Update Newsletter: Volume Five

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Back again for installment #5 of the **Omega Update**! This past summer we began our series on Metallurgy, dealing with Steel Metallurgy. Since the science of Metallurgy is broad and quite detailed we elected to break our Metallurgy Update series into two parts. This way not only can we cover the subject of Metallurgy better, but also possibly not bore those out there who maybe concentrate their business in either metallic plating or aluminum processing. (All past issues of the Omega Update can be found on our web site noted on page 8 or actual hard copies can be requested by calling us at Omega.)

As we learned in Update # 4 on **Steel Metallurgy**, physical metallurgy is the science that relates structure to properties. By structure we mean the internal atomic arrangement. As discussed before, all metals naturally occurring in the universe are crystalline in nature. Crystals are ordered structures; an arrangement of the atoms in certain geometric shapes or positions, very similar in nature to minerals found in the field of geology. Aluminum and its alloys differ from steel alloys. Steels are allotropic in form meaning that they can exist in many different crystal structures depending on chemistry and also temperature. Aluminum is different. It is not allotropic it exists only in the crystal phase known as face centered cubic (FCC). It was found in the 1920's that aluminum alloys do not respond to heat treatment methods like steels do . They do not go through a phase or crystal structure change like steels. However, depending on alloy additions like copper, zinc, manganese, silicon & magnesium, these alloys can be solution heat treated and precipitation hardened. This solution treat (ST) and precipitation harden (natural and artificial age) are the two important steps in the vast improvement in strength for aluminum alloys.

Now we realize that many of you out there in the metal finishing business also do aluminum processing. Normally aluminum processing involves chemical treatments of the aluminum alloy itself and not applying a plating to the surface. However, sometimes we do see Electroless Nickel plate and other types of plating applied to aluminum alloys, but probably 90% of the metal finishing that happens with aluminum alloys involves chemical processing of the aluminum itself.

As we talked about in Update # 4 on Steel Metallurgy, Metallurgists spend a good portion of their working lives manipulating the chemistry and internal structure of metals to achieve better properties of the metal alloys. This involves not only changing the melt chemistry, but also heat treatments, hot and cold working via forging, extruding, rolling etc. Aluminum alloys are somewhat easier to study and understand than steels. This update will concentrate on 5 sections:

1) Types of aluminum alloys
2) Aluminum alloy heat treatment
3) Chemical processing
4) How aluminum alloys can fail us
5) Mechanical properties and how they are measured

You, the aluminum processor, have a critical role in making safe, durable aluminum alloy products for aircraft, missiles and space!

So as they say, sit back, pour yourself a cup of coffee and read about

Aluminum Metallurgy

What Metal Finishers Should Know

1) Types of Aluminum Alloys:

In the United States, the alloy designation system is derived from the Aluminum Association. For cast alloys a 3 digit system is used. For wrought products (sheet, plate, forgings, extrusions) a 4 digit system is used. These digits are followed by a letter digit that denotes the temper or heat treat condition.

1000 Series Aluminum: 99% pure aluminum. No major alloying additions. Most common type is I 100 which is commercially pure aluminum It is soft and very ductile, having excellent workability. Well suited for applications involving severe forming as it work hardens more slowly during forming. It is the most weldable of all aluminum alloys. It can not be heat treated. It has the best resistance to corrosion of any aluminum alloy, and is widely seen in the food and chemical processing industry. Can be chem film treated and anodized easily. Commonly used as the top or Alclad layer in other aluminum alloys needing extra corrosion resistance. Poor machineability due to soft nature.

2000 Series Aluminum Alloys: Principal alloying element is copper with minor additions of manganese and magnesium. This series of aluminum is the original heat treatable alloy group developed in the 1920's. The best known, most widely used heat treatable alloy for aircraft and aerospace is 2024. Can be spot and friction welded but not fusion welded (a few exceptions being tank structures in the Titan Missile). Has good formability in the annealed temper condition and some formability in the solution treated and aged condition, but needs intelligent application in complex designs. Has excellent fatigue properties when compared to other aluminum alloys, excellent strength to weight ratio. Good machinability. Poor resistance to corrosion without alclad layer or secondary chem film, anodize and/or prime and paint. Can be chem film and anodized readily. Other 2000 series alloys include 2017 seen widely in aluminum rivets, fasteners and screw machine parts and 2014 which is used heavily in forgings. These three alloys, 2024, 2014, and 2017 can be considered the foundations of aluminum aircraft, missiles and space vehicles during these past 75 years.

