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Metallurgy

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Overview

Metalworking fluids are exactly what the term means: the fluids are used to work the metal. The work can be any method that changes the shape of the metal. This applies to both metal deformation, as in drawing and stamping, as well as metal removal, as in machining and grinding. Understanding the basics of metallurgy provides sufficient background to know how the various metals we encounter differ. These differences impact the types of fluids chosen for the individual operations. However, remember that this is just one piece of the puzzle in choosing a fluid for an application.

What is Metallurgy

Metallurgy is the science and understanding of metals. There are many properties that are important to a metallurgist. The structure of the metal, down at the atomic level, is where most properties are defined. The specialized three-dimensional arrangements are called the crystalline structure. It is this crystalline structure that defines the strength, malleability, electrical conductivity, thermal expansion, specific heat, and melting point. However, not all of these apply to or impact a fluid selection. The main features that we must concern ourselves with are hardness and carbon content for ferrous alloys. The hardness predicts the machineability while the carbon content impacts the hardness and resistance to corrosion. For non-ferrous, we focus on the alloying contents and the stain potential.

Ferrous and Non-Ferrous

In its simplest terms, metals are viewed as either ferrous or non-ferrous. The term "ferrous" means that iron is included. Iron is an element with a chemical term of "Fe" which is derived from the Latin word "ferrum." Steel and cast iron are both ferrous alloys. Non-ferrous, therefore, is any metal that does not contain any iron, except for trace amounts. Aluminum is the largest category of non-ferrous alloys that we typically encounter in metalworking applications. However, non-ferrous alloys also include the categories of brass, bronze, copper, nickel and titanium. Materials like glass and quartz and other ceramics will not be discussed here.

Ferrous Alloys

Steel and cast iron are both ferrous alloys and contain the element iron (Fe) and carbon (C). The carbon content differentiates these two. Steel can contain up to 1.5% carbon while cast iron may contain from 2.0 to 4.0% carbon. Other elements that are added into this mixture impact the properties and performance of the metals. A four-digit number system was adopted by the organizations involved with the metals. The first two digits indicate the major metallic alloys present while the last two digits represent the carbon content in hundredths of a percent. These combinations yield the numerical designations as listed in Table 1. As an example, 4140 steel contains iron with chromium and molybdenum and 0.40% carbon. Aside from the specific steel alloys listed in Table 1, there are two other categories for steel: tool steel and stainless steel. Metalworking product selection is driven by the hardness of the alloy and the application.

Table 1
Carbon and Alloy Steel Designation System

Alloy Series	Alloy Content
10XX	Plain Carbon
11XX	Resulfurized
12XX	Resulfurized and rephosphorized
13XX, 15XX	Manganese
23XX, 25XX	Nickel
31XX, 32XX, 33XX, 34XX	Nickel plus chromium
40XX, 44XX	Molybdenum
41XX	Chromium plus molybdenum
43XX, 47XX, 81XX, 86XX, 87XX, 88XX, 93XX, 94XX, 97XX, 98XX	Nickel plus chromium plus molybdenum
46XX, 48XX, 97XX, 98XX	Nickel plus molybdenum
50XX, 51XX	Chromium
51XXX, 52XXX	Chromium plus greater than 1.0% carbon
61XX	Chromium plus vanadium

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Tool Steels

Tool steel covers more than just tooling. It also covers molds, bearings, wear parts and other structural components. Tool steels are categorized by function as defined by a letter and two numbers. High-speed steel is used in tooling where high speeds create large amounts of frictional heat. Tungsten, chromium, and vanadium are added to increase the durability of this metal. This is commonly referred to as T1. When molybdenum is used, it is referred to as M-type. Details on tool steels can be found in Table 2. The metalworking fluid will mostly be higher lubrication technologies. This will be soluble oils and heavy-duty solution synthetics. Lower speed operations will require straight oils.

Stainless Steels

As its name implies, stainless steel is "stainless" because of the incorporation of chromium at a minimum of 12%. This produces a protective surface oxide film. The alloying elements also make stainless steel very difficult to machine. See Table 3 for a brief description of these alloys. There is also a process called precipitation hardness (pH) that involves specific heat treating steps to increase the strength of the alloy. For example, 17-7 pH stainless steel contains 17% chromium and 7% nickel. pH can also be used for aluminum but at lower temperatures. The metalworking fluid will mostly be higher lubrication technologies. This will be soluble oils and heavy-duty solution synthetics. Lower speed operations tend to use straight oils.

