Metals – Aluminum   http://www.bikepro.com/products/metals/alum.html

Aluminum is used for many parts on bicycles because of its desirable properties, which include low density (light weight), high specific strength (which is commonly known as strength-to-weight ratio), its resistance to corrosion, and in the case of brake pad holders and rims, its thermal conductivity. Aluminum has approximately one third the density of copper or steel, which is why its used where weight is an important consideration, like bikes. While it has just 50% of copper's thermal conductivity, it has four times that of low-carbon steel.

Aluminum is extracted electrolytically from bauxite ore. It is made by the electrolysis of aluminum oxide which is found in larger concentrations within bauxite ore. Bauxite is a mixture of the hydroxides of aluminum, together with other impurities such as oxides of iron, titanium, and silicon. Bauxite is produced by the weathering and change of aluminum silicate rocks usually found in tropical and semitropical regions where climate has produced an accelerated weathering process. Bauxite is not a rare ore and is widely available in the US, the Caribbean, and Europe. Approximately 4 pounds of ore are required to produce 1 pound of aluminum. The process used almost universally to purify bauxite is the Bayer process, which separates aluminum dihydrate from the bauxite and then uses a calcination process to convert it to oxide of aluminum, which has 2 aluminum and 3 oxygen atoms.

The aluminum oxide is dissolved in electric furnaces, (resembling melting pots) in a molten bath of sodium-aluminum fluoride at 940 to 980 degrees centigrade (1725 to 1800 degrees fahrenheit). Using a method developed by Charles M. Hall in 1886, the furnace pots are made of carbon lined steel. The carbon is also an electrode, in this case an anode, and current introduced through it electrolytically separates the aluminum and also provides the heat necessary to keep the bath molten. With electricity applied, the oxygen in the ore combines with the carbon in the pot, leaving at the bottom of the pot or vessel 99.9% pure molten aluminum. The molten aluminum is removed periodically from the bottom of the furnace or "cell" as it collects. It takes approximately 9 to 10 kilowatt hours of electricity to make each pound of aluminum, for that reason aluminum refining is done in areas of the world where electricity is relatively cheap. The molten aluminum, once siphoned off, is poured into molds to form what is known as a primary ingots. If alloying with other metals is desired, the molten aluminum is sent to a remelt furnace where pure alloying elements or master alloys (concentrated alloys within an aluminum base) are added to produce the desired aluminum alloy. The alloyed aluminum is then poured into molds to make primary aluminum ingots.

Aluminum Casting / Wrought

The ingots can be remelted to make cast aluminum products, using various methods of casting including (in the bike industry), die casting where molten aluminum is injected under high pressure into the cavity of a metal die. Aluminum alloys have a reasonably low melting point which makes a dense, fine-grain surface structure with excellent wear and fatigue properties when die cast. Also permanent mold casting may be used, which uses a metal mold repeatedly for producing many castings of the same form. These casting techniques are the way many crank arms, pedal bodies, hub shells, seatpost head pieces, stems, and some headset parts are commercially made in volume.

The ingot can also be mechanically "worked" to make "wrought" aluminum products. The designation "wrought" indicates that the aluminum, when it leaves the mill, takes the form of a worked product, which includes, sheet, foil or plate aluminum. It also includes rod, bar, or tubing, and includes extrusions, and some forgings. The transformation from ingot to wrought product is known as "working" the metal. The working operations and thermal treatments transform the cast ingot's metallurgic structure into a wrought structure whose "grain" and crystalline structure may range from fully recrystallized (re-melted) to fibrous depending on the metallurgic characteristics of the alloy, the work techniques employed, and the product manufactured. This metallurgic structure influences the strength, corrosion resistance, and several other properties of the finished good. For bicycle purposes, we find wrought aluminum must generally be machined again and assembled into the finished bicycle part. This is the basic material, in its many forms, that is used by small run, or one-off manufacturers of bicycle parts. The wrought alloy pieces are what the more expensive after market replacement parts are engineered and machined from, including, hubs, seatposts, stems, bottom bracket cups, headset parts, some pedal bodies, nearly all aluminum handlebars, all rims, many expensive crank arms, and the alloy rail assembly found in a few saddles.

Another technique for aluminum alloy manufacture is known as "P/M" or Powder Metallurgy. This process involves compressing under great pressure and heat, a powdered form of the alloy within a shaped die. The compressed powders at high temperature densify into a solid, shaped "piece". This technique could be used effectively to mass produce headset cups.

