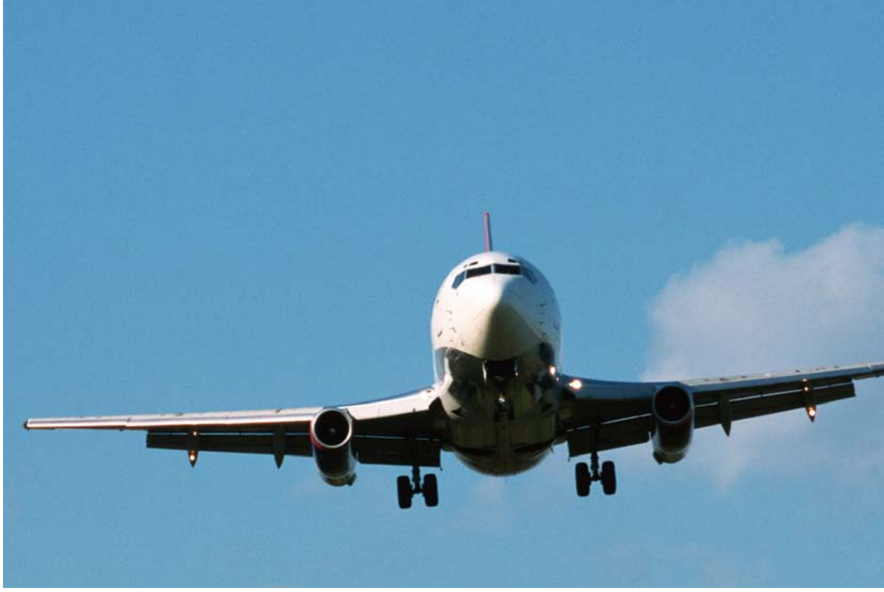

A Primer on Aerospace Fastener Materials

by Laurence Claus

Perhaps unlike any other segment of the fastener consuming market, aerospace fasteners use a more diverse range of materials than any other segment. On the surface one might wonder why, but this makes sense when one considers the wide assortment of applications and performance needs on aircraft and spaceships. Like most fasteners, aerospace fasteners must exhibit good strength properties. However, in many instances they must not only possess strength within normal ambient temperature ranges but also at elevated or subzero temperatures. In fact, some aerospace fasteners are expected to toggle between and perform well at both extremes.

In addition to maintaining strength in some challenging environments, aerospace fasteners must have excellent corrosion or oxidation resistance, fatigue strength, and be light in weight. These are the primary things that influence the Aerospace Engineer and lead to design choices of one material over another.

Aerospace fasteners may be divided into four general categories:

1. Steel and Alloy Steel
2. CRES (Corrosion Resistant Steel)
3. Lightweight Materials
4. Materials for Elevated and Subzero Temperature and Harsh Environment Service

Regardless of the category, aerospace fasteners often have fatigue related performance requirements. This places some special requirements on the raw material that are not found with more general use, industrial fasteners. These special needs equate to certain standard practices unique to the aerospace fastener market. In particular, many of the specialty metals are melted or remelted in a vacuum. In fact, some heats of raw material may be double or triple vacuum melted. These repeated vacuum processing steps serve to draw more impurities to the surface where they can be removed, leaving a "cleaner" and more homogenous batch of raw material. This is especially advantageous as these impurities have a way of lessening fatigue strength and reducing toughness.

The other process that is commonly employed by aerospace manufacturers is to remove the top layer of the material from the wire. This is generally known as "seam and decarb free" wire for steel and alloy steel raw materials and "seam free" for non-ferrous and specialty metal varieties. Often these are referred to as "shaved" or "peeled" wire, denoting the method by which the top surface is removed. Regardless of the process, however, the intent is to provide a quality level that prevents the manufacturer from creating surface discontinuities on the fastener that are the result of small imperfections in the surface of the raw material. Again, this is especially critical to improve fatigue strength in fasteners that are exposed to cyclic loading.

The choice of the raw material will be determined by the designer. It should be a function of matching the material's properties with the requisite needs of the component in its application. For example, a fastener that is integral to a jet engine will likely require strength at elevated service temperatures. For the remainder of this article, we will explore the different materials that comprise the four classes of aerospace fastener materials above.

Steel and Alloy Steels:

By far, the most commonly used material for fasteners across all market segments are plain carbon and alloy steels. Plain carbon steels are those that are essentially just an interstitial alloy of carbon and iron. The more carbon contained in the variant, the greater potential for the material to be hard and strong. Although carbon, on its own, provides a significant strengthening capability, it can be further improved with the addition of selected alloying elements. Those steels that have small amounts of alloying elements such as Molybdenum, Chromium, and Nickel added are known as alloy steels. To reiterate, they differ from plain carbon steels by the specific addition of certain alloying elements.

