>T6</b>	<b>Solution heat treated and artificially aged</b>	<b>45,000</b>	<b>40,000</b>

The 7005 series aluminum is alloyed primarily with zinc, making it even stronger than the proverbial 6061. As mentioned, this aluminum does not always require a solution heat treatment, as it loses less of its overall strength when annealed. An artificial aging treatment is all that is required making this aluminum desirable for frame builders who don't have heat-treating resources. On the downside, some metallurgist suggest that any of the 7000 series aluminums (although a stronger aluminum) do not stand up to fatigue as well as the 6061 series aluminum. Perhaps this is why no one has produced a heat-treated 7005 aluminum frame, as it may lead to premature failure. Therefore, it is predictable that a 7005 aluminum frame may not hold up as long as a heat-treated 6061 frame.

### 7005 Series Aluminum

<b>Temper</b>	<b>Process</b>	<b>Tensile Ult(PSI)</b>	<b>Yield(PSI)</b>
<b>T0 or O</b>	<b>fully annealed aluminum</b>	<b>28,300</b>	<b>11,600</b>
<b>T6</b>	<b>heat treated and artificially aged</b>	<b>50,800</b>	<b>42,100</b>

Just for conversation, I'll also mention the 7075 series aluminum. As with 7005, this type of aluminum is heavily alloyed with zinc making it incredibly tough and strong. However, it has so much zinc, it cannot be easily welded, making it's use limited to machined components or glue bonded assemblies.

In closing 6061-T6 aluminum is .29 the weight of normalized 4130 CroMo steel and is .4 times as strong. Hence, aluminum's strength to weight ratio is higher.

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## Titanium (3Al-2.5V)

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3Al-2.5V titanium is an exotic alloy metal that has properties roughly that of 315 Stainless steel. However, this alloy is almost half the weight and is as strong as 4130 CroMo. As with aluminum, titanium metal is not found as a free element. However, it is the ninth most abundant mineral in the earth's crust. It is usually present in igneous rocks and in the sediments derived from them. It is found in the minerals rutile (TiO<sub>2</sub>), ilmenite (FeTiO<sub>3</sub>), and sphene, and is present in titanates and in many iron ores. The energy and process to produce titanium makes this metal very expensive.

The 3AL-2.5V series of titanium alloy is 40 to 60% stronger than unalloyed titanium. The main alloys in this series include aluminum and vanadium.

Back in the mid '70s, Teledyne manufactured the first commercial titanium bicycle frame called the "Titan". Although a technical marvel (extremely light frame in its day), the Titan was plagued by reliability problems and production was short lived. This negative publicity gave titanium the reputation as an exotic, over-priced, and unreliable material for bicycles. The root cause of the Titan's demise was the type of titanium used. Back in the mid '70s high performance titanium alloys were not commercially available. It would be another 15 years before the 3Al-2.5V series of titanium alloy would become readily available to the consumer market.

With the advent of the 3Al-2.5V series of titanium alloy, many bicycle manufacturers have produced frames of unequalled performance. The 3AL-2.5V series of titanium alloy is 40 to 60% stronger than unalloyed titanium. The main alloys in this series include aluminum and vanadium. There are other titanium alloys much stronger than the 3Al-2.5V series, but these alloys are difficult to weld and machine.

### 3AL-2.5V Titanium

Process	Tensile Ult(PSI)	Yield(PSI)
Alpha annealed	90,000	72,500
ST 925 deg. C, Aged at 480 deg. C	132,500	120,000

For manufacturing, titanium presents a few challenges. First, the metal is extremely tough and doesn't machine as easily as 4130 Cro-Mo or aluminum. Many machinists have compared its qualities to that of nickel or hardened stainless steel. Secondly, when molten titanium is subjected to oxygen (>1130 c), it produces a titanium dioxide making the structure extremely brittle. TIG welding titanium requires intense consideration, as any heated zones of the weld (both upper and lower sides) must be in a total inert



environment, free of oxygen. Once an inert environment is made, titanium welding is comparable to stainless steel. Last, a post heat treatment is required for ultimate strength.