Table 2 - Tool Steel Categories

Tool Steel Categories Name	Application	Alloying Element(s)	Reference
High-speed	High-speed machining	Tungsten or molybdenum	T-type and M-type
Hot Work Die	Die casting	Chromium	H1-H19
Hot Work Die	Die casting	Tungsten	H20-H39
Hot Work Die	Die casting	Molybdenum	H40-H59
Cold Work	Forming at <500°F	Oil hardened	O-type
Cold Work	Forming at <500°F	Air hardened	A-type
Cold Work	Forming at <500°F	High carbon, high chromium	D-type
Shock-resisting	Chisels, punches, etc.	Not Applicable	S-type
Mold	Plastic Molding	Not Applicable	P-type
Water-hardening	Slow-speed tooling	Low alloy, high carbon	W-type
Special purpose	Collets, cams, arbors	Varies depending on need	L-type

Table 3 - Stainless Steel Designation System

Series	Alloying Elements
2XX	Chromium plus manganese plus nickel
3XX	Chromium plus nickel
4XX	Chromium (12-20%)
5XX	Chromium (5%)
pH	Chromium plus nickel plus molybdenum or aluminum or copper

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Cast Iron

As mentioned above, cast iron differs from steel by the carbon content. Cast iron contains 2.0 to 4.0% carbon. In addition, cast iron also contains from 1.0 to 3.0% silicon (Si). The combination of these elements creates a unique microstructure that leaves excess carbon. It is the excess carbon that further defines the forms of iron known as malleable, nodular, ductile, gray and white iron.

The most common type of cast iron is called gray iron. A freshly fractured surface has a dull gray texture that is related to the graphite flakes that form. The flaking also means that this form of cast iron has very little strength. However, if the carbon and silicon content are kept at their lowest levels, there is less graphite. A freshly fractured surface takes on a white appearance, hence the name white iron. This form is very hard and has extremely good wear resistance. Heat treating white iron creates malleable iron. Adding specific rare earth metals to gray iron creates nodules of graphite rather than flakes. Nodular iron is also very ductile.

There are different forms of hardening and tempering that produce different effects on cast iron. This involves different aspects of heating and cooling the iron at different rates. This can also include quenching (in both air and liquids) along with exposing the cooling iron to an atmosphere other than oxygen.

The two big issues we face with cast iron alloys are corrosion protection and detergency. The corrosion threshold of the metalworking fluid becomes more of a critical factor when considering the application. Further, the very small grains of cast iron often become very dirty and are referred to a cast iron "smut." The detergency of the coolant machining the alloy is very important. This also impacts the handling of the cast iron fines. Generally speaking, solution synthetics and semi-synthetics handle both of these issues quite well.

Aluminum

Aluminum can be found in two forms: cast and wrought. The associations that deal with these alloys created a numbering system used to identify the alloys. In brief, the three-digit series are cast alloys and the four-digit series are the wrought alloys. Please see Table 4 for generic information and Table 5 and Table 6 for detailed information.

Table 4 -
Cast Aluminum Designation System

Alloy Series	Nominal Alloy Content
1XX	99.0% purity
2XX	Copper
3XX	Silicon with minor additions of copper and/or magnesium
4XX	Silicon
5XX	Magnesium
6XX	Unused
7XX	Zinc
8XX	Tin
Wrought Aluminum Designation System	
1XXX	99.0% purity
2XXX	Copper plus minor additions of manganese and magnesium
3XXX	Manganese plus magnesium
4XXX	Silicon
5XXX	Magnesium plus minor additions of manganese and chromium
6XXX	Silicon and magnesium plus minor additions of copper, manganese or chromium
7XXX	Zinc and magnesium plus minor additions of copper and chromium

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Aluminum is used because of its density and strength. It is lighter than ferrous alloys and, depending upon the application, stronger than a ferrous alloy. There are two main problems with aluminum: surface finish and staining. Cast aluminum is easy to machine based on machineability ratings but difficult to obtain a good surface finish. It is the porosity of this alloy, created in the casting process, which can create havoc with tooling and, subsequently, the surface finish. It is Quaker's experience that the gummy nature of aluminum makes it difficult to machine. This has been confirmed with several end users. We do know that very good boundary lubrication is typically required to handle the finish requirements. This demands soluble oils and heavy-duty solution synthetics. Some semi-synthetics can handle some grades of cast aluminum depending upon the surface finish requirements. The predominant alloys we see are 308, 356, 380 and 390 and are highlighted red on Table 5.