Although some low, plain carbon steels such as SAE 1022 are used for non-critical and "mundane" aerospace applications, usage of these materials tends to be relatively rare. It is much more common to find fasteners made of SAE 8740, SAE 8640, and SAE 4340 for aerospace use. These are all alloy steels that contain Chromium, Molybdenum, and Nickel. These alloying elements, along with a medium level of carbon, provide exceptional hardenability, and, thus, the ability to be strengthened. These materials are normally heat treated to provide parts with tensile strengths ranging from 120 ksi to 180 ksi.

Corrosion Resistant Steel (CRES):

It is very common for aerospace standards to refer to a variety of different materials that exhibit excellent corrosion or oxidation resistance as corrosion resistant steels or CRES. One such material that normally gets described this way is A286 (a nickel-iron alloy). Although A286 is a corrosion resistant material, I will discuss it with the Nickel alloys and reserve this section to just stainless steels.

Stainless steels fall into one of five different categories; austenitic stainless steels, ferritic stainless steels, martensitic stainless steels, precipitation hardening stainless steels, and duplex stainless steels. Although all are considered to be stainless steels, (materials that contain a minimum of 11.5% Chromium), these general families can have markedly different traits and properties. However, they all form a chromium rich oxide, Cr2O3, which is self-healing in the presence of oxygen and explains much of their ability to provide corrosion protection.

Austenitic Stainless Steels:

When individuals "think" of stainless steels, it is most likely materials from this family that they are thinking of. Austenitic stainless steels are the ones used to make cookware and fancy stainless steel appliances which we daily interact with. These materials are generally non-magnetic, not heat treatable, and possess the best corrosion protection of the five stainless steel categories. They work harden very quickly, which can make them somewhat tricky to form, although rarely do these materials need any heat to help form them. In the US, these materials are given numeric designations starting with 200 or 300. The most common fasteners are made of 304 and 316 varieties, although 302, 302 HQ, 321, and 204-Cu are used for fasteners as well.

Aerospace applications that might utilize these materials are similar to industrial applications that use them, high strength is not required but excellent corrosion protection is. This means anywhere that high strength is not needed but corrosion protection is, the designer might choose to use an austenitic stainless steel.

Precipitation Hardening Stainless Steels:

Aerospace also uses precipitation hardening stainless steels. The two most common varieties for fasteners are 17-4 PH and PH 13-8Mo. These stainless steels may be hardened (or strengthened) by solution heat treating and aging. Without going into any great detail this means that the material is heated up until all of the material's constituents go into solution. Then as the material cools, the materials begin to form new combinations of the constituent atoms, which then drop out (or precipitate from) solid solution. These metallic compounds are harder and stronger than the unprecipitated form.

Precipitation hardening stainless steels have about the same corrosion protection as the austenitic grades, but significantly greater strength. This combination of strength and corrosion resistance is what makes them attractive to a designer.

Precipitation hardening materials possess moderate to high work hardening rates, which make them difficult to work with and, often, unpopular with manufacturers.

Other Stainless Steel Categories:

The following three stainless steel families generally are not used much or at all in aerospace applications. It is important, however, to know how these different materials are distinctly different from one another and possess different properties.

Ferritic stainless steel generally does not possess more than a trace of nickel. They provide moderate corrosion protection, but definitely inferior to either austenitic or precipitation hardening varieties. Ferritic stainless steels are magnetic, not heat treatable, relatively low in strength, and possess a moderate work hardening rate. Work hardening, therefore, generally does not present a problem during forming and no heat is required. Ferritic stainless steel is designated with numbers in the 400s. Unfortunately, and users must show caution, martensitic stainless steels also use 400 numbers. Therefore, unless one has the designations committed to memory, they likely will have to look up and find out whether the materials are ferritic or martensitic.

Martensitic stainless steels usually contain between about 12% and 17% Chromium. Of all the families of stainless steel, martensitic stainless steel has the lowest corrosion resistance. It makes up for this limitation, however, by being heat treatable to high strength levels. Other things that set this family of stainless steel apart are that they are magnetic and have a low to moderate work hardening rate. Therefore, of all the cold heading varieties they are the easiest to form. Like ferritic stainless steels, they are designated with 400 numbers.

Duplex stainless steels are relatively new to the market. They are essentially a 50-50 split between austenitic and ferritic stainless steels. As such they combine some of the advantageous traits to improve over ferritic stainless steel but rarely meet the same level of behavior of austenitic stainless steel.

