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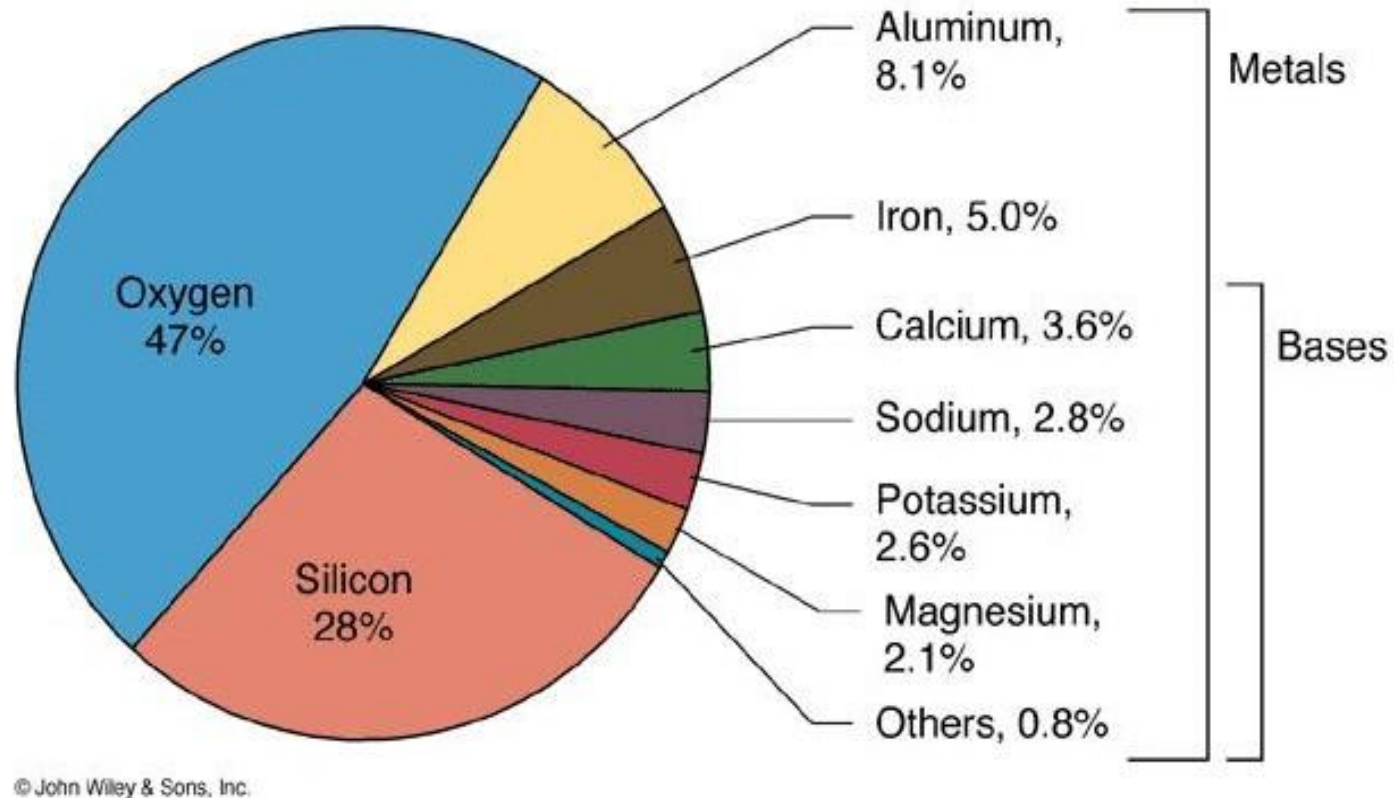
# A) Aluminium and Aluminium Alloys

*Dr Anand Mohan*

# Introduction



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❑ Al is the third most abundant element present in the earth's crust

# History of Aluminium

- Abundant element of 8% on earth crust and normally found in oxide forms ( $\text{Al}_2\text{O}_3$ ), i.e., **bauxite**, **kaolinite**, **Diaspore** etc.,
- Found mostly in United states, Italy, France.



Bauxite



Bauxite-peggily



Kaolinite

| Minerals                 | Chemical composition                                                  |
|--------------------------|-----------------------------------------------------------------------|
| Gibbsite (hydrargillite) | $\alpha\text{-Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$              |
| Baehmite                 | $\alpha\text{-Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$               |
| Diaspore                 | $\beta\text{-Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$                |
| Hematite                 | $\alpha\text{-Fe}_2\text{O}_3$                                        |
| Goethite                 | $\alpha\text{-FeOOH}$                                                 |
| Magnetite                | $\text{Fe}_3\text{O}_4$                                               |
| Siderite                 | $\text{FeCO}_3$                                                       |
| Ilmenite                 | $\text{FeTiO}_3$                                                      |
| Anatase                  | $\text{TiO}_2$                                                        |
| Rutile                   | $\text{TiO}_2$                                                        |
| Brookite                 | $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$ |
| Kaolinite                | $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ |
| Quartz                   | $\text{SiO}_2$                                                        |

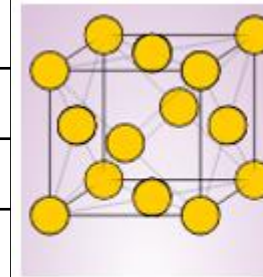
Table: Other Minerals commonly found in Bauxite, where as **Bauxite** is common ore of Al