In summary, the finest, most expensive bicycle frames produced today are made of titanium. Building frames from titanium is not for the novice or intermediate skilled person, as it requires following intense processes and having sophisticated resources.

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## Carbon Composites

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As a former aerospace Engineer, I've had the opportunity to work intensively with a variety of exotic structural materials. One of the most fascinating materials used was Composites. Composites include Kevlar or graphite fiber mixed with epoxy. Kevlar composites have been used in the aerospace industry since the mid'60s, while Carbon composites are a bit younger. Composite construction is similar to fiberglass. Therefore, the part dimensions can be molded into the part. In aerospace applications, carbon composites have replaced aluminum as a staple material, as it is lighter, can be formed into any shape, and can resist fatigue.

Carbon composite shapes and sizes are almost limitless making the design uncompromised to anyone's imagination. The strength and durability are phenomenal. The chief concern with composites is manufacturing defects. This is the number one root cause for failure, with inadequate design being number two. Although one might think that good design practices and process control could alleviate these problems, they still exist. Efficient composite designs require reducing the amount of epoxy resin from the carbon fibers, and orienting the fibers strands to produce the maximum amount of strength. In my experience, most composite home projects produce machines having more emphases on artistic qualities than performance.

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## **CroMo Vs. Aluminum**

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In the bicycling community, a lot of debate is being stirred up between the use of Aluminum and 4130 CroMo. Each material is popular and both have good and bad points as presented in this chapter. However, I wish to dispel some unfounded myths between the two.

### ***CroMo is stronger than Aluminum.***

Yes and No. The strength to weight ratio of WQ&T 4130 CroMo is slightly more than 6061-T6. However, it is unlikely a frame builder would choose this temper for building bike frames. Even so, the strength difference of the highest temper is about even with 7005-T6 aluminum, with aluminum taking the advantage. In practical applications in frame building and design, aluminum has a much higher strength to weight ratio to CroMo.

### ***Aluminum frames tend to crack more easily than Steel.***

False. First, aluminum frames are generally manufactured as a medium to high-end market. Therefore, the fabrication is of higher quality. Up until recently, the same was true with CroMo, but since new manufacturing technologies have evolved, a CroMo frame is now found on many low quality bicycles. Obviously, a low quality frame with marginal workmanship has more of a chance of failure than one of higher quality. Secondly, aluminum frames are built lighter than CroMo making them more susceptible to breakage. This gives the impression that aluminum breaks easily. Lastly, many CroMo frame builders do not post heat treat their frames making them weak. In the last 25 years, many aluminum frame designers (such as myself) have learned to use oversized tubing and web gussets to reduce tube flexing. The major cause of failure with aluminum is fatigue caused by over-flexing. Unlike CroMo, aluminum is not resilient and shall eventually fail if allowed to over flex. Using a rigid frame design, aluminum becomes a very reliable material.

Aluminum is used extensively in commercial aircraft. Although recent material science has displaced some aluminum applications in favor of composite materials, the use of CroMo in the aircraft industry is diminishing.





***Aluminum frames do not last as long as CroMo frames.***

True. The use of aluminum in mass production bicycles is only recent. Therefore, not enough data exist to compare aluminum to CroMo. It is theorized that a 6061-T6-aluminum frame shall eventually fail as the aluminum ages over time and becomes brittle. This aging can be reversed by re-heat treating the frame (a costly undertaking). It should also be noted that CroMo frames could rust, eventually leading to premature failure. However, this condition can be prevented by performing periodic maintenance. More importantly, the attributes of aluminum allow frames to be designed much lighter than they should be. Although the strength to weight ratio of aluminum has a slight advantage over CroMo (it is approx. 15% lighter at the same strength), a frame designed with little margin has the opportunity for premature failure.

