GRANTA TEACHING RESOURCES

Introductory Level MS&E
Case Study: Al Strengthening

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1. Metal Strengthening Mechanisms

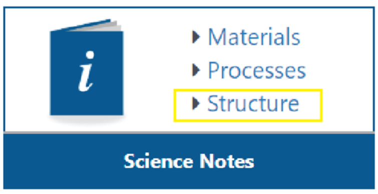
Materials scientists and metallurgists are often interested in designing alloys for specific applications. One property that is of prime importance is strength; the ability of a material to withstand an applied stress without failure. For metals, strength can be improved by restricting dislocation motion during plastic deformation. There are several techniques that can accomplish this, such as:

1. Solid Solution Strengthening
2. Strain Hardening
3. Precipitation Strengthening
4. Grain Size Strengthening

The connection between these concepts, dealing with dislocations and microstructures, and real-world properties such as tensile strength, can be difficult to grasp. In this simplified case study, we will use the Materials Science and Engineering (MS&E) Edition of CES EduPack to explore the three main hardening mechanisms for *aluminum alloys* and how the composition and processing of Al dramatically impact material properties, ultimately dictating the performance of the material.

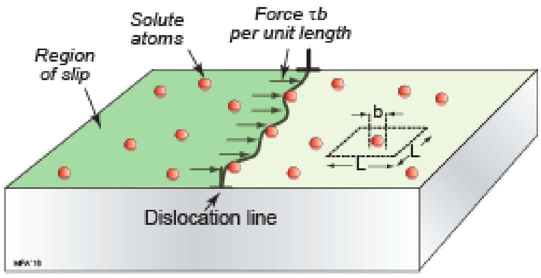
2. Exploring Strengthening of Al

The MS&E Edition of CES EduPack has an expanded section of Science Notes, labelled *Structure,* providing details on different strengthening mechanisms. These notes include helpful schematics for visualizing dislocations and microstructures, some of which are shown to the right in this page of the case study.



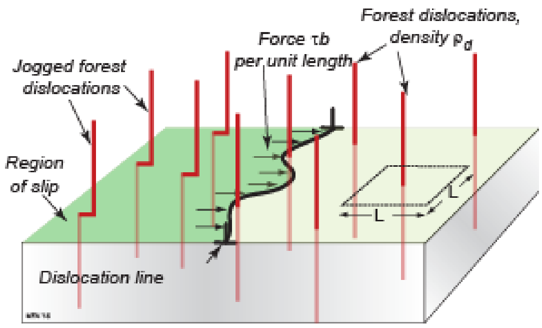
Three main strengthening mechanisms are common in Al alloys: *solid solution strengthening*, *strain hardening*, and *precipitation strengthening*.

Solid solution strengthening involves alloying metals with elements that form either substitutional or interstitial solid solutions with the native material. These solute atoms act as the dislocation motion inhibitors. A schematic of how these solutes can impede dislocations is shown below.



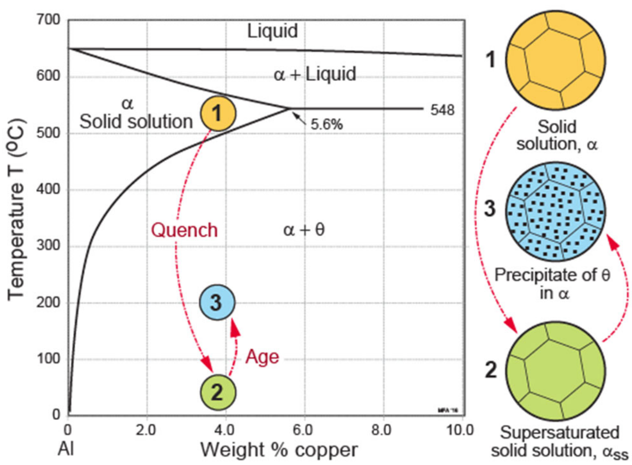
Solution hardening

Strain hardening (or work hardening) uses dislocations generated through plastic deformation to impede dislocation motion, as indicated below. Annealing can be used to control the degree of strain hardening and help tailor properties.



Work hardening

Precipitation strengthening (sometimes referred to as precipitation hardening or age hardening) hampers dislocation motion through small, strong particles dispersed within the microstructure. The mechanism of forming these *in situ* particles is shown below.



In the diagram above, an Al alloy with around 4 wt% copper is solution heat treated at 550 °C, allowing the Cu to complete dissolve into solid solution (Step 1). Upon cooling/quenching (Step 2), an aging step can be performed at either a slightly elevated temperature (Step 3) or room temperature. Decreasing the temperature moves the alloy to a low-Cu solubility region of the phase diagram; this allows Cu-rich precipitates to form. The size and shape of these precipitates depend on the time and temperature of this aging step, so understanding these effects is key to proper processing. Many different alloys can undergo precipitation hardening: magnesium-based, titanium-based, copper-cobalt and copper-beryllium systems as well as stainless steels, and more.