# Properties of Aluminium

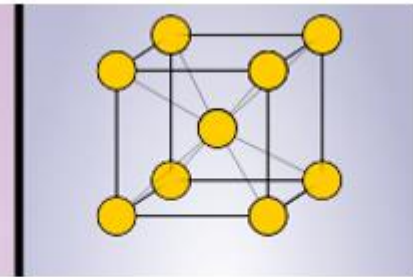


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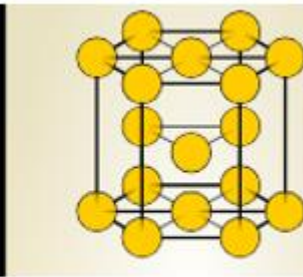
|                                                                    |               |
|--------------------------------------------------------------------|---------------|
| Atomic Number                                                      | 13            |
| Atomic Weight (g/mol)                                              | 26.98         |
| <b><i>Density (g/cm<sup>3</sup>)</i></b>                           | <b>2.6898</b> |
| Valency                                                            | 3             |
| <b>Crystal Structure</b>                                           | <b>FCC</b>    |
| <b><i>Melting Point (°C)</i></b>                                   | <b>660.2</b>  |
| Boiling Point (°C)                                                 | 2480          |
| <b><i>Mean Specific Heat (0-100°C) (cal/g. °C)</i></b>             | <b>0.219</b>  |
| <b><i>Thermal Conductivity (0-100°C) (cal/cm s. °C)</i></b>        | <b>0.57</b>   |
| Co-Efficient of Linear Expansion (0-100°C) (x10 <sup>-6</sup> /°C) | 23.5          |
| <b><i>Electrical Resistivity at 20°C (μΩcm)</i></b>                | <b>2.69</b>   |
| <b><i>Modulus of Elasticity (GPa)</i></b>                          | <b>68.3</b>   |
| Poisson's Ratio                                                    | 0.34          |



FCC



BCC

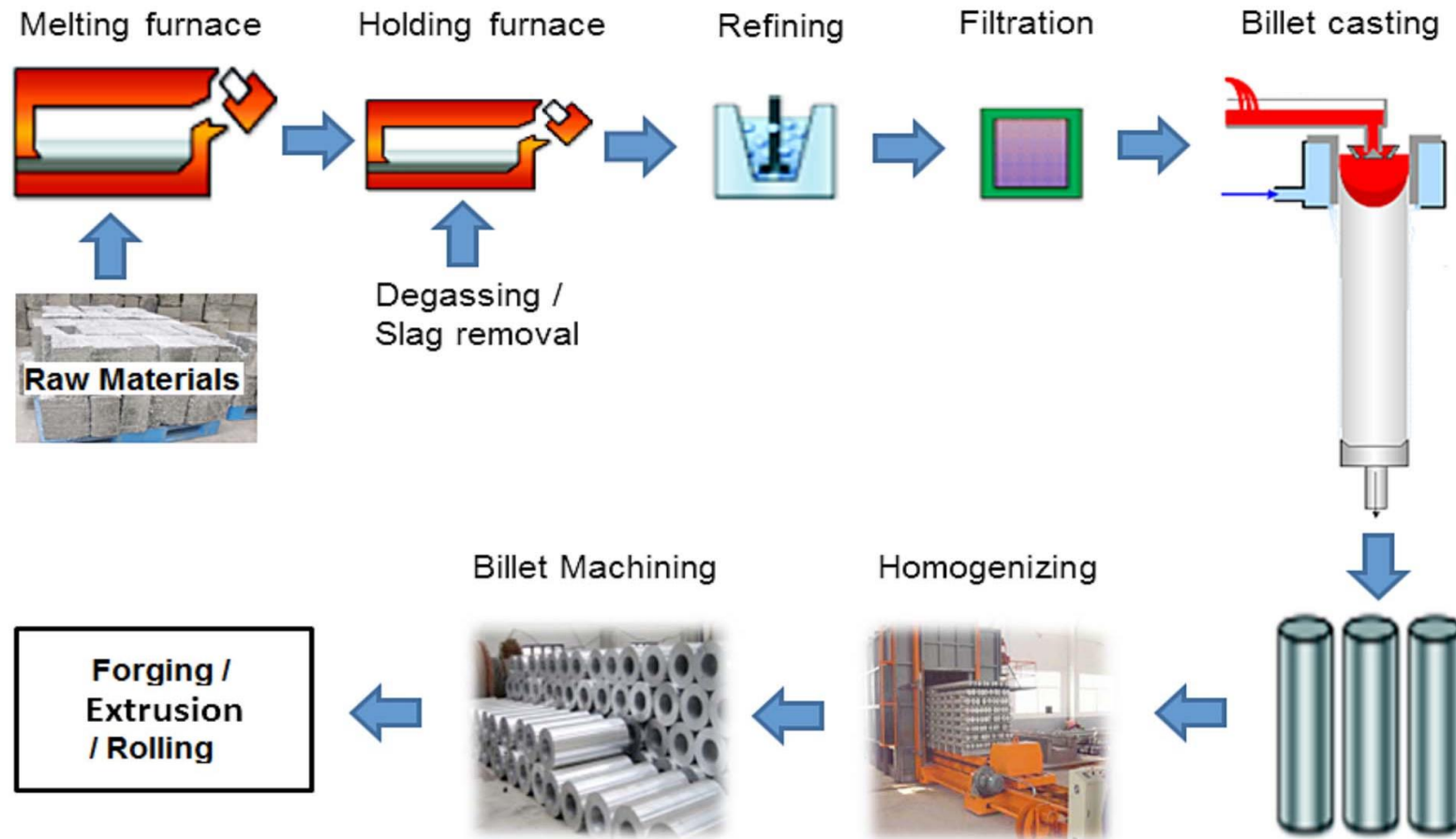


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# Production of wrought Al alloy



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# Production of wrought Al alloy



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- Wrought aluminium is produced by smelting pure aluminium ingots with the specific alloying elements required to make a given grade of aluminium.
- The smelted alloy is then cast into billets or large slabs.
- This material is then either rolled, forged or extruded into its final shape.
- In some cases, the alloys are heat treated to further enhance their properties.

## **Wrought alloy applications**

Wrought aluminium tends to have better tensile strength when compared to cast alloys. Their typical uses are listed below:

- Extrusions
- Electrical conductors & bus bars
- Aircraft airframes
- Cooking utensils
- Welding rods
- Pressure vessels
- Motorcycle frames
- Sheeting

# Production of wrought Al alloy



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## **Wrought alloy advantages**

Wrought aluminium alloys offer numerous advantages when compared to cast aluminium as indicated in the list below;

- Excellent mechanical properties
- Structural integrity i.e. no defects from casting
- Better surface finishes
- Ease of manufacture for example welding and machining
- Ease of forming, for example, aluminium can be extruded into an almost endless range of cross sections that can be custom designed to suit a specific application

# Outstanding attributes of Al



- **Good corrosion and oxidation resistance**
- **High electrical and thermal conductivity**
- **Low density**
- **High reflectivity**
- **High ductility and reasonably high strength**
- **Relatively low cost**
- **High strength-to-weight ratio**

# Microstructural Control of Al



- Important microstructural features include constituent particles and dispersoids.
- **Constituent particles are coarse intermetallic compounds** that form by eutectic decomposition during ingot solidification.
- Some are soluble, while others are virtually insoluble.



