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Update Four: Steel Metallurgy

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Here we are, back again for installment #4 of the ***Omega Update!*** Yes it has been a while since our last update #3 on *Test Sample Goofs*. Update #2 covered Specifications and the original Update #1 covered *Plating Goofs - The Legacy of Hydrogen Embrittlement*. (All previous Omega Updates can be found on our Web Site www.OmegaResearchInc.com or original copies can be obtained by calling us at Omega Research.) This update is dedicated to ***Steel Metallurgy***. Aluminum metallurgy will follow this summer of 2002 in Update # 5.

Metals comprise almost 75 percent of the known elements of the universe - their usefulness to man is unparalleled! They are widely available, inherently ductile - able to take damage, strong, easy to manufacture, and useful to conduct heat and electricity. But making metals useful involves far more than just taking raw metals found in the earth and putting them to work. Probably 95 percent or more of all metals used today are really metal alloys, or combinations of metals and other elements that can make the alloy even better than the sum of the parts. Most of the time, even precious metals such as gold and platinum used for jewelry and coinage are alloys, combinations of elements making the gold, platinum etc. more durable and useable. Besides just changing the chemical elements of the alloys, many times it is essential to change the *structure* or atomic arrangement found within the metal alloy. For this Omega Update we don't need to go deeply into the physics of metallurgy; suffice it to say that all metals naturally occurring within 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. Physical Metallurgists build upon these ordered structures to understand and utilize metals and their alloys.

The fundamental definition of Physical Metallurgy is:

The field of Metallurgy that relates structure to properties

By structure we mean the internal atomic ordered structure. By properties we mean strength, hardness, ductility etc. Metallurgists spend a good portion of their working lives manipulating the chemistry and internal structure of metals and alloys to achieve better properties. This involves not only changing the melt chemistry, but also heat treatment, hot and cold working via rolling forging, cold forming etc. What we want to relate in this Omega Update is some fundamentals of steel, a little bit on heat treatment used for steel, and also some short notes and tables on mechanical properties, Rockwell hardness etc. These pages are by no means a complete documentary on metallurgy - only some essentials are presented. If you desire more information, call us at Omega for more detailed data.

You as a Metal Finisher are given metals and their alloys as the basic building blocks to useful products. You are a critical step in delivering not only useful products but also durable and safe ones too. As a key player, you should know the basics of the metals and alloys delivered to your door.

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

Steel Metallurgy

Types of Steel:

Steels are classified per the SAE or AISI standard system. Using digits and sometimes letters, with a little knowledge you can quickly tell the type and grade of steel. Normal carbon and alloy steels use a 4 digit system, such as 4130 (sometimes you will see it stated as SAE/AISI 4130. SAE stands for Society of Automotive Engineers. AISI stands for American Iron and Steel Institute). The last two digits denote the carbon level, so for 4130 steel, it has 0.30 % carbon. 1018 steel has 0.18% carbon and so forth. The first two digits denote the general grade of steel, whether plain carbon, low or high alloy etc. For plain carbon steels the system is:

10xx Non-resulphurized plain carbon group

11xx Resulphurized plain carbon group (machinable commercial steels)

12xx Rephosphorized-resulfurized plain carbon group (machinable commercial steels)

15xx Manganese fortified carbon steels - merchant grade sometimes heat treatable

As we will see later, carbon is the most powerful alloy ingredient in steel - in fact the carbon level in iron defines the metal. For iron with little or no carbon, it is called *wrought iron* (the Eiffel tower in Paris is made of wrought iron) For iron containing 0 - 2% carbon we have *steel*. For iron containing > 2% carbon we have *cast iron*.