Alloy Composition/Designation

Aluminum alloy composition designations, in the United Sates, are made under the guidance of the Aluminum Association. The major aluminum producers have agreed upon a four digit numerical system for designating specifically the composition of wrought aluminum and aluminum alloys, while a three digit system is used for casting aluminum alloys. The first of the four digits in the alloy number indicates the alloy group which identifies the primary alloying element or elements within the alloy.

The 1XXX group is at least 99% pure aluminum

The 2XXX group is alloyed primarily with Copper, which is added for higher strength but reduces the corrosion resistance

The 3XXX group is alloyed primarily with Manganese, for moderate strength

The 4XXX group is alloyed primarily with some Silicon to lower the melting point and increase fluidity for casting

The 5XXX group is alloyed primarily with Magnesium to make a moderate strength alloy

The 6XXX group is alloyed primarily with both Magnesium and Silicon to make a moderate strength alloy

The 7XXX group is alloyed primarily with Zinc to make a high strength alloy.

The 8XXX group is used to indicate an alloy whose primary alloy element is other than those above

In the alloys designated from the 2XXX to the 7XXX group, the last two digits identify the uniquely different alloys in the series. As new alloys become commercially available, the last two digits are assigned consecutively beginning with XX01, (wouldn't you think they would be running short on these by now?). The two digits bring with them a specific chemical composition range, which must be adhered to.

The second digit indicates any modifications in the composition of the original alloy used. If the second digit is "0", zero, there have been no modifications made to the original assigned and designated alloy. If modifications are made to the original alloy, integers 1 to 9, which are assigned consecutively, are used to indicate the modification, and note commonly its existence. New, experimental aluminum alloys are grouped with the appropriate 1XXX to 9XXX series above but are prefixed with an "X". The "X" is discontinued when the alloy becomes standard.

Do not make the mistake of believing that a higher alloy designation number means the aluminum alloy is stronger, harder, or more resistant to failure. Sometimes that is true but the alloy's temper also says something about its strength, and hardness.

Temper

Aluminum alloys are sometimes "tempered". Tempering is the process of raising the alloy's hardness. The vernacular term for temper in the bike industry is to say that it's "heat treated", which is borrowed term from the aluminum industry, but the words don't reflect the actual process which might better be called "solution heat treatment" or "thermal treatment".

Temper designations for aluminum and its alloys fall into two general categories, which depend on the alloy's responsiveness to heat treatment, the heat-treatable and the non-heat-treatable. The non-HT type generally fall into the 3XXX and the 5XXX series, which owe their strength to the hardening effects of either manganese or magnesium. They can be strengthened however by cold working. The 2XXX, 6XXX, and 7XXX series which have copper, magnesium, and zinc along with small percentages of other elements are known as heat treatable alloys.

These alloying elements show increasing solubility in aluminum at raised temperatures, the alloys can be strengthened through "solution heat treatment", also known as "thermal" or "heat" treatment. The alloy can also be strengthened through "strain hardening".

Strain Hardening

Greater strength can be achieved through "cold working", where the alloy can be subjected to a "strain hardening" or "work hardening" process. Cold working involves mechanically changing the shape through rolling, drawing, straightening, or flattening the aluminum into another shape, without re-melting it. When the alloy is re-melted, it is said to be "recrystallized". (Strain hardening increases the strength and hardness of a metal, and correspondingly decreases its "ductility", making it less able to stretch or bend, in essence, making it more brittle.)

Remember, metals, like many other compounds, are made from a crystal structure. The sides of the crystal lie next to one another with common flat surfaces or "planes". As the crystals of metal grow, while cooling, they clump into smaller masses of cooling metal, until the piece reaches a common lower temperature. The "clumps" take the form of "grains" within the metal. The grains have crystallographic planes in various orientations. The grain of the metal, when cooled, establishes the reasonably stable structure of the metal. When the metal is cold worked, the crystal forming the grain shears or "slips" along the crystallographic plane, against one another, leading to an even more stable structure. With increased cold working the grains elongate in the direction of the "work".

The greater the metal is squeezed to reduce its original cross section the more elongated the grains become. This increases the density, squeezing the grain, reducing what ever space exists microscopically. The crystals are forced to "slip" against one another to further compress out microscopic space. Extreme cold working leaves very few crystallographic planes unaffected by this "slip" as the hardness, yield strength, and tensile strength increase. Remember, increased strength decreases ductility. Cold working, or strain hardening of metal changes its internal grain characteristic. The metal parallel to the direction of cold working, (the direction that the metal squeezed, elongating its grain), exhibits an increase in tensile strength, yield strength and hardness. The opposite occurs when these properties are measured in the perpendicular or transverse direction.