3000 Series Aluminum Alloys: 3003 is the most widely used of all aluminum alloys when measured in thousands of tons per year. It is essentially commercially pure aluminum with the addition of manganese which increases its strength about 20% over the 1100 series aluminum. Normally not heat treatable. A popular alloy in this group is 3003, which is used as a general purpose alloy for moderate strength applications requiring good formability. Applications include home, recreational, commercial and light industrial. Not normally seen for aircraft and aerospace uses.

5000 Series Aluminum Alloys: Magnesium is the principal alloy addition. A higher strength, non heat treatable family of alloys. 5005 is an improved version of 3003, better suited for anodizing with less tendency to streak or discolor. Similar applications to 3003. 5052 is the highest strength. Has good resistance to marine atmosphere and salt water corrosion. Excellent formability. Good fatigue properties in higher temper conditions. Used in a variety of applications including home, marine, ground transportation and aircraft. Good weldability by all methods. Probably over a dozen different alloys in this 5000 series group. Other popular alloys include 5056, 5083, & 5086. Many times used for aluminum rivets (bucked and pulled).

6000 Series Aluminum Alloys: Magnesium and silicon are the major alloy additions, making these alloys heat treatable. 6061 is the principle alloy. It is one of the least expensive and most versatile aircraft aluminum alloys available. A good range of mechanical fatigue properties and excellent corrosion resistance for a heat treatable aircraft alloy. Can be fabricated by virtually all methods. Excellent spot and fusion weldability for a heat treatable grade. Can also be furnace brazed. Available as a clad alloy for even better corrosion resistance. Although not as strong as the 2000 or 7000 series of heat treatable alloys, its corrosion resistance is far greater. Far ranging applications including aircraft, missiles and space, ground and marine transportation, screw machine parts and some industrial commercial uses. 6063 is widely seen in extrusion products for architectural applications. Has excellent finishing characteristics it is the best alloy for anodizing applications, either plain or dyed.

7000 Series Aluminum Alloys: Probably the highest strength series of aluminum alloys for aircraft applications. Relies on zinc as the primary alloy addition. Excellent fatigue properties, but in the T6 temper the fracture toughness can be inferior to other alloy choices. Many aircraft applications in the late 1940's and 1950's used 7075 T6 before some bad habits were understood. Normally formed fabricated in the annealed (0) condition. Can be spot welded but not fusion welded. Poor corrosion resistance if not protected by chem film, anodize, prime or paint. In sheet forms almost always used as a clad alloy. Other popular alloys now include 7049, 7050 in the overaged temper condition (T7xxx).

Clad Aluminum: Sometimes called Alclad. Many times the design engineer specifies a clad alloy, or a specific alloy type with a very thin layer of pure aluminum roll bonded to both sides of the alloy sheet. This provides us with the best of both worlds the high strength of the heat treatable alloy with the superb corrosion resistance of a purer aluminum top layer. This roll bonding is a true metallurgical bond and it's strong as the aluminum itself. Our U.S. coins are roll bonded clad alloys take a look at the dime or quarter in your pocket. Yes, it is nickel, roll bonded to a copper core!

2) Heat Treating Aluminum Alloys:

Aluminum alloys are not allotropic they do not undergo a phase or structure change like steels when heating. But if the right alloying additions are present they can be heat treated by solution heat treating and precipitation hardening. In the early days (1930's) solution heat treatment was referred to as ST, and many times precipitation hardening was referred to as aging.

Solution heat treatment involves temperatures very close to the melting point of the aluminum alloy, usually 200 300 deg. below the melting point. The purpose is to provide enough thermal energy to dissolve, in a solid solution, the alloy elements present. In the case of 2024, the major alloy element is copper, and by taking the part to 920 deg. F, the copper present within the 2024 will dissolve or disperse uniformly throughout the solid aluminum part. This can be difficult to comprehend how can something dissolve and still be solid? As Einstein once said, “...everything is relative...” Without getting into the solid state physics of the metallurgical reactions, dissolution ***does*** occur but only at this high temperature. However, if you slowly cool down the part, the copper wants to come back out of solution. Here is where the important step of quenching takes place. Quenching is a very rapid cool down, using water, on the order of 500 600 deg. per second. Quenching locks in place all alloy elements that have been dissolved at the high solution heat treat temperature. Before the alloy additions can think about changing places and moving back out of solution wham! they are locked in place by the rapid quench cool down. The result is called a "super saturated solid solution" an unstable condition. Quenching is critical to proper solution heat treatment.