$\text{CuAl}_2$  or  $\text{SiMg}_2$



$\text{Al}_6(\text{Fe}, \text{Mn})$ ,  $\text{Al}_2\text{Fe}$ ,  $\text{Al}_7\text{FeCu}_2$ , and  $\alpha\text{Al}(\text{Fe}, \text{Mn}, \text{Si})$ .

- One of the major reasons for ingot homogenization before hot working is to dissolve these soluble compounds.
- During hot working, the large insoluble compounds are broken up and accumulate to be removed from the slag

# Microstructural Control of Al

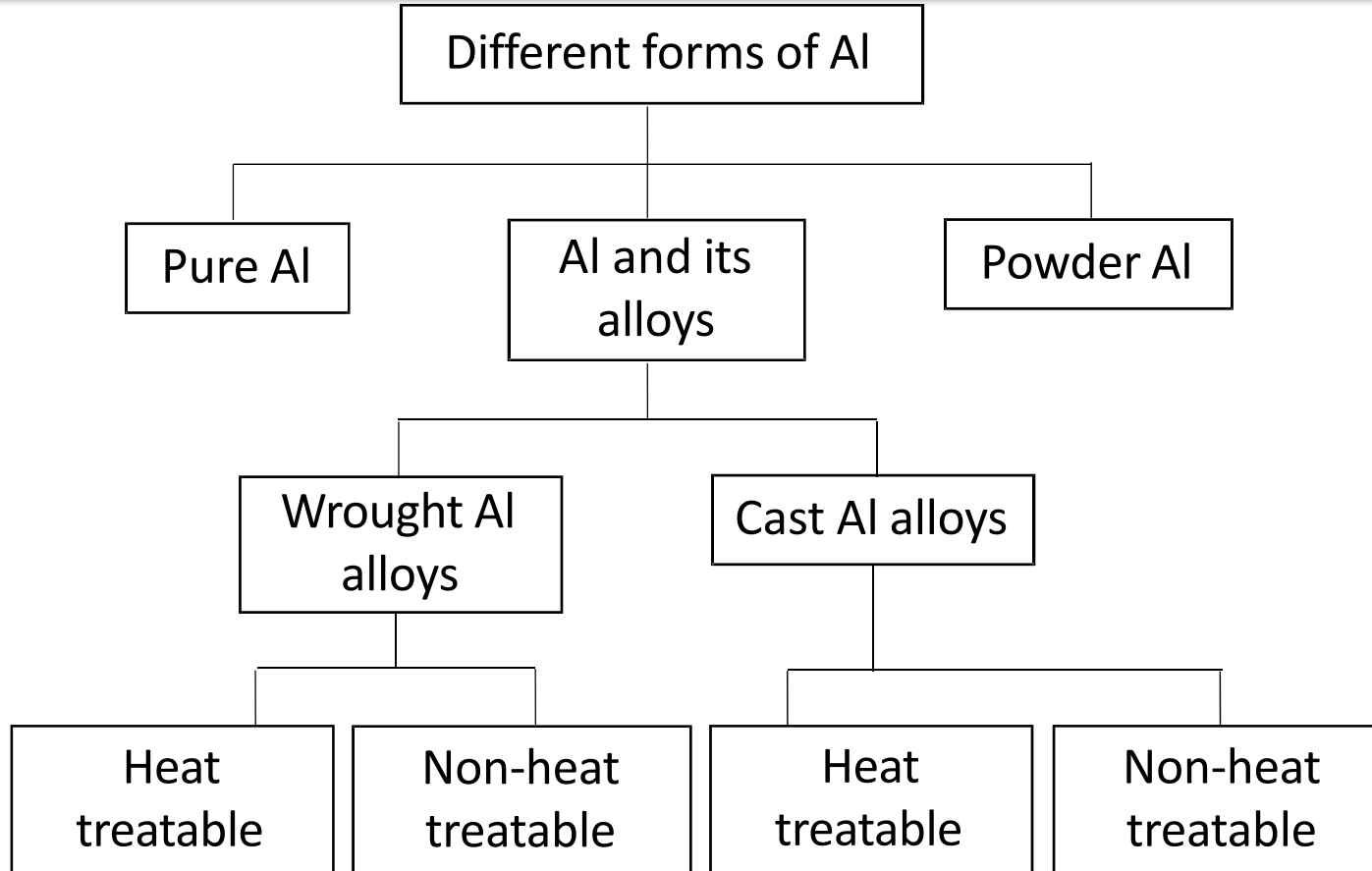


- **Dispersoids** are smaller submicron particles (**typically 0.05 to 0.5  $\mu\text{m}$** ) that form during ingot homogenization by solid-state precipitation from elements that have only limited solubility and that diffuse slowly.
- Once they form, they resist dissolution and/or coarsening.
- They usually consist of one of the transition elements; examples are  $\text{Al}_{20}\text{Cu}_2\text{Mn}_3$ ,  $\text{Al}_{12}\text{CrMg}_2$ , and  $\text{Al}_3\text{Zr}$ .
- Dispersoids are useful in retarding recrystallization and grain growth.
- Other microstructural features that can affect properties include oxide inclusions, porosity, grain size and shape, and crystallographic textures that can lead to anisotropic properties.

