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Mechanisms for Strengthening Aluminum

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Aluminum is the second most commonly used metal after steel. Common engineering applications of aluminum include aerospace, automotive, buildings, and soda and beer cans. Aluminum has some unique properties: it is very light compared to steel, it has very good electrical and thermal conductivity, and it does not rust like steel if left in air. However, pure aluminum is soft. So, it has to be strengthened in order to use it for engineering structures.

This article explains about the different families of aluminum alloys and the metallurgical mechanisms for strengthening the different alloys. This article is an abbreviated version of our on-demand course Aluminum Metallurgy.

Families of Aluminum Alloys

There are several families of wrought aluminum alloys. Each family is based on specific major alloying elements added to the aluminum. These alloying elements have a large influence on the properties. The different families of alloys and the major alloying elements are

- 1xxx: no alloying elements
- 2xxx: Copper
- 3xxx: Manganese
- 4xxx: Silicon
- 5xxx: Magnesium
- 6xxx: Magnesium and silicon
- 7xxx: Zinc, magnesium, and copper

The first number in the alloy designation indicates the particular alloy family. Within each family there are different alloys based on the amounts of the major alloying elements present and the types and amounts of minor alloying elements that have been added. The XXXôs are used to indicate the different alloys in each family.

The strength of aluminum alloys can be modified through various combinations of cold working, alloying, and heat treating. All the alloys can be strengthened by cold working processes such as cold rolling or wire drawing. Except for the 1xxx alloys, additional strength can be obtained by solid solution strengthening, dispersion strengthening, and precipitation strengthening. The particular strengthening mechanisms possible depend on the alloy.

This table shows the maximum nominal yield and tensile strengths for the different alloy families and the methods by which the strength is increased. There is a wide range of strengths possible with aluminum alloys. The yield and tensile strengths possible in the different alloy families depends on the strengthening mechanisms available.

Alloy series	Methods for increasing strength	Yield Strength ksi (MPa)	Tensile Strength, ksi (MPa)
1xxx	Cold-working	4-24 (30-165)	10-27 (70-185)
2xxx	Cold-working, Precipitation	11-64 (75-440)	27-70 (185-485)
3xxx	Cold working, solid solution, dispersion	6-36 (40-250)	16-41 (110-285)
4xxx	Cold working, dispersion	46 (315)	55 (380)
5xxx	Cold working, solid solution	6-59 (40-405)	18-63 (125-435)
6xxx	Cold working, precipitation	7-55 (50-380)	13-58 (90-400)
7xxx	Cold working, precipitation	15-78 (105-540)	33-88 (230-605)

Cold working

Cold working involves the reduction in thickness of a material. Plate and sheet of different thickness are produced by cold rolling. Wire and tubes of different diameter and wall thickness are produced by drawing. All aluminum alloys can be strengthened by cold working.

During the cold working, the strength of a metal increases due to the increase in the number of dislocations in the metal compared to its pre-cold-worked condition. Dislocations are defects in the arrangement of atoms within a metal (discussed in Principles of Metallurgy). Dislocations move through a metal when it is exposed to stresses that exceed its yield strength. The strength of a metal depends on the ease of dislocation motion.

The increase in the number of dislocations due to cold working is responsible for the increase in strength. Pure aluminum at room temperature has yield strength of 4 ksi (30 MPa). In the fully cold-worked state the yield strength can be as high as 24 ksi (165 MPa). Depending on the strength requirements the amount of rolling can be controlled.

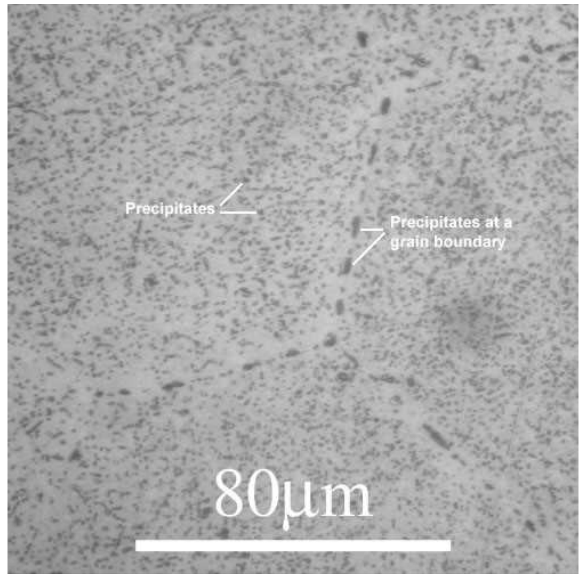
Solid solution strengthening

Certain alloying elements that are added to aluminum mix with the aluminum atoms at the atomic level in a way that result in increased metal strength. This mixture is called a solid solution because the alloying atoms are mixed in with the aluminum atoms. This is discussed in detail in Principles of Metallurgy and Aluminum Metallurgy.

The presence of the alloying elements affects dislocations in a way that increases the stress required for dislocation motion, which results in an increase in a metalôs yield and tensile strength. The extent of strengthening depends on the type and amount of the alloying elements. Manganese and magnesium are examples of elements added to aluminum for the purpose of solid solution strengthening. Solid solution strengthening can increase the yield strength of aluminum up to six times that of unalloyed aluminum.

Solid solution strengthening occurs in 3xxx and 5xxx alloys through the addition of manganese (3xxx) and magnesium (5xxx) to the aluminum. The manganese and magnesium atoms are obstacles to the motion of dislocations through aluminum. Aluminum can hold more magnesium than manganese in solid solution. Consequently, greater solid solution strengthening is possible in 5xxx alloys than in 3xxx alloys.

Precipitation strengthening



With precipitation strengthening, particles less than 0.001 mm in diameter form inside the metal. These particles are called precipitates and consist of compounds of aluminum and alloying elements or compounds of the alloying elements. This figure shows Al-Cu precipitates in an Al-Cu alloy.

Precipitates are formed as a result of a series of heat treating processes. The step of the process during which precipitates form is called aging.

Precipitation strengthening can increase the yield strength of aluminum from about five times up to about fifteen times that of unalloyed aluminum. The strength depends on the specific alloy and the aging heat treatment temperature.

Only certain alloys can be precipitation strengthened. The 2xxx, 6xxx, and 7xxx alloys can be precipitation strengthened through the formation of Al-Cu (2xxx), Mg-Si (6xxx), and Al-Zn-Mg-(Cu) (7xxx) precipitates. The 1xxx, 3xxx, 4xxx, and 5xxx alloys cannot be precipitation strengthened.

Dispersion strengthening

Dispersoid particles form during the aluminum casting process when manganese in 3xxx series alloys reacts with aluminum and iron and silicon. These particles are less than 0.001 mm in diameter. Dispersoid particles influence the grain structure that forms during heat treating so that there is increased strength compared to an alloy without dispersoids. Fully-annealed 1100 aluminum has tensile strength of 13 ksi and yield strength of 5 ksi. Fully-annealed 3003 has minimum tensile strength of 16 ksi and minimum yield strength of 6 ksi. This increase in strength is due to the grain structure formed as a result of the presence of dispersoids.

Additive strengthening

Finally, the methods of strengthening aluminum discussed here are often combined to provide even higher strength alloys. Solid solution strengthened alloys are often cold-worked and precipitation strengthening is sometimes combined with cold working prior to the aging step.

I hope this article was helpful. However, if you still have a specific metallurgy question that was not addressed, I offer a 15-minute phone consultation for $60. Iôve found that many questions can be answered in 15 minutes, helping to get people back on track. Hereôs the link to purchase the consultation http://www.imetllc.com/metallurgy-consultation/.

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