Aging Precipitation Hardening can now happen under the right conditions. In the case of natural aging of 2024, or aging at room temperature, the dissolved copper slowly comes back out of solution over an extended time (96 hours minimum), forming CuAl precipitants. Precipitants or precipitated particles can be thought of as army commandos, coming from nowhere out of the sky to stand guard, strengthening the territory. Indeed the word precipitant comes from the weather term precipitation meaning to separate and fall from solution (clouds). Precipitated particles in heat treatable aluminum alloys strengthen the alloy by pinning or locking up numerous microstructural features in the aluminum. Other heat treatable alloys like 6061 and 7075 undergo very similar precipitation reactions, with the actual precipitated particles differing depending on whether zinc, magnesium, manganese, silicon or copper additions are present. The way that metallurgists control the formation of these precipitants will determine the mechanical and corrosion properties later.

In the case of artificial aging or precipitation hardening, the previously solution heat treated and quenched parts are subjected to elevated temperatures (instead of room temperature) in the range of 225-375 deg. F over extended periods of time (4-24 hours). The precipitants formed and grown here are more controlled and substantial in nature, resulting in higher mechanical properties as compared to naturally aged conditions.

Temper Designations - Non-Heat Treatable Alloys:

O Annealed to softest condition
H1 Strain or work hardened
H2 Strain or work hardened then partially annealed
H3 Strain or work hardened, then stabilized (thermally)
The H designation is usually followed by additional digits noting the degree of strain-work hardening.

Temper Designations - Heat Treatable Aluminum Alloys:

0 Annealed to softest condition
T3 Solution treated, cold worked, then naturally aged
T351 Solution treated, stress relieved by stretching then naturally aged
T4 Solution treated and naturally aged
T42 Solution treated and naturally aged by the user
T5 Artificially aged only
T6 Solution treated and artificially aged at an elevated temperature to highest strength
T651 Solution treated, stress relieved by stretching, then artificially aged to highest strength
T652 Solution treated, stress relieved by compression, then artificially aged to highest strength
T62 Solution treated and artificially aged to highest strength by the user
T7 Solution treated and over aged to a point beyond maximum strength (T6) (Usually 2 step age)
T7xx As above with specific aging - stress relief goals for improved corrosion properties.

T8 Solution treated, cold worked, and artificially aged. (Usually only seen in sheet and extrusions)
T8xx As above but also cold worked/stress relieved

Examples:

2024-T4 - A 2000 series aluminum alloy with the major alloy addition being copper. Solution heat treated, quenched and naturally aged at room temperature.

7075-T73 - A 7000 series aluminum alloy with the major alloy addition being zinc. Solution heat treated, quenched, then 2 step artificially over aged.

3) Chemical Processing of Aluminum:

Chemical Conversion Coatings: Many times called chem-film or Alodine, this treatment involves a pre-treatment de-oxidizing etch, rinse, and immersion into a chromate based solution to effect the conversion coat or film. In addition to the enhanced corrosion benefits, improved adhesion of prime-paint is also seen compared to bare aluminum. More detailed information on the chem film or chemical conversion coat treatment of aluminum alloys will be covered in the future in Omega Update #6 - Corrosion.

Anodizing: This is an electro chemical treatment that radically improves the corrosion resistance of the aluminum alloy. It is an electrolytic oxidation process where the surface is made the anode in an electrolyte bath with a metal or carbon cathode, and electrical current is passed through the cell. The aluminum surface is converted to aluminum oxide, $A1_2O_3$. The oxide coating is integral to the base aluminum, i.e. it does not simply sit on the surface but is part of, or integral to the base aluminum alloy. As formed, it is porous and capable of being dyed or tinted different colors. However, in the as anodized state, it provides poor corrosion resistance due to the porous nature. It must be sealed, a process that causes the aluminum oxide to swell and "seal itself off' from permeation of water or liquids later on. There are numerous types of anodize such chromic and sulfuric acid anodize, hard anodize, and others. A more detailed commentary on anodizing will follow in the future in Omega Update #6 Corrosion.

Test Samples used in Chem Processing: 2024 and 7075 alloys are dominant alloys in the aerospace industry. They are widely used for their high strength, but are more prone to corrosion and heat treat problems. As such, required samples for process control of chem film and anodize many times are 2024 and 7075. The rational is to use these higher strength alloys for samples in order to better control the chem processing of actual parts and flight hardware.