# Classification of Al Alloys



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# Classification of Al Alloys



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**Table 26.2 Designations for aluminum wrought alloys**

| Series | Aluminum content or main alloying element |
|--------|-------------------------------------------|
| 1xxx   | 99.00% minimum                            |
| 2xxx   | Copper                                    |
| 3xxx   | Manganese                                 |
| 4xxx   | Silicon                                   |
| 5xxx   | Magnesium                                 |
| 6xxx   | Magnesium and silicon                     |
| 7xxx   | Zinc                                      |
| 8xxx   | Others                                    |
| 9xxx   | Unused                                    |

**Table 26.3 Designations for aluminum casting alloys**

| Series | Aluminum content or main alloying element |
|--------|-------------------------------------------|
| 1xx.0  | 99.00% minimum                            |
| 2xx.0  | Copper                                    |
| 3xx.0  | Silicon with copper and/or magnesium      |
| 4xx.0  | Silicon                                   |
| 5xx.0  | Magnesium                                 |
| 6xx.0  | Unused                                    |
| 7xx.0  | Zinc                                      |
| 8xx.0  | Tin                                       |
| 9xx.0  | Other                                     |



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# Designations of wrought aluminium alloys

- ❑ International Alloy Designation system (IADS) designated Al alloys on the basis of major alloying elements
  - 1xxx (pure Al - 99 % purity)
  - 2xxx (Al-Cu alloys)
  - 3xxx (Al-Mn alloys)
  - 4xxx (Al-Si alloys)
  - 5xxx (Al-Mg alloys)
  - 6xxx (Al-Mg-Si alloys)
  - 7xxx (Al-Zn alloys)
  - 8xxx (Al-other elements like Fe, Cr, Ti, Zr, Pb, Bi etc.,)
  - 9xxx (Unused series) - yet to be invented
- The **first digit** indicates the **major alloying element**
- The **second digit** indicates **modification of alloy or impurities limit** : Original (basic) alloy is designated by "0" as these second digit. Numbers 1...9 indicate various alloy modifications with slight differences in the compositions. In the alloys of the 1xxx series the second digit indicates modifications in impurity limits: 0 means natural impurity limit, 1...9 indicate special control of one or more impurities or alloying element.

# Designations of wrought aluminium alloys



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- The **last two digits** tells the **purity of alloy** : If the aluminium is 1xxx then the last two digits designate the amount of aluminium above 99%. For example, 1025 signifies a non alloyed aluminium that is 99.25% pure aluminium with the remaining 0.75% uncontrolled impurities. In the remaining 2xxx to 8xxx series, the last two digits have no special significance. They serve only to identify the specific individual alloys and mean nothing in terms of the sequence in which the alloys were developed or registered.
- Example: In alloy 5183, the number 5 indicates that it is of the magnesium alloy series, the 1 indicates that it is the 1st modification to the original alloy 5083, and the 83 identifies it in the 5xxx series.
- The only exception to this alloy numbering system is with the 1xxx series aluminium alloys (pure aluminium) in which the last 2 digits provide the minimum aluminium percentage above 99%, i.e., Alloy 1350 (99.50% minimum aluminium).

# Temper designations (suffix after series name)



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**Table 26.4 Temper designations for aluminum alloys**

| Suffix letter “F,” “O,” “H,” “T,” or “W” indicates basic treatment condition              | First suffix digit indicates secondary treatment used to influence properties | Second suffix digit for condition H only indicates residual hardening |
|-------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| F—As-fabricated                                                                           |                                                                               |                                                                       |
| O—Annealed-wrought products only                                                          |                                                                               |                                                                       |
| H—Cold worked, strain hardened                                                            |                                                                               |                                                                       |
|                                                                                           | 1—Cold worked only                                                            | 2— $1/4$ hard                                                         |
|                                                                                           | 2—Cold worked and partially annealed                                          | 4— $1/2$ hard                                                         |
|                                                                                           | 3—Cold worked and stabilized                                                  | 6— $3/4$ hard                                                         |
|                                                                                           |                                                                               | 8—Hard                                                                |
|                                                                                           |                                                                               | 9—Extra hard                                                          |
| W—Solution heat treated                                                                   |                                                                               |                                                                       |
| T—Heat treated, stable                                                                    |                                                                               |                                                                       |
| T1—Cooled from an elevated-temperature shaping operation + natural aged                   |                                                                               |                                                                       |
| T2—Cooled from an elevated-temperature shaping operation + cold worked + natural aged     |                                                                               |                                                                       |
| T3—Solution treated + cold worked + natural aged                                          |                                                                               |                                                                       |
| T4—Solution treated + natural aged                                                        |                                                                               |                                                                       |
| T5—Cooled from an elevated-temperature shaping operation + artificial aged                |                                                                               |                                                                       |
| T6—Solution treated + artificial aged                                                     |                                                                               |                                                                       |
| T7—Solution treated + overaged                                                            |                                                                               |                                                                       |
| T8—Solution treated + cold worked + artificial aged                                       |                                                                               |                                                                       |
| T9—Solution treated + artificial aged + cold worked                                       |                                                                               |                                                                       |
| T10—Cooled from an elevated-temperature shaping operation + cold worked + artificial aged |                                                                               |                                                                       |