For alloy steels, the designation system is as follows:

13xx High manganese > 1.75%

40xx Molybdenum fortified in the 0.2 - 0.25% range

41xx Chromium (0.5-0.9%) and Molybdenum(0.1-0.3%) added

43xx Chromium (0.5-0.8%), Molybdenum(0.25%) and Nickel(1.8%) added

44xx Molybdenum (0.5%) added

46xx Molybdenum (0.2%) and nickel(0.8-1.8%) additions

47xx Chromium (0.45%) and nickel (1%) additions

50xx Chromium (0.4%)

51xx Chromium (0.8 - 1%)

61xx Chromium (0.6-0.9%) & Vanadium (0.1-0.15%)

86xx Chromium (0.5%) Nickel (0.5%) Molybdenum(0.25%)

87xx Chromium (0.5%) Nickel (0.55%) Molybdenum(0.35%)

For the metal finisher, steels can be grouped into 6 basic categories :

- 1) Plain low carbon steel (see designation system p.2)
- 2) Plain high carbon steels (see designation system p.2)
- 3) Low alloy steels (see designation system above)
- 4) High alloy steels

5) Stainless steels

6) Tool steels.

Of course there are many other sub-types or variances to the above, but this covers the basic types you in the metal finishing industry commonly see.

Plain low carbon steels

1010 This is one of the most widely used low carbon steels for low strength applications. Best suited for parts with fabrication involving moderate to severe forming. Weldability is excellent. No fears of hydrogen embrittlement as strength is very low (hardness-strength measured on Rb scale). Needs surface finishing to prevent corrosion. Standard surface prep before plating. Sometimes case hardened by carburizing to improve wear resistance.

1018 A popular carburizing grade of steel for commercial uses. Can be strengthened by cold work, forming, bending, rolling etc. Relatively soft (hardness-strength measured on Rb scale). Weldability is excellent as is formability. No fears of embrittlement as strength is very low. Needs surface finishing to prevent corrosion. Standard surface prep before plating.

1020 A general purpose low carbon "mild" steel. Easy to fabricate, easy to weld, widely used for commercial, industrial and consumer products. Needs surface finishing to prevent corrosion. Standard surface prep before plating. No fears of embrittlement as strength is low (hardness-strength measured on Rb scale).

Plain high carbon steels:

1055 & 1095 High carbon (0.55% & 0.95%) steels sometimes called spring steel, piano wire or music wire. Usually heat treated to very high strength-hardness (Rc50 and up). Widely used for tension or compression springs in addition to flat, conical, or Belleville washer type springs. Usually requires surface finishing for corrosion protection. Care should be exercised in surface prep before plating to prevent pitting or embrittlement from pickles. Can be very susceptible to hydrogen embrittlement - caution should be exercised when cleaning and plating. Sometimes requires baking at lower temperatures (275 deg. F) to prevent overtempering during an embrittlement relief bake

Low Alloy Steels

4130 The original "chrome moly" steel. Widely used since the 1930's, a workhorse steel alloy during World War II. Still one of the most widely used aircraft grade low alloy steels because of its combinations of weldability, ease of fabrication, and mild hardenability from heat treatment. In thin sections, can be hardened and tempered to high strength levels, although caution is advised here. In its most widely used normalized heat treat condition, it has good strength levels in the 90,000-125,000 psi tensile range (Rc20-27) Excellent weldability for an aircraft alloy. Can be case hardened by nitriding, carbonitriding and at times carburizing. Needs surface finishing for corrosion protection. Standard surface prep before plating. Can be very susceptible to hydrogen embrittlement in the very high heat treat conditions > Rc 36. □ Many times used as a casting alloy, although now being replaced by PH grade stainless steels.

4140 Very similar to 4130 except higher carbon (0.4% vs 0.3% carbon) Higher strength levels possible from this alloy due to the higher carbon content. Better fatigue properties than 4130. Many times nitrided for better surface wear properties. Needs surface finishing for corrosion protection. Standard surface prep before plating. Can be very susceptible to hydrogen embrittlement in heat treat conditions above Rc36.