The concept of metal having grain directional properties is called "anisotropy" Anisotropy is desirable if the cold worked metal is "loaded" (having applied force), in a way that uses the increased strength developed in the cold working direction. Metal that has this increased strength in all directions, not just the worked grain, is said to be "isotropic" and is generally achieved through "annealing heat treatment". This process consists of heating the metal to a suitable temperature, holding it at temperature, and then cooling it at a suitable rate. During the annealing, the metal reverts back to a softer condition with three major changes occurring to the crystal and grain structure, which are known as recovery, recrystallization, and then grain growth. In essence you've begun the process over again.

Solution Heat Treatment

But what is "solution heat treatment" and this "solubility"? This process involves heating the aluminum alloy to a temperature where the alloying element or elements are dissolved into what is known as a "solid solution". Solution heat treatment, referred in some cases to as "heat treated" is really the fine melding of the alloy metal at a specific temperature. Not all alloy compositions are capable of combining this way, when alloy elements are known to not dissolve at elevated temperatures to a solution this way, they are said to be "insoluble".

Pure aluminum, for example, can't be strengthened through thermal treatment because there are no alloying elements. The solution heat treatment process consists of heating the aluminum and the alloying elements up to an appropriate temperature to dissolve the elements in the aluminum. Time and temperature control are an important part of solution heat treatment. During the heating the alloy must approach, but not quite reach, the melting point. The beginning of melting temperature is known as the alloy's "solidus". To obtain the full effect of solution heat treatment, the importance of temperature regulation can't be understated, if the alloy temperature is not controlled well, there is the possibility of localized melting, which is referred to as "burning".

When an area of the alloy actually melts, you find that area of the has now expanded from the heat. Later as the metal cools, the tiny areas where the localized expansion occurred through melting, shrink. This shrinking leaves a tiny void in the metal which will be very effective in causing a failure from stress, or fatigue in the future finished product. For this reason, "burned" metal is near valueless, good only for its foundry scrap value. In this combining process, the more sluggish the alloying elements are to dissolve, the higher the temperatures must be, some solution treatment temperatures reach up to 1,000 degrees fahrenheit. When the aluminum has decomposed the alloying elements, the structure is called a "solid solution", which usually takes between 2 and 3 hours to form.

Solid solutions are formed when the base or "solvent metal" (aluminum) incorporates atoms of the alloy element or "solute metal". The final step of solution heat treatment is to "quench" or cool the material (rod, bar plate, extrusion) rapidly with hot water to lower the material to room temperature. Lowering the temperature "arrests" the structure of the metal obtained from the thermal treatment. Small parts may be dipped in hot water, while large pieces can be sprayed with hot water. Hot water is used because cold water has been found to develop small cracks in some wrought aluminum pieces. The required rate of cooling is more critical for some alloys than others, also the thickness in cross section of the piece affects the cooling rate, in some instances just still air may be adequate. At this point, the cooled alloy in the solution treated condition, is in most cases fully "annealed", rendering the metal both less brittle and more soft.

"Cold working", (discussed above), may be carried out after the solution heat treatment to increase the metal's strength, however, properties of the solution heat treatment alloy may spontaneously change with the passage of time at room temperature. The solution treated alloy may noticeably increase in strength due to a phenomenon called "precipitation hardening". The alloy, on its own, will naturally harden and strengthen from this solution treatment process through this "precipitation hardening" or "age hardening" process.

Precipitation Hardening or Aging

Some aluminum alloys begin the aging process almost immediately after they are quenched in the solution heat treatment process. After a period of a few days aluminum alloys become considerably stronger. Those alloys that contain magnesium and zinc or magnesium and silicon continue to age harden over a long period of time at room temperature. As soon as the alloy reaches room temperature, the elements added to the aluminum in making the alloy, begin to form fine particles within the crystal and at the grain boundaries.

Technically the added alloy elements are known as "phases" and the action of their separating out of the alloy microscopically is called "precipitation". More technically, for chemistry students, the alloy has become "supersaturated", meaning at the lower room temperature the alloy is less capable of carrying the dissolved phases and the phases, in attempting to separate, or precipitate out, are trying to reduce the saturation content. In most alloys, precipitation occurs very slowly at room temperature and becomes even slower at lower temperatures where molecular movement is more difficult. In fact, this precipitation action in most alloys can be completely stopped or "arrested" by lowering the metal to subzero temperatures. The converse is also true, if the temperature of the solution treated alloy is raised, the action is greatly increased and the process can be completed in relatively short time.