Source: Ref 3

# Temper and ageing treatments



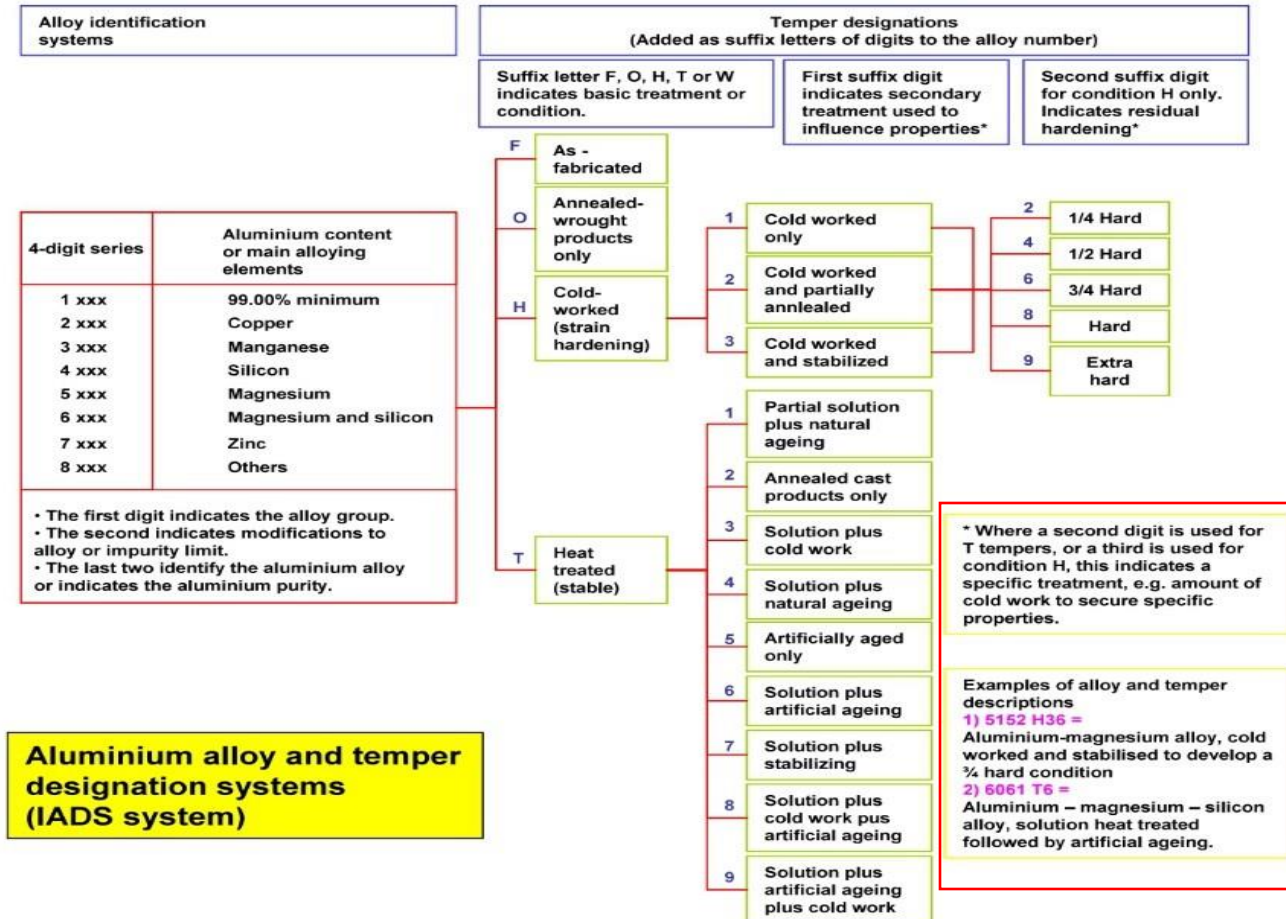
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| Temper | Description                       |
|--------|-----------------------------------|
| O      | Mill annealed                     |
| F      | As fabricated                     |
| T31    | Solution heat treat + Stretch     |
| T37    | Solution heat treat+ 8% Cold work |
| T4     | Solution heat treat+ natural aged |
| T62    | T4 aged 36h at 190°C              |
| T81    | T31 aged 18h at 177°C             |
| T87    | T37 aged 24h at 163 °C            |

# Broad Temper designations of Al alloy



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# Temper designations



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| Temper | Designations                                                                                                                                                              |                                                                                                                                                                                                                           |
|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| H12    | Strain-hardened - 1/4 hard.                                                                                                                                               |                                                                                                                                                                                                                           |
| H14    | Strain-hardened - 1/2 hard.                                                                                                                                               |                                                                                                                                                                                                                           |
| H16    | Strain-hardened - 3/4 hard.                                                                                                                                               |                                                                                                                                                                                                                           |
| H18    | Strain-hardened - 4/4 hard (fully hardened).                                                                                                                              |                                                                                                                                                                                                                           |
| H19    | Strain-hardened - extra hard.                                                                                                                                             |                                                                                                                                                                                                                           |
| Hxx4   | Applies to embossed or patterned sheet or strip, fabricated from the corresponding Hxx temper.                                                                            | Hxxx<br>The third digit indicates a variation of the two digit H temper. It is used when the degree of temper is close to the 2 digit H temper.                                                                           |
| Hxx5   | Strain-hardened - applies to welded tubes.                                                                                                                                |                                                                                                                                                                                                                           |
| H111   | Annealed and slightly strain-hardened (less than H11) during subsequent operations such as stretching or levelling.                                                       | H111<br>Applies to alloys which are strain-hardened less than the amount required for a controlled H11 temper.                                                                                                            |
| H112   | Slightly strain-hardened from working at an elevated temperature from a limited amount of cold work (mechanical property limits specified).                               | H112<br>Applies to alloys that acquire some temper from shaping processes which do not have special control over the amount of strain-hardening or thermal treatment, but for which there are mechanical property limits. |
| H116   | Applies to aluminium-magnesium alloys with a magnesium content of 4% or more and for which mechanical property limits and exfoliation corrosion resistance are specified. |                                                                                                                                                                                                                           |
| H22    | Strain-hardened and partially annealed - 1/4 hard.                                                                                                                        |                                                                                                                                                                                                                           |
| H24    | Strain-hardened and partially annealed - 1/2 hard.                                                                                                                        |                                                                                                                                                                                                                           |
| H26    | Strain-hardened and partially annealed - 3/4 hard.                                                                                                                        |                                                                                                                                                                                                                           |
| H28    | Strain-hardened and partially annealed - 4/4 hard (fully hardened).                                                                                                       |                                                                                                                                                                                                                           |
| H32    | Strain-hardened and stabilized - 1/4 hard.                                                                                                                                |                                                                                                                                                                                                                           |
| H34    | Strain-hardened and stabilized - 1/2 hard.                                                                                                                                |                                                                                                                                                                                                                           |
| H36    | Strain-hardened and stabilized - 3/4 hard.                                                                                                                                |                                                                                                                                                                                                                           |
| H38    | Strain-hardened and stabilized - 4/4 hard (fully hardened).                                                                                                               |                                                                                                                                                                                                                           |
| H42    | Strain-hardened and painted or lacquered - 1/4 hard.                                                                                                                      |                                                                                                                                                                                                                           |
| H44    | Strain-hardened and painted or lacquered - 1/2 hard.                                                                                                                      |                                                                                                                                                                                                                           |
| H46    | Strain-hardened and painted or lacquered - 3/4 hard.                                                                                                                      |                                                                                                                                                                                                                           |
| H48    | Strain-hardened and painted or lacquered - 4/4 hard (fully hardened)                                                                                                      |                                                                                                                                                                                                                           |