4340 A widely used alloy for aircraft structures today. Nickel added to chemistry to vastly improves ductility and toughness. Can be heat treated to very high strength levels (variants like 300M 4330V, D6AC and Hy-Tuf have specialized properties allowing heat treatment to very high strength levels for landing gear struts, Navy aircraft arrestor hooks, etc.). One variant can be welded (D6AC) and is widely used in Space Shuttle booster components. Excellent, almost unparalleled fatigue properties in the right heat treat conditions. Standard 4340 normally is not weldable. Has some "habits" that need special attention during heat treatment. Good machinability. Most definitely needs surface protection to prevent corrosion. Standard surface prep before plating but care should be exercised to prevent pitting and embrittlement from pickle. Can be very susceptible to hydrogen embrittlement in the higher strength levels (> Rc 36). Sometimes found in casting applications. Tremendous data base from decades of commercial and military aircraft use.

6150 A chrome vanadium alloy similar to 4340. Similar comments on uses and plating precautions as for 4340.

8620 & 9310 & 4620 Chrome-Molybdenum-Nickel alloys widely used as a carburizing grade of steel (surface hardened for wear resistance-surface hardness Rc 60+). High core hardness (Rc30-40 range) usually. Excellent toughness and strength. Can be welded but not widely seen. Similar comments on uses and metal finishing precautions as for 4340. If carburized: a) baking must be at the lower 275 deg. F temperature b) extra precautions during acid cleaning due to the very high strength-hardness carburized surface.

52100 A high carbon (1%), high chrome alloy steel. The workhorse steel for ball and roller bearings. Commonly heat treated to very high strength - Rc 60 and up. Usually does not see metal finishing as corrosion protection is afforded by oils and grease within bearing assemblies. Care should be exercised to prevent pitting and hydrogen embrittlement if surface finishing - surface preparation is called for. Newer bearing applications sometimes require thin dense chrome plating. Almost always requires baking at lower temperatures - 275 deg. F - for embrittlement relief to avoid over tempering during the bake.

High Alloy Steels

Maraging - 9Ni-4Co - AF1410 - Aero-Met 100 group. Higher alloy content than the low alloy steels, but not to the level of stainless or heat resistance alloys. Usually have high nickel, moly or cobalt contents, but lower chrome (<12%). Very high strength (above 250,000 psi or >Rc50). A sophisticated alloy group, used for critical high strength applications in aircraft and missiles. Usually requires metal finishing for corrosion or surface wear improvement. Caution during metal finishing is recommended to prevent pitting and hydrogen embrittlement. Surface prep is more complicated due to high cobalt and nickel content. Stripping of nickel type plating from these steels can be tricky due to the high nickel content of the steel. Can be susceptible to hydrogen embrittlement in these higher strength levels.

Stainless Steels

Stainless steels must contain at least 12% chromium in order to form a stable chromium oxide surface layer which provides the self-protection against corrosion-oxidation (a stable passive film). They usually contain nickel and/or other elements for enhanced corrosion protection over varying temperature ranges or expected chemical environments. Some have very little carbon - some moderate to high carbon content. Many times, stainless steels require passivation to re-establish the passive chromium oxide layer inherent to this type steel.

There are 4 basic groups for stainless steels:

200 series - Plain, mid to high chromium, non heat treatable. Usually seen in sheet metal form as the grade is highly formable. Good corrosion protection. Seen in consumer goods, automotive trim and exhaust tubing. A magnetic stainless alloy. If surface finishing is called out, standard prep usually required.

300 series - High chromium-high nickel (18%Cr 8% Nickel) sometimes called the 18-8 series. Not heat treatable. Normally used in sheet, plate & tubing forms. Can be readily cold worked to improve strength with a resulting drop in ductility. When cold worked to improved properties, temper call-outs such as 1/4 hard, 1/2 hard and full hard are noted. Not magnetic in annealed form, becoming slightly magnetic as cold work percentage increases (a mechanical transformation to low strain martensite occurs). Excellent corrosion protection across a wide range of reactive environments. One of the original grades of stainless. Only a few grades (321, 347) can be welded. Sometimes cadmium plated (believe it or not!). Normally only passivation is called out if required. Standard surface prep required, but some grades such as 303Se (selenium modified) can cause problems during passivation. 316 best grade for corrosion resistance. Normally immune to hydrogen embrittlement.