The wrought alloys have a higher tendency toward staining because of the higher concentrations of copper, magnesium, and zinc as alloying elements. Good non-ferrous inhibitors usually handle these alloys quite well. Usually, solution synthetics and semi-synthetics are good for these applications. The predominant alloys we see are 2024, 6061, and 7075 and are highlighted red on Table 6.

Summary

As you can see, there are several aspects to understand. To make things easier for you, keep the attached tables with you for quick reference. However, you will find that, while these lists appear to be extensive, you will actually encounter a smaller percentage in use.

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Table 5
Cast Aluminum Chemical Composition (% Alloying Elements)

Alloy	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Tin	Titanium
208	2.5 - 3.5	1.2	3.5 - 4.5	0.50	0.10	----	0.35	1.0	----	0.25
213	1.0 - 3.0	1.2	6.0 - 8.0	0.60	0.10	----	0.35	2.5	----	0.25
222	2.0	1.5	9.2 - 10.7	0.50	0.15 - 0.35	----	0.50	0.8	----	0.25
242	0.7	1.0	3.5 - 4.5	0.35	1.2 - 1.8	0.25	1.7 - 2.3	0.35	----	0.25
295	0.7 - 1.5	1.0	4.0 - 5.0	0.35	0.03	----	----	0.35	----	0.25
308	5.0 - 6.0	1.0	4.0 - 5.0	0.50	0.10	----	----	1.0	----	0.25
319	5.5 - 6.5	1.0	3.0 - 4.0	0.50	0.10	----	0.35	1.0	----	0.25
328	7.5 - 8.5	1.0	1.0 - 2.0	0.20 - 0.60	0.20 - 0.60	0.35	0.25	1.5	----	0.25
A332	11.0 - 13.0	1.2	0.50 - 1.5	0.35	0.7 - 1.3	----	2.0 - 3.0	0.35	----	0.25
F332	8.5 - 10.5	1.2	2.0 - 4.0	0.50	0.50 - 1.5	----	0.50	1.0	----	0.25
333	8.0 - 10.0	1.0	3.0 - 4.0	0.50	0.05 - 0.50	----	0.50	1.0	----	0.25
355	4.5 - 5.5	0.6	1.0 - 1.5	0.50	0.40 - 0.60	0.25	----	0.35	----	0.25
356	6.5 - 7.5	0.6	0.25	0.35	0.20 - 0.40	----	----	0.35	----	0.20
357	6.5 - 7.5	0.15	0.05	0.03	0.45 - 0.60	----	----	0.05	----	0.20
360	9.0 - 10.0	2.0	0.60	0.35	0.40 - 0.60	----	0.50	0.50	0.15	----
380	7.5 - 9.5	2.0	3.0 - 4.0	0.50	0.10	----	0.50	3.0	0.35	----
A384	10.5 - 12.0	1.3	3.0 - 4.5	0.50	0.10	----	0.50	1.0	0.35	----
390	16.0 - 18.0	1.3	4.0 - 5.0	0.10	0.45 - 0.65	----	----	0.10	----	0.20
413	11.0 - 13.0	2.0	1.0	0.35	0.10	----	0.50	0.50	0.15	----
B443	4.5 - 6.0	0.80	0.15	0.35	0.05	----	----	0.35	----	0.25
514	0.35	0.50	0.15	0.35	3.5 - 4.5	----	----	0.15	----	0.25
518	0.35	1.8	0.25	0.35	7.5 - 8.5	----	0.15	0.15	0.15	----
520	0.25	0.30	0.25	0.15	9.5 - 10.6	----	----	0.15	----	0.25
535	0.15	0.15	0.05	0.10 - 0.25	6.2 - 7.5	----	----	----	----	0.10 - 0.25
705	0.20	0.80	0.20	0.40 - 0.60	1.4 - 1.8	0.20 - 0.40	----	2.7 - 3.3	----	0.25
707	0.20	0.80	0.20	0.40 - 0.60	1.8 - 2.4	0.20 - 0.40	----	4.0 - 4.5	----	0.25
712	0.15	0.50	0.35 - 0.65	0.05	0.60 - 0.80	----	----	6.0 - 7.0	----	0.25
713	0.25	1.1	0.40 - 1.0	0.6	0.20 - 0.50	0.35	0.15	7.0 - 8.0	----	0.25
850	0.70	0.70	0.7 - 1.3	0.10	0.10	----	0.7 - 1.3	----	5.5 - 7.0	0.20