4) How Aluminum Alloys Can Fail Us:

Corrosion Damage: Even though pure aluminum has wonderful corrosion resistance, when we begin to add alloy additions, corrosion resistance almost always goes down. You as the aluminum metal finisher are a key player in providing parts capable to performing over many years of time. Aluminum finishing for improved corrosion protection can involve chemical conversion coatings (chem film alodine), anodizing, prime and paints. Corrosion is an immense topic to be covered soon in Omega Update #6. But for now we can generally say that corrosion of aluminum alloys can be catastrophic many fatal aircraft accidents have been caused by corrosion damage of critical structures. Corrosion in aluminum alloys can take the form of:

a) general attack or oxidation of the aluminum
b) pitting attack
c) intergranular attack, or attack along grain boundaries. A sub type is called exfoliation.
d) stress corrosion cracking a serious type of cracking failure involving corrosion along grain boundaries.

Heat Treatment Damage: Can take the form of improper solution heat treat temperatures resulting in a) under soak from low temperatures low mechanical properties or b) excessive temperatures resulting in eutectic melting within the aluminum microstructure. Heat treat damage can also happen from improper artificial aging temperatures and times, resulting in lower mechanical properties also.

Hydrogen Damage: Can also happen during solution heat treatment if it is done in a air furnace rich in moisture. The water vapor breaks down into elemental hydrogen, entering the aluminum. During the quench, this high level of dissolved hydrogen suddenly comes out of solution, popping into hydrogen bubbles or blisters on the surface of the aluminum. Our Omega Update #4 shows a picture of this type of damage. Although this is not hydrogen embrittlement it is still damaging to the mechanical properties of the aluminum alloy.

Damage from Metal Finishing: Two areas of concern are present when finishing aluminum alloys. The first is aggressive attack of the aluminum from excessive or multiple deoxidize etching or cleaning operations. Here general, pitting or intergranular attack (IGA) of the aluminum happens resulting in scrapped parts. A second area of concern is damage from excessive heat from baking or hardening treatments. Curing of subsequent lubricants or PTFE treatments must be done at temperatures that will not stress relieve or partially anneal the aluminum. It is important to always remember that aluminum alloys can have their temper conditions changed by thermal treatments easily reached in a embrittlement relief baking oven (temperature ranges of 300 deg. F and up). In addition, electroless nickel plating applied to aluminum alloys need special attention if the electroless nickel is a Class 2, hardened E.Nickel.

5) Mechanical and Physical Properties:

Aluminum alloys are useful to us due to their light weight and good strength. Commonly referred to as the strength to weight ratio, high strength aluminum alloys are at the top of the list of choices for critical efficient structures. Aluminum alloys have one-third the density of steel and approximately 50% lower density than titanium alloys. However, they are not as strong as high strength steels or titanium, therefore more aluminum is needed to carry the same stresses.

Many times a mechanical structure is not primarily based on simple strength vs. load bearing area (psi). The design may be based on bending loads, buckling resistance or other criteria more based on the geometry of a part rather than area. Here aluminum alloys shine as they can prove to be highly efficient and light weight in nature. Good examples of the efficiency of aluminum alloy components are commercial and general aviation aircraft wing, fuselage and tail structures.

The mechanical properties most often utilized by design engineers are: tensile, and yield strength (in psi), % elongation and % reduction in area, shear and bearing strength (in psi), fracture toughness (in K_{IC} - square root inch) and possibly fatigue strength (fatigue limit - psi at run out cycles). Mechanical properties can be most readily measured by using a Hardness test such as Rockwell or Brinell. Hardness tests are simply an easy method to estimate the true mechanical properties of the aluminum and are not as accurate a correlation as with steel alloys. The purpose of mechanical property tests for aluminum alloys is only to determine the temper condition or heat treat condition. Numerous aircraft company and industry specifications show minimum and maximum hardness requirements for various aluminum alloys, but the reader is cautioned that differences of opinion vary from company to company and specification to specification. In addition, another type of test called electrical conductivity can be used to help determine the temper condition. This is many times called a conductivity test measured in % I.A.C.S or % of International Annealed Copper Standard. The use of a good Rockwell hardness test in conjunction with a conductivity test can reliably determine the proper temper condition or heat treat condition of aluminum alloy parts.

Well there you have it, possibly your first introduction to ***Aluminum Metallurgy***. We hope this short course will help in your processing of critical aircraft and aerospace aluminum alloy components.

Omega Research now offers a complete range of testing services for aluminum alloy processing including:

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