400 series - Low chromium, (12-15%) moderate carbon heat treatable stainless steels. The earliest type of heat treatable stainless steels. Somewhat basic in metallurgy. Several grades such as 431 have many bad habits as an alloy. Care should be exercised in surface prep and plating to prevent pitting and hydrogen embrittlement. Fully magnetic in heat treated conditions. Many times high carbon grades such as 440 and 440C are referred to as surgical stainless steel. These are heat treatable to very high levels for sharpness and wear resistance. Also seen in ball and roller bearings. Can involve tricky heat treatments and surface finishing. Passivation treatments can present a challenge with these alloys. Extra care should be exercised during any plating and cleaning operations. □ Can be very susceptible to hydrogen embrittlement.

PH grades - Probably one of the best all around structural steels available today. Sees wide use in aircraft and aerospace structures. Heat treatable by solution treatment and precipitation hardening (hence the PH designation) to high strengths with good toughness, corrosion resistance and fatigue life. Moderate to good machinability. Can be readily welded. Originally invented in the 1960's. North American Aviation XB-70 Valkyrie bomber used as a test bed for this new family of alloys. Alloy types seen today are 17-4, 15-5, 13-8Mo, 15-7, and 17-7 with the first digits denoting the chrome content and the second digit the nickel

content. Many times plating or other coatings are specified for a surface finish. Passivation also a popular callout. Standard surface preparation methods needed - usually requires a strike or underplate prior to plating. Fully magnetic in heat treated conditions. Can be susceptible to hydrogen embrittlement, although to a lesser degree than the 400 series stainless or the low alloy steels. (PH grades known under other trade names are AM-350 or 355, Custom 450 & 455)

Tool Steels

Many different families developed over the past 75 years, initially for machine shop tools, later expanded to structural applications during past few decades. Almost all have high carbon contents in addition to high chromium, tungsten, vanadium, and molybdenum contents (all strong carbide formers during heat treatment).

W1 - S2 - F2 - O2 - L6 - D2 & D3 - A2 & A6 are common industrial grades, with the designations corresponding to alloy content, heat treatment method, and wear and shock resistance. Not commonly seen by metal finishers. If plating is specified, it is usually for extended wear life in tool and die applications.

H11 - H13 - M2 - M50 are common grades of tool steels seen in structural applications in aircraft and aerospace structures due to their very high strengths, wear resistance and temperature resistance. Can be very tricky to heat treat, clean during metal finishing and also plating. Can be very susceptible to hydrogen embrittlement if not processed correctly. Also can be susceptible to stress corrosion cracking not only during service but also during actual metal finishing operations. Being phased out of critical aircraft applications in favor of newer alloys such as Aero-Met 100 etc.

Steel Heat Treatment:

Adding heat or thermal energy to steels does more than just soften it. Steels are known as allotropic alloys - capable of existing in many forms. The thermal energy supplied during precise heat treatment can transform the crystal structure into vastly different forms. Metallurgists call them phases, and such terms as ferrite, austenite, martensite and bainite denote these phases present in steels after heat treatment. For metal finishers this is not important to know, but it can be important to be familiar with heat treat terms that can give you a clue as to how the steels will react to your metal finishing operations. Common heat treat terms seen in the industry are:

Normalize: Consists of uniform heating in a controlled atmosphere to a very high temperature (1500 deg. F and up) above a certain critical temperature, followed by cooling in still air down to room temperature. This produces a uniform structure & properties through the steel. Better properties than annealed result. No special precautions for metal finishers - resulting condition not conducive to hydrogen embrittlement.