Lightweight Materials:

The two most interesting materials for aerospace applications are Titanium and Aluminum. These are the "lightweight" materials because they have significantly lower densities than the steel or nickel alloys. Although when compared for brute strength, these lightweight materials simply do not provide what is desired. However, when comparing strength versus weight, they perform very well. Since aircraft and spacecraft designers are ultra-sensitive to weight, this strength-to-weight ratio makes them especially attractive materials for consideration.

Aluminum:

Aluminum is about 1/3rd the weight of steel, so that even though its direct strength is much less than steel, its strength-to-weight ratio may be superior. Aluminum is non-magnetic, possesses excellent thermal and electrical conductivity, and, when anodized, possesses good corrosion resistance. Aluminum alloys are found in both cast and wrought varieties. For designation purposes these are broken up into two entirely different systems. Fasteners fall into products from the wrought aluminum family.

Wrought aluminum is divided into eight different categories. These are distinguished from one another by a four digit number where the first digit (one through eight) designates which alloy family it belongs to. In this four digit numbering system the first number represents the principal alloying element, the second any modifications and the third and fourth number are simply a sequential number designating the sequence in the alloy series represented by the particular set of constituents. The only exception to this are the alloys in the first family (1000 series alloys). In these, the last two digits represent the purity of the aluminum above 99%. As an example, 1050 aluminum would, therefore, be 99.50% pure aluminum.

Wrought aluminum designations are normally accompanied with an additional string of letters and numbers following the primary, four digit designations. These additional letters and numbers are the Temper Designation. They describe one of five categories; "F" for As-Fabricated, "H" for Strain Hardened, "O" for Annealed, "T" for Thermally Treated, and "W" for Solution Heat Treated. The only one of these that generally applies to fasteners is the "T" designation codes. "T4" are materials that are solution heat treated and naturally aged, "T6" are materials that are solution heat threated and artificially aged, and "T73" are solution heat treated and overaged (a temper condition occasionally desired for its improvement of stress corrosion behavior).

Aluminum materials used for fasteners represent a small number of actual alloys. In fact, besides the pure aluminum alloys that may be used for rivets, the three alloys that are essentially used for fasteners are 2024 (Aluminum-copper alloy), 6061 (Aluminum-Magnesium-Silicon alloy), and 7075 (Aluminum-Zinc-Magnesium alloy). Of these three, only 2024 and 7075 are used in aerospace. 7075 in a T6 temper is the strongest of all the aluminum alloys with a tensile strength of 83ksi. Again, in raw strength that isn't very impressive, but when considering the strength-to-weight ratio it is pretty good (although not the best.)

Titanium:

The material with the absolute best strength-to-weight ratio is Titanium. Titanium is about 45% less dense than steel but can have a raw strength as high as about 138 ksi. That puts it at the top of the chart for strength-to-weight ratio. It also explains why Titanium is so desirable for aircraft and other products where lower density and strength are desired together. Although Titanium is known for its strength-to-weight ratio, its excellent corrosion resistance in harsh environments should not be overlooked. This property makes it a preferred choice in chemical processing applications such as pulp and paper production, desalination, and oil & gas. Additional properties include good high and low temperature properties, non-magnetic, a low coefficient of thermal expansion, and biocompatibility (which explains its preferred use as human bone implants). Unfortunately, Titanium is extremely difficult to form at room temperature and must have heat added (warm formed) to provide extra workability.

Many materials exist in different internal configurations (phases) depending on the conditions the material is exposed to. Titanium is no different and exists in two different phases depending on the temperature the material is at. At room temperature (actually temperatures below 890°C) Titanium naturally exists in its Alpha phase and above 890°C its Beta Phase. Alpha Titanium is weldable, not heat treatable, possesses low to medium strength, has good notch toughness, good ductility, and excellent mechanical properties at low temperatures. Along with pure Titanium, Alpha Titaniums possess the best corrosion resistance of the titanium varieties and they provide the best high temperature creep strength and oxidation resistance. Beta Titaniums are heat treatable, usually weldable, high strength, possesses good creep resistance at intermediate temperatures, and good formability. Since the Beta phase is the high temperature phase, stabilizers have to be added to get this material stable at temperatures below 890°C.

Past Material Scientists have also discovered ways to create Titanium alloys that share the two phases. These are known as Alpha-Beta Titaniums and create alloys that combine some of the best properties of Alpha and Beta Titaniums. In fact, the most common Titanium material for fasteners is an Alpha-Beta Titanium, Ti6Al-4V, or what is simply referred to as "6-4 Titanium". This particular alloy achieves a minimum tensile strength of about 138 ksi.