3. Processing of Al Alloys

Aluminum alloys play a very important role in product manufacturing today. From buildings to computers to airplanes. It is second only to steel in world production. There are many different classes of Al alloys, each with their own numeric classification. The International Alloy Designation System (IADS) gives wrought alloys four digits, where the first digit shows the main alloying element. In the AAUS system, cast alloys have four digits, with the fourth separated by a decimal point indicating the product form. Specifics of these designations can be found inside the three Al records within the MS&E Edition; age-hardened wrought, non age-hardened wrought, and cast Al alloys. Each of the records shows general properties and highlights how, even within an alloy class, processing can impact properties. To explore this and see the effect of hardening mechanisms in Al in more detail, the *Property-Process Profiles* data table can be used. A comparison between *Fracture Toughness* and *Yield Strength* is shown below for multiple Al alloys.

This plot illustrates the impact of different hardening mechanisms and their processing conditions on the mechanical properties of Al. Each record is labeled with its designation and thermal processing conditions (T=heat treated, O=annealed, F=as fabricated). Precipitation (or age) hardening has the largest impact on both fracture toughness and yield strength, but all hardening mechanisms can change the properties compared to pure Al. More importantly, the impact of the aging process details, such as time and temperature, can be seen in this chart. By examining alloys and their processing conditions side by side, more advanced understanding of materials selection and decisions can be made.

4. Conclusions

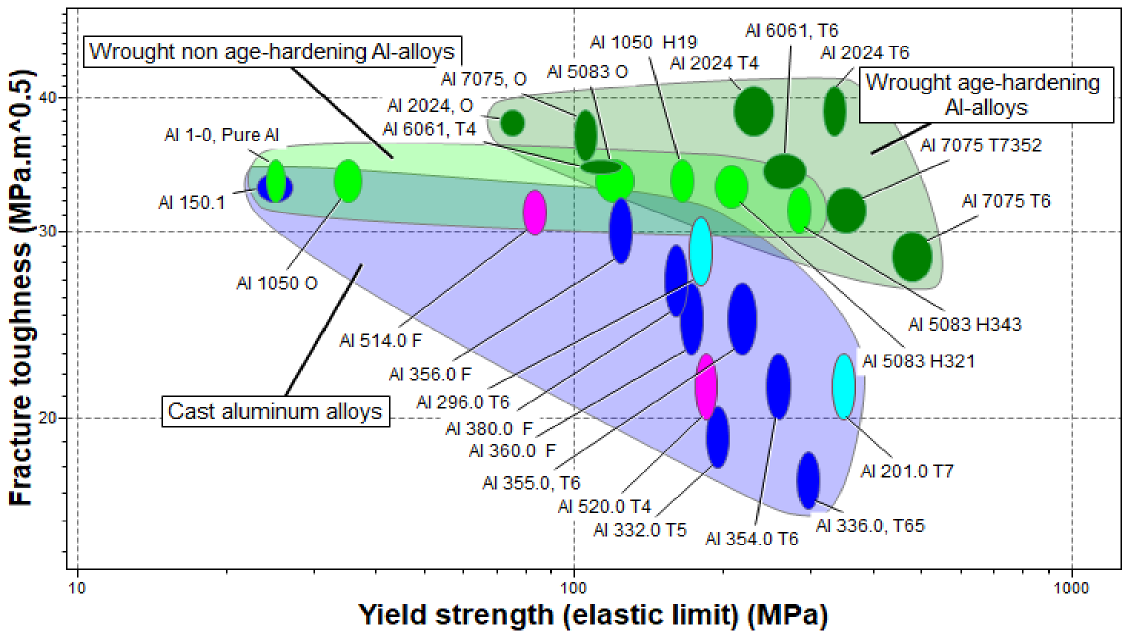
In this simplified case study, we have explored strengthening mechanisms in Al alloys and the impact they have on properties, utilizing the MS&E Edition of CES EduPack.

The three most common strengthening mechanisms in aluminum were discussed and compared using process schematics and property charts:

- Solid-solution strengthening
- Strain hardening (work hardening)
- Precipitation strengthening (age hardening)

The *Structure* Science Notes provided explanations of how each impede dislocation motion to improve strength.

To demonstrate how the different strengthening mechanisms and their heat treatments impact material properties, the *Property-Process Profiles* were examined for various Al alloy classes in a property chart.



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