Anneal: Consists of uniform heating in a controlled atmosphere below a certain critical temperature, holding for some period of time, then slowly cooling down to room temperature. Produces the softest, lowest strength condition. Removes stresses, lowers hardness, increases ductility by producing metallurgical phases good for forming. No special precautions needed by metal finishers here, as resulting metallurgical phases are not conducive to hydrogen embrittlement. Several types of annealing possible such as Full Anneal, Partial Anneal, Spheroidize Anneal, Induction Anneal, and Stress Relief Anneals.

Hardened or Hardened and Quenched: Consists of uniform heating in a controlled atmosphere above a certain critical temperature (usually > 1500 deg. F), holding for some period of time, followed by rapid cooling by immersion into quench oil or water.

Result = the steel has changed phases internally to a very high strength - but brittle structure called Martensite. Must be followed by tempering.

Tempering: Consists of uniform heating in air to relatively lower temperatures (300 - 1200 deg. F depending on desired properties), holding for some period of time usually 1-4 hours, then air cooling to room temperature. Result = the high strength but brittle martensitic structure has now been tempered or relieved of the ultra high stresses that made the martensite brittle. Metallurgically the structure is now called *tempered martensite* a very useful structure or phase in steel. As the tempering temperature goes up, more and more of the ultra high martensite stresses are relieved - therefore the strength of the tempered martensite goes down.

Tempering temperature goes up >> strength (hardness) goes down

Tempering is a critical step in the heat treatment of steels. Although the temperatures seen here are relatively lower, their precise range varies widely for most steels. There can be tempering ranges or curves

that behave strangely, causing unpleasant surprises for those not schooled in the art of heat treating.

Solution Anneal - Precipitation Hardening: Heat treat terms seen for precipitation hardening (PH) stainless steels, some high alloy steels, and tool steels. Solution annealing consists of heating in an inert gas or vacuum atmosphere to very high temperatures (many times 1700 deg F and up) followed by controlled atmosphere cooling down to room temperature. Solution annealing dissolves (just like liquid solutions) in the solid state, alloying additions needed to strengthen the alloy. The cool down freezes these alloy additions into a new over-saturated solid solution. The second step, precipitation hardening, occurs at much lower temperatures in the range of 800-1150 deg. F. Here the dissolved alloy additions slowly rearrange themselves during the reheating, into distinct precipitated particles within the steel causing a rise in the strength-hardness of the steel. Solution annealing and precipitation hardening are direct cousins of the fundamentals of aluminum heat treating, which will be covered in Omega Update # 5.

Engineers are always seeking better properties from metals. As noted before, the properties we seek improvements are tensile, yield and shear strength, better ductility or elongation under load, enhanced fracture toughness and superior fatigue properties. Sometimes better properties simply can be obtained from changes in the chemistry of the metal, but most of the time heat treatment must happen. Regardless of how metallurgists arrive at better properties, we always have to have methods to measure these properties. A handy chart that relates tensile strength to hardness for steels that have been heat treated is reproduced on page 8. It also shows the relationship between Rc hardness, Knoop and Vickers microhardness. Hardness-to-tensile strength relationships can provide us with a quick and easy estimate of the underlying mechanical properties of the alloys evaluated. (Sometimes tensile strength is called out in pascals (Pa) or mega pascals (MPa = Pa x one million). The conversion factor is: One psi = 6895 Pa One KSI = 6,895,000 Pa or 6.895 MPa)

Congratulations! You have survived your first course in Metallurgy 101. Omega Update # 5 on Aluminum Metallurgy will be coming out later this summer, 2002. We hope this information will be helpful to you in your metal finishing work.

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NOTE:

The reader is cautioned that the subject nature of metal finishing and hydrogen embrittlement is technical and complex. Some simplification of metallurgical concepts may be presented in order for an easier understanding of the subject matter for the intended reader.

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