When the "precipitation" or "aging" process is allowed to be completed at room temperature, over the necessary period of time, it is known as "natural aging". When the aging process is performed in heated or "elevated temperature" conditions, it is said to be "artificially aged". Whether the aging process is performed naturally or artificially, the metal's structure goes through a similar change and a submicroscopic precipitate will form throughout the grain structure. The larger the precipitate formation, the less opportunity there will be for atoms to dislocate into a cluster of "slip planes". With fewer common planes for the slip to occur, the metal structure becomes more stable, which to the outward examiner would be noted as increased hardness, tensile strength, and maximum yield strength.

Actual Temper Designations

Now that we have you up to speed on what the aluminum alloy hardening processes actually are, and the terms are all defined, we can now tell you what the most used temper designations are and what they really mean. Temper designations occur as a suffix at the end of the alloy's numeric designation, an example would be 6061-T6, the "T6" is the temper designation.

Remember when we started this process, you probably thought "heat treated" had something to do with flame or a torch.

F - means the alloy is "as fabricated", no special control over strain hardening is noted

O - means that is has been annealed only, the alloy has been recrystallized, this is the softest temper

H1 - means that it has strain hardened only

H2 - means that it has been strain hardened and partially annealed

H3 - means that it has been strain hardened and thermally stabilized

W - means that is has been solution heat treated

T1 - means that it has been partially solution heat treated (cooled from an elevated-temperature shaping process such as extrusion), and naturally aged

T2 - means that it has been cooled from an elevated-temperature shaping process, (casting), cold worked, and naturally aged

T3 - means that it has been solution heat treated, then cold worked and naturally aged

T4 - means that it has been solution heat treated, and naturally aged, it applies to alloys not cold worked after solution treatment, or where the effect of cold working may not be recognized in applicable specifications

T5 - means that it has been partially solution heat treated and artificially aged, the temper is produced after an elevated temperature, rapid cool fabrication process, (like extrusion)

T6 - means that it has been solution heat treated and then artificially aged, without cold working

T7 - means that it has been solution heat treated and stabilized to control characteristics such as grain growth, distortion, or residual stresses

T8 - means that it has been solution heat treated, then cold worked, and artificially aged

T9 - means that it has been solution heat treated, artificially aged, and then cold worked

T10 - means that it has been partially solution treated (cooled from an elevated shaping process, such as extrusion), cold worked, then artificially aged

Aluminum Surface Treatment - Anodizing

Very few people actually know what anodizing is, and because so many bicycle parts are made of aluminum and then anodized, it bears some discussion. We'll first overview, and then detail the process.

Several metals are capable of being anodized, aluminum is the most common but the process may also be applied to magnesium, titanium, and tantalum. Anodizing is an "electrochemical conversion process" that changes the outer structure of the metal, rather than an applied coating, like paint. The anodizing of aluminum is performed by making the part that is to be anodized, the "anode" or positive end of an electrical circuit within an acid electrolyte. With electricity applied through the acid from the cathode an oxide layer develops in and on the outer layer of the metal. This outer layer can be formed so that it has a porous quality and the aluminum oxide layer can be dyed in many colors.

Now the details. Aluminum, as we have mentioned, on exposure to air develops a thin aluminum oxide film that seals the aluminum from further oxidation. For most purposes, this thin oxide layer doesn't enhance the protection or surface hardness enough, anodizing makes a much thicker oxide coating, up to several thousandths of an inch thick. The anodizing process was developed in the 1930's. Because it adds surface hardness, it has permitted aluminum to be used in applications where it wouldn't have been considered before. The hardness of the anodized aluminum oxide coating rivals that of a diamond, so aluminum's abrasion resistance is enhanced. The added depth of the oxide layer improves the aluminum's corrosion resistance, while making cleaning of the surface easier, and potentially if the metal is dyed, more attractive.

The aluminum part is hung on metal "racks" which are designed to hold many of the same parts spaced an even distance from one another. The racks can be made of aluminum, but after each use they must be "stripped" of the anodized coating that forms on them so they will continue to make good electrical contact, or they may be made of more expensive commercially pure (CP) titanium, which needn't be stripped after each use. The racks with the parts affixed are suspended in a series of tanks that can be made of lead lined steel, stainless steel, lead lined wood, fiberglass lined concrete or plastic. The yet to be anodized aluminum part must first be cleaned and have its natural oxide coating removed. The part on the rack is dipped in a tank for cleaning usually containing a cleaning agent of the non-silicated, inhibited soak cleaner type at 140 degrees to 160 degrees F temperature to remove all surface dirt. After cleaning, the part is rinsed to avoid contaminating the solution in subsequent tanks.