# Temper designations



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- |            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>T5</b>  | Artificially aged only. Applies to alloys which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be significant in mechanical property limits.                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>T51</b> | Stress relieved by stretching. Applies to the following products when stretched the indicated amounts after solution heat-treatment or cooled from a high temperature shaping process: Plate—1.5-3% permanent set; Rod, bar, shapes, and extruded tubes—1-3% permanent set; Drawn tubes— 1.5-3% permanent set. Applies directly to plate, and rolled or cold finished rod and bar which receive no further straightening after stretching. Applies to extruded rod, bar, shapes, tubing, and to drawn tubing when designated as follows: T510 Products that receive no further straight ending after stretching; T511 Products that may receive minor straightening after stretching to comply with standard tolerances. |
| <b>T52</b> | Stress-relieved by compressing. Applies to alloys which are stress-relieved by compressing after solution heat-treatment, or cooled from a high temperature shaping process to produce a permanent set of 1 to 5%.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| <b>T54</b> | Stress-relieved by combined stretching and compressing. Applicable to die forging which are stress-relieved by restriking cold in the finish die.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |

# Temper designations



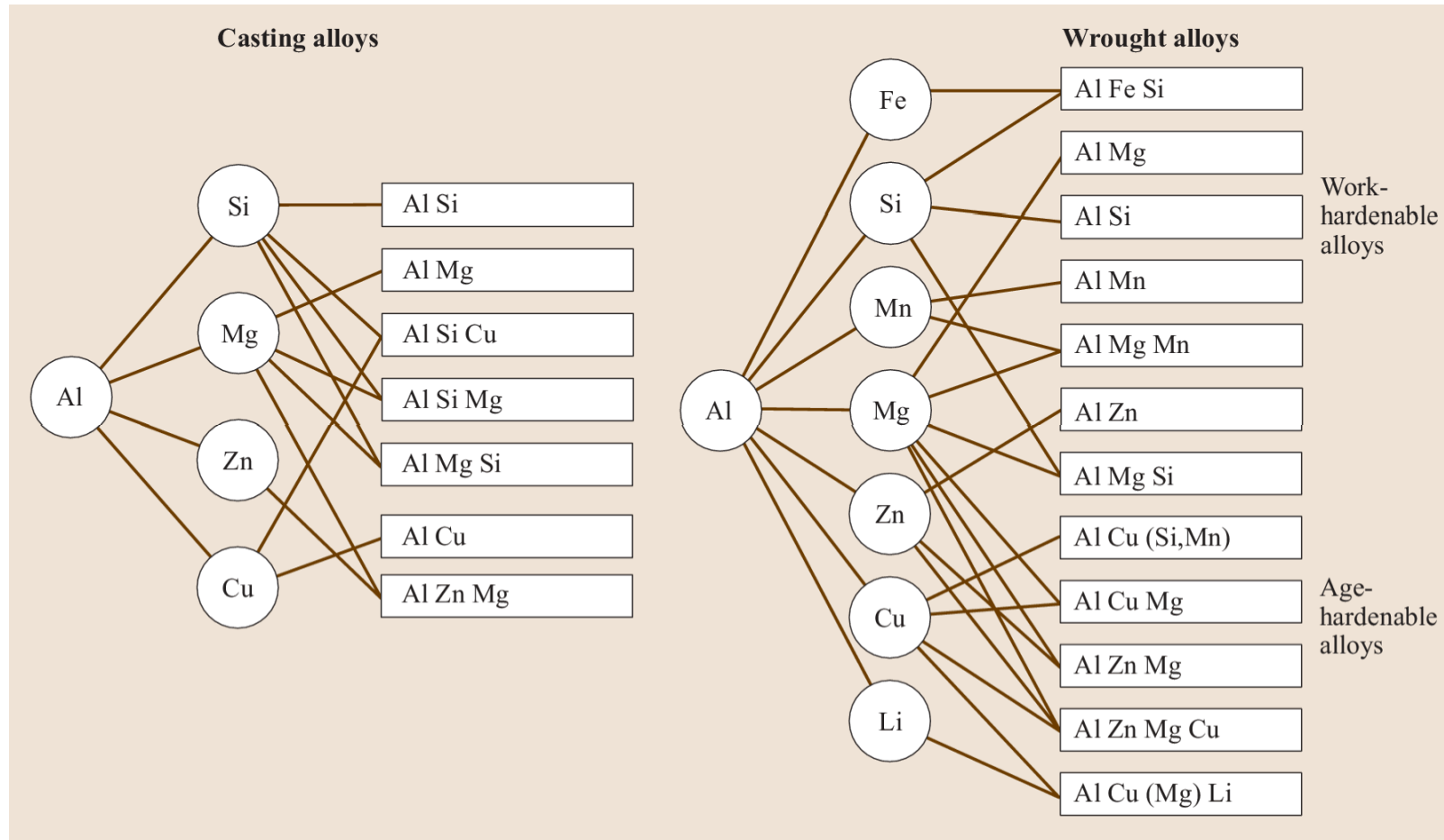
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- T42** (Wrought products only). Applicable to products solution heat-treated and naturally aged which have mechanical properties different from those of the T4 temper.
- T62** (Wrought products only). Applicable to products solution heat-treated and artificially aged which have mechanical properties different from those of the T6 temper.

# Major alloying additions in wrought and cast Al alloys



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# Heat treatable and non-heat treatable wrought Al alloys



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- **Non-heat-treatable alloys**

- 1xxx series (commercial pure aluminum)

- 3xxx series (Al-Mn & Al-Mn-Mg alloys)

- 5xxx series (Al-Mg alloys)

- 8xxx series (Miscellaneous alloys)

- **Heat-treatable alloys**

- 2xxx series (Al-Cu & Al-Cu-Mg alloys)

- 6xxx series (Al-Mg-Si alloys)

- 7xxx series (Al-Zn-Mg and Al-Zn-Mg-Cu alloys)

❑ **Aluminium** alloys within the **4xxx series (Al-Si)** group are both **heat treatable** and **non-heat treatable** alloys.