Earlier aluminum frames used a bonding process that glued the tube into a lug. These frames were infamous for their tendencies to fatigue and crack. Additionally, they were fabricated using small diameter tubing causing the frame to flex easily. Today, a small number of aluminum frames are still bonded. However, the processes have been refined and the tubing diameters have been increased to provide a rigid more reliable frame. Additionally, these frames use the stronger 7075-T6 aluminum. Some of the lightest frames available (with the exception of composites and titanium) are made from bonded 7075-T6 aluminum. Although the 7075-T6 aluminum has a much higher strength to weight ratio, it does have a higher tendency of cracking than 6061 T6.

These facts only prove that the reliability of a bicycle frame is more dependent on the quality of the design and manufacturing process rather than the type of material it is made of.

***Aluminum corrodes***

Yes it does. The 6061 series of aluminum has good corrosion resistance. However, if left partially submerged in salt water it will eventually corrode. Once aluminum is placed in an oxygen environment, it builds a protective layer of oxidation. Although this layer plays havoc during any welding process, it does protect the aluminum from many outside elements. As for bicycle frames, this corrosion is benign, as it possesses no threat to the structural integrity. The same cannot be said about steel, as it can and will rust. If left unchecked, a rusting steel frame shall fail.





## ***Aluminum frames are lighter than CroMo frames***

This is generally a true statement, but not always true. As pointed out, WQ&T 4130 CroMo has a strength-to-weight ratio advantage over 6061-T6 aluminum. However, very few bicycles are built completely out of 4130 CroMo. Most cases, mild or low carbon steel are used for lugs, crowns, dropouts, and various tubes on the frame. Secondly, most 4130 CroMo frames are not heat-treated. In order to retain ample strength at the welded seam, the tube wall thickness is increased making the overall frame heavier. Last, as mentioned throughout this chapter, the weaker normalized temper of 4130 CroMo is used for frame building. All three of these statements result in a steel frame that is heavier than aluminum. Only the finest steel frames can rival aluminum frames in lightness.

Ultimately, the frame designer decides how much the frame weighs and how strong it's going to be.

## ***The facts about Aluminum and CroMo***

1. Aluminum cost more than CroMo
2. CroMo is relatively inexpensive (cost a fraction more than carbon steel)
3. Aluminum welding requires a high degree of skill than CroMo, aluminum cannot be brazed.
4. CroMo (4130) can be brazed, TIG, or MIG welded, but is difficult to weld with an oxyacetylene torch.
5. Aluminum frames do not rust, CroMo and Carbon steel do rust.
6. CroMo is difficult to machine
7. Aluminum tubing comes in a much wider range of sizes and thickness than CroMo
8. Aluminum is a reliable metal; after all, most aircraft use aluminum, go figure.

From the arguments covered, you must obviously think I am biased towards aluminum. Could it be that many quality bicycle built today are made of aluminum? CroMo is indeed great for a small shop, as it requires little resources to work with. However, for lightweight and strength performance, it is taking the back seat. On the other side of the coin, aluminum is being eclipsed by carbon composites and titanium alloy frames. The reliability of these two relatively new materials is yet to be proven.



My preference for building recumbent trikes out of aluminum is because I am one of the few HPV frame builders who have mastered the technique of aluminum welding and manufacturing. Most HPV or recumbent manufacturers rely on working with CroMo as it takes little skill to TIG or MIG weld this material and it is cheap. In my opinion, an aluminum frame properly welded is a work of art that has no steel equal.

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## Closing

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**I**n this chapter, I have presented all the materials currently used for building bicycle frames. I have placed these materials in hierarchy order based on their performance potential, as applied for constructing a recumbent trike. To cover all bases, I'll mention that companies such as Columbus and Reynolds produce specialized steel tubing that exceeds the specifications and performance of commercially available CroMo. Obviously, the performance of these alloys deserves praise, but because of their specific application they have no purpose in this discussion.