The next tank is used for de-oxidizing the part with an acid solution at a temperature generally between 120 degrees and 160 degrees F. This acid bath removes the natural, thin, non-uniform aluminum oxide surface on the aluminum. The de-oxidizing agents are typically mixtures of chromic, sulfuric, nitric, or phosphoric acids. Again the part is rinsed to avoid contaminating future tanks.

The part is now ready for etching step. Etching is carried out to remove the natural shine of the metal and provide a soft, matte, textured appearance. Etching is performed by suspending the racked part in a tank containing a 5% sodium hydroxide solution at a temperature between 90 degrees and 120 degrees fahrenheit for a period of 3 to 5 minutes.

The part is now ready for the anodizing tank. Still mounted on the rack with other like parts, the rack is suspended in the anodizing tank, which contains a diluted acid and water mixture that is capable of permitting electrical current flow. The acid is generally a 15 % solution of sulfuric (165 g/L), with the temperature of the solution maintained between 70 degrees and 80 degrees F depending on whether the final coating is to be left clear or dyed a color. Temperature control is important so the coating process and properties will be consistent from batch to batch.

The negative leg of the electrical circuit is connected to the rack of parts and the positive side of the circuit is connected to one or more "cathodes" made generally of aluminum. The cathodes introduce the electricity into the tank, there placement and number may vary on the size and shape of the part as well as the total square footage of aluminum surface to be treated, and the surface's distance from the cathode. Occasionally a metal stainless steel tank itself may be connected as the cathode leg of the circuit. Those surfaces closest to the cathode will receive a thicker anodic coating. For normal sulfuric anodizing a Direct Current power source capable of producing up to 24 volts is used, with the voltage held generally between 18 and 24 volts, variables in the needed voltage include, the amount of surface to be treated, the temperature of the solution (electrolyte), and the acid dilution and balance.

The amount of current applied to the anodizing tank will vary depending on the amount of surface to be treated, as a rule between 12 and 16 amps are required for each square foot of coverage. The electrolyte solution is agitated during the anodizing process to provide uniform solution temperature . The anodizing tank process, under normal conditions, takes between 12 and 60 minutes.

The anodizing process conditions have a great influence on the properties of the oxide film formed. If low temperatures and acid concentrations are used, it yields a less porous and harder coating. Higher temperatures, higher acid content, and longer immersion times will produce softer, more porous, and even powdery coatings. Changing just one of these parameters will influence all the others because they are interrelated.

Even the specific aluminum alloy itself introduces changes in these relationships, for this reason many anodizers keep a log of the process parameters, so that replication of a particular finish is possible.

Adding color to the aluminum part, is called "dyeing". The parts are dipped in a tank with a diluted from concentrate, water soluble, organic dye. Each dye varies in the length of time and temperature for this immersion. It is this process which forms the Blue, Black, Lavender, Red, and many shades of other colors, on so many of the aluminum bike parts we sell.

The final consideration in the anodizing process is sealing the now dyed outer surface so it doesn't sunlight bleach, or stain. Unsealed the porous outer surface has a lowered corrosion resistance. For "clear" coatings, (the aluminum remains un-dyed or "Silver"), the anodized aluminum part is put into boiling de-ionized water, which will convert the amorphous, unstructured form of the aluminum oxide to a more stable crystalline hydrate form. This conversion reaction closes off the "pores" in the aluminum oxide surface. If the anodized parts are dyed, the sealing process is performed in a tank with a nickel acetate solution. The sealing times are between 3 and 5 minutes for nickel acetate sealings and 20 to 30 minutes for water sealing.

Hard Anodizing

Many want to know the difference between the "hard anodizing" surface on rims and the colored anodized surface on, say, a cantilever brake arm. The hard anodized rim may be treated in one of two ways depending on the country of origin. Japanese hard anodizing is performed in a tank filled with, not sulfuric, but oxalic acid in a 3% solution with water. It's carried out at a temperature between 75 degrees and 95 degrees F, using between 10 and 20 amps per square foot of surface treated, frequently with Alternating Current (AC) voltage for a period of time between 30 and 40 minutes.

In the United States, a mixed acid solution of sulfuric and oxalic acid with water is used to hard anodize aluminum. It's performed at low temperature, between 30 degrees and 50 degrees F, using 24 to 36 amps of current for each square foot of surface treated at a much higher voltage, between 75 and 100 volts.

Both of these produce an oxide layer that is about 3 thousandths of an inch thick, in the Grey color we have come to recognize as "hard anodized", that is very dense, and extremely wear or corrosion resistant.

http://www.bikepro.com/products/metals/alum.html