# Strengthening of Non-Heat treatable Al alloys



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- **Non-heat-treatable alloys**

- 1xxx series (commercial pure aluminum)

- 3xxx series (Al-Mn & Al-Mn-Mg alloys)

- 5xxx series (Al-Mg alloys)

- 8xxx series (Miscellaneous alloys)

- ❑ **Combination of solid-solution strengthening, second-phase constituents, dispersoid precipitates, and work hardening.**
- ❑ **1xxx, 3xxx, 4xxx, 5xxx Aluminium** alloys can be work hardened to various strength levels with a concurrent reduction in ductility.
- ❑ Since these alloys will undergo recovery at moderate temperatures, they are used mainly for lower-temperature applications.



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# 1xxx (commercially pure Al alloys)

**1xxx: Pure Al.** The major characteristics of the 1xxx series are:

- Strain hardenable
- Exceptionally high formability, corrosion resistance, and electrical conductivity
- Typical ultimate tensile strength range: 69–186 MPa (10–27 ksi)
- Readily joined by welding, brazing, soldering

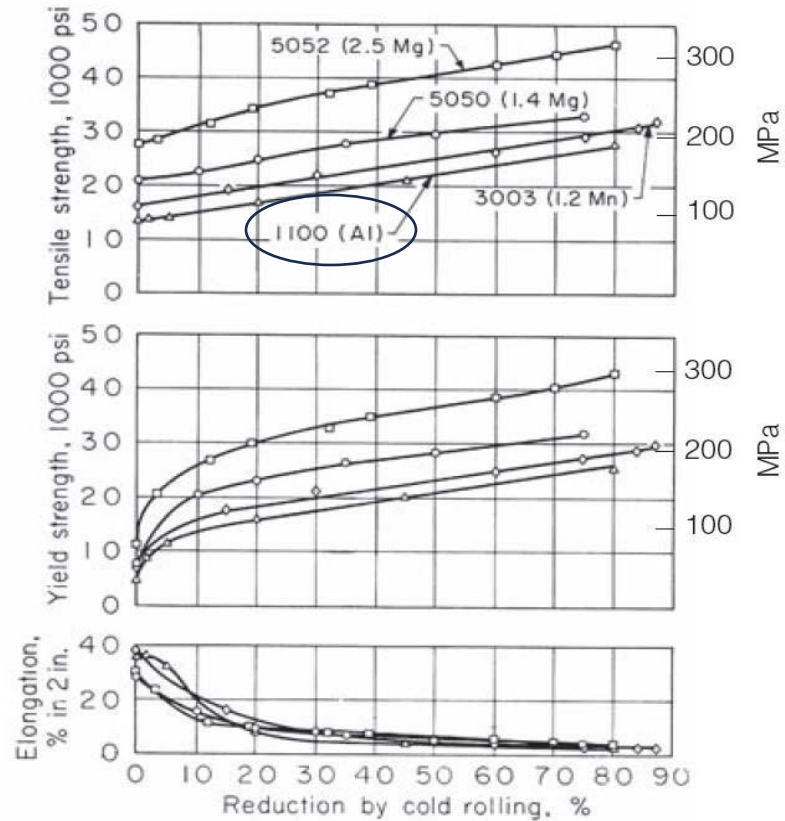


# 1xxx (commercially pure Al alloys)

- Used for applications such as electrical conductors, chemical processing equipment, aluminium foil, cooking utensils, and architectural products.
- Since these alloys are essentially free of alloying additions, they exhibit excellent corrosion resistance to atmospheric conditions.



# 1xxx (commercially pure Al alloys)

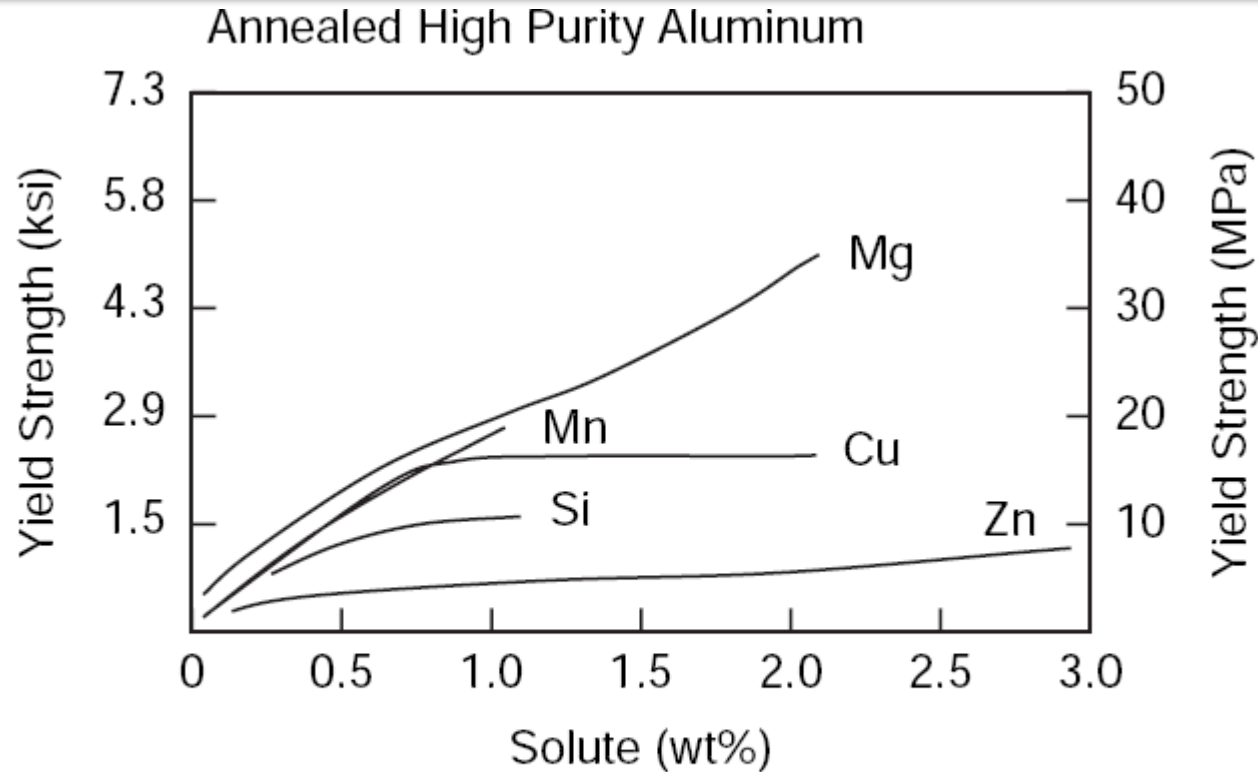


**Fig. 26.3** Work-hardening curves for wrought non-heat-treatable aluminum alloys. Source: Ref 5

# Solid solution strengthening of aluminium



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**Fig. 26.2** Solid-solution strengthening of aluminum.  
Source: Ref 4