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Table 6
Wrough Aluminum Chemical Composition (% Alloying Elements)

Alloy	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Zinc	Vanadium	Titanium	Other
1050	0.25	0.40	0.05	0.05	0.05	----	0.05	0.05	0.03	0.03
1070	0.20	0.25	0.04	0.03	0.03	----	0.04	0.05	0.03	0.03
1200	<1.0	0.05	0.05	----	----	----	0.10	----	0.05	0.03
2011	0.40	0.70	6.0	----	----	----	0.30	----	----	Bismuth & Lead
2014	0.5 - 1.2	0.70	3.9 - 5.0	0.4 - 1.2	0.2 - 0.8	0.10	0.25	----	0.15	0.15
2024	0.50	0.50	3.8 - 4.9	0.3 - 0.9	1.2 - 1.8	0.10	0.25	----	----	----
3003	0.60	0.70	0.05 - 0.2	1.0 - 1.5	----	----	0.10	----	----	0.05
3004	0.30	0.70	0.25	1.0 - 1.5	0.8 - 1.3	----	0.25	----	----	0.05
3005	0.60	0.70	0.30	1.0 - 1.5	0.2 - 0.6	0.10	0.25	----	0.10	0.05
3103	0.50	0.70	0.10	0.9 - 1.5	0.30	0.10	0.20	----	----	0.05
5005	0.30	0.70	0.20	0.20	0.5 - 1.1	0.10	0.25	----	----	0.05
5049	0.40	0.50	0.10	0.5 - 1.1	1.6 - 2.5	0.30	0.20	----	0.10	0.05
5052	0.25	0.40	0.10	0.10	2.2 - 2.8	0.15 - 0.35	0.10	----	----	0.05
5083	0.40	0.40	0.10	0.4 - 1.0	4.0 - 4.9	0.05 - 0.25	0.25	----	0.15	0.05
5086	0.40	0.50	0.10	0.2 - 0.7	3.5 - 4.5	0.05 - 0.25	0.25	----	0.15	0.05
5154	0.25	0.40	0.10	0.10	3.1 - 3.9	0.15 - 0.35	0.20	----	0.20	0.05
5251	0.40	0.50	0.15	0.1 - 0.5	1.7 - 2.4	0.15	0.15	----	0.15	0.05
5454	0.25	0.40	0.10	0.5 - 1.0	2.4 - 3.0	0.05 - 0.20	0.25	----	0.20	0.05
5754	0.40	0.40	0.10	0.50	2.6 - 3.6	0.30	0.20	----	0.15	0.05
6005	0.6 - 0.9	0.35	0.10	0.10	0.4 - 0.6	0.10	0.10	----	0.10	0.05
6060	0.3 - 0.6	0.1 - 0.3	0.10	0.10	0.35 - 0.6	0.05	0.15	----	0.10	0.05
6061	0.4 - 0.8	0.70	0.15 - 0.4	0.15	0.8 - 1.2	0.04 - 0.35	0.25	----	0.15	0.05
6063	0.2 - 0.6	0.35	0.10	0.10	0.45 - 0.9	0.10	0.10	----	0.10	0.05
6082	0.7 - 1.3	0.50	0.10	0.4 - 1.0	0.6 - 1.2	0.25	0.20	----	0.10	0.05
6101	0.3 - 0.7	0.50	0.10	0.03	0.35 - 0.8	0.03	0.10	----	----	0.03
6351	0.7 - 1.3	0.50	0.10	0.4 - 0.8	0.4 - 0.8	----	0.20	----	0.20	0.05
6463	0.2 - 0.6	0.15	0.20	0.05	0.45 - 0.9	----	----	----	----	0.05
7010	0.12	0.15	1.5 - 2.0	0.05 - 0.1	2.1 - 2.6	0.05	5.7 - 6.7	----	0.06	0.05
7020	0.34	0.40	0.20	0.05 - 0.5	1.0 - 1.4	0.1 - 0.35	4.0 - 5.0	----	----	Zirconium
7021	0.25	0.40	0.25	0.10	1.2 - 1.8	0.05	5.0 - 6.0	----	0.10	Zirconium
7075	0.40	0.50	1.2 - 2.0	0.30	2.1 - 2.9	0.18 - 0.28	5.1 - 6.1	----	0.20	0.05

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