Although Ti6Al-4V is the predominant form of Titanium used for fasteners, it does have some limitations. In a chlorine rich environment it is known to experience stress corrosion. Therefore, care must be taken to prevent exposure during manufacturing to cutting or lubricating oils that contain halides. Likewise, this form of Titanium requires heat to form the parts. However, if heated too high, the Titanium has a strong affinity to react with Oxygen, Nitrogen, and Hydrogen (all constituents that could be present in the normal air surrounding the part). When exposed above the critical temperature, these create what is known as Alpha Case, a hard, brittle, and undesirable surface layer. When Titanium parts form Alpha Case it must be either mechanically removed (not always easy) or parts are scrapped.

Materials for Elevated and Subzero Temperature and Harsh Environment Service:

In aerospace and certain other market segments, fasteners are often exposed to extreme conditions of elevated temperatures such as those experienced in and around a jet engine or very low temperatures as fasteners might be exposed to in space. The challenge with these conditions is to maintain strength and fend off oxidation. For these situations, standard, high-strength fastener materials will simply not do the job. For these, we have to turn to the super alloys. Super alloys are ones that provide and maintain high strength at elevated temperatures, maintain toughness at very low temperatures, and/or resist oxidation, even in the harshest of environments.

A286:

A286 is an Iron-Nickel alloy. It is by far the most common of the Nickel alloys used in aerospace. In fact, it is so common that it is not unheard of for the customer to specify or purchase A286 parts for applications that really do not require the level of performance that they can achieve. It has corrosion protection nearly equivalent to 304 stainless.

A286 is heat treatable through solution hardening and aging. It maintains its strength and corrosion resistance up to about 1200°F. Most aerospace A286 is finely processed so that it is vacuum melted and, perhaps, once or twice vacuum remelted. A286 can be developed to different minimum strength levels; 120/130ksi, 160/180ksi, >200ksi. Achieving the desired strength will depend on a number of factors such as whether the wire was pre-strained prior to forming and the sequence and settings of the heat treating process.

Alloy 718:

Alloy 718, otherwise known as Inconel, is another relatively common Nickel alloy. It can possess strength greater than 200ksi at or near room temperature and possesses exceptional yield, tensile, and creep rupture properties all the way to 1300°F. Like A286 it is heat treatable through solution hardening and aging. It is very difficult to form at room temperature and heat is almost always added for both forming and rolling the threads.

Waspaloy:

Waspaloy is considered a Nickel Super Alloy. It contains a high percentage of Nickel, Chromium, and Cobalt. It possesses excellent strength, corrosion, and stress rupture up to 1400°F and useful performance all the way to 1800°F. It has excellent corrosion resistance and is almost impervious to oxidation. This makes it particularly well suited to harsh or extreme service environments. It is heat treatable through solution hardening and aging. Like Alloy 718, it may possess room temperature tensile strength in excess of 200ksi and better strength properties than Alloy 718 above 1300°F. It also is difficult to form and likely requires heat to assist its workability.

Hastelloy and Hastelloy X:

These are Nickel-Chromium-Iron- Molybdenum super alloys. They possess excellent strength and oxidation resistance at high temperature to about 1400°-1600°F. These materials have excellent resistance to stress corrosion cracking, particularly from a chloride environment. Therefore they are commonly used in aerospace engines and petrochemical applications. They are heat treatable through solution heat treatment and aging and have moderate formability.

Multi-Phase Alloys:

The two common multi-phase alloys used for fasteners are MP35N and MP159. These materials are capable of room temperature tensile strength of 240-260ksi. They do not maintain this strength performance at elevated temperatures as well as most of the preceding materials, but still maintain good strength performance up to 700°F for MP35N and 1100°F for MP159. These materials have excellent strength and corrosion resistance at both high temperature and subzero conditions, making them some of the most versatile of the Nickel alloys. They are also the most corrosion resistant fastener alloy available, even holding up in sour well conditions.

AMS Standards:

For aerospace, all of these materials are controlled with different AMS standards (Aerospace Material Standards). AMS standards are currently developed and maintained by an aerospace arm of SAE International. If doing aerospace work, it is important that one has access to these standards as they provide critical information on what is required to properly choose or heat treat these different materials.

Summary:

There is a great deal to know about aerospace fastener materials. Whereas almost all other segments of the fastener industry use a relatively narrow band of materials (such as steel and stainless steel), full service aerospace producers have to be knowledgeable about all of these materials and how they are best processed.

It is also evident that some of these materials are truly “super” performers, possessing room temperature strengths well above 200psi and maintaining those without significant drop-off well into the elevated and/or subzero ranges. Additionally, some of these materials possess excellent corrosion resistance, even in the harshest environments.

In many cases, these truly are “super alloys” and companies that process these types of materials should take pride in their capabilities, as this is a feat that not every fastener manufacturer can perform.