**Table 26.5** Compositions of select wrought non-heat-treatable aluminum alloys

| Alloy | Alloying element content, wt % |      |     |      |
|-------|--------------------------------|------|-----|------|
|       | Cu                             | Mn   | Mg  | Cr   |
| 3003  | 0.12                           | 1.2  | ... | ...  |
| 3004  | ...                            | 1.2  | 1.0 | ...  |
| 3005  | ...                            | 1.2  | 0.4 | ...  |
| 3105  | ...                            | 0.6  | 0.5 | ...  |
| 5005  | ...                            | ...  | 0.8 | ...  |
| 5050  | ...                            | ...  | 1.4 | ...  |
| 5052  | ...                            | ...  | 2.5 | 0.25 |
| 5252  | ...                            | ...  | 2.5 | ...  |
| 5154  | ...                            | ...  | 3.5 | 0.25 |
| 5454  | ...                            | 0.8  | 2.7 | 0.12 |
| 5056  | ...                            | 0.12 | 5.0 | 0.12 |
| 5456  | ...                            | 0.8  | 5.1 | 0.12 |
| 5182  | ...                            | 0.35 | 4.5 | ...  |
| 5083  | ...                            | 0.7  | 4.4 | 0.15 |
| 5086  | ...                            | 0.45 | 4.0 | 0.15 |

All contain iron and silicon as impurities. Source: Ref 6

# 3xxx series – Al-Mn alloys

**3xxx: Al-Mn Alloys.** The major characteristics of the 3xxx series are:

- High formability and corrosion resistance; medium strength
- Typical ultimate tensile strength range: 110–283 MPa (16–41 ksi)
- Readily joined by all commercial procedures
- Hardened by strain hardening



# 4xxx series – Al-Si alloys

**4xxx: Al-Si Alloys.** The major characteristics of the 4xxx series are:

- Some heat treatable
- Good flow characteristics; medium strength
- Typical ultimate tensile strength range: 172–379 MPa (25–55 ksi)
- Easily joined, especially by brazing and soldering



# 5xxx series – Al-Mg alloys



**5xxx: Al-Mg Alloys.** The major characteristics of the 5xxx series are:

- Strain hardenable
- Excellent corrosion resistance, toughness, weldability; moderate strength
- Building and construction, automotive, cryogenic, marine applications
- Typical ultimate tensile strength range: 124–352 MPa (18–58 ksi)

Note: Alloy 5005 is not hardenable by heat treatment. It can be significantly hardened by cold work (eg by cold rolling) and various “H” tempers are produced – most commonly H32 ( $\frac{1}{4}$  Hard) and H34 ( $\frac{1}{2}$  Hard) – as well as the soft annealed Temper O condition.



# Mechanical properties of Al alloys



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**Table 26.6 Mechanical properties of select wrought non-heat-treatable aluminum alloys**

| Alloy | Temper | Tensile strength |     | Yield strength |     | Elongation<br>in 50 mm<br>(2 in.), % |
|-------|--------|------------------|-----|----------------|-----|--------------------------------------|
|       |        | MPa              | ksi | MPa            | ksi |                                      |
| 3003  | O      | 100              | 16  | 40             | 6   | 30                                   |
|       | H14    | 125              | 18  | 115            | 17  | 9                                    |
|       | H18    | 165              | 24  | 150            | 22  | 5                                    |
| 3004  | O      | 180              | 26  | 70             | 10  | 20                                   |
|       | H34    | 240              | 35  | 200            | 29  | 9                                    |
|       | H38    | 285              | 41  | 250            | 36  | 5                                    |
|       | H19    | 295              | 43  | 285            | 41  | 2                                    |
| 3005  | O      | 130              | 19  | 55             | 8   | 25                                   |
|       | H14    | 180              | 26  | 165            | 24  | 7                                    |
|       | H18    | 240              | 35  | 225            | 33  | 4                                    |
| 3105  | O      | 115              | 17  | 55             | 8   | 24                                   |
|       | H25    | 180              | 26  | 160            | 23  | 8                                    |
|       | H18    | 215              | 31  | 195            | 28  | 3                                    |
| 5005  | O      | 125              | 18  | 40             | 6   | 25                                   |
|       | H34    | 160              | 23  | 140            | 20  | 8                                    |
|       | H38    | 200              | 29  | 185            | 27  | 5                                    |
| 5050  | O      | 145              | 21  | 55             | 8   | 24                                   |
|       | H34    | 190              | 28  | 165            | 24  | 8                                    |
|       | H38    | 220              | 32  | 200            | 29  | 6                                    |
| 5052  | O      | 195              | 28  | 90             | 13  | 25                                   |
|       | H34    | 260              | 38  | 265            | 31  | 10                                   |
|       | H38    | 290              | 42  | 255            | 37  | 7                                    |
| 5252  | O      | 180              | 26  | 85             | 12  | 23                                   |
|       | H25    | 235              | 34  | 170            | 25  | 11                                   |
|       | H28    | 285              | 41  | 240            | 35  | 5                                    |
| 5154  | O      | 240              | 35  | 115            | 17  | 27                                   |
|       | H34    | 290              | 42  | 230            | 33  | 13                                   |
|       | H38    | 330              | 48  | 270            | 39  | 10                                   |
|       | H12    | 240              | 35  | 115            | 17  | 25                                   |
| 5454  | O      | 250              | 36  | 115            | 17  | 22                                   |
|       | H34    | 305              | 44  | 240            | 35  | 10                                   |
|       | H111   | 250              | 36  | 125            | 18  | 18                                   |
|       | H112   | 250              | 36  | 125            | 18  | 18                                   |
| 5056  | O      | 290              | 42  | 150            | 22  | 35                                   |
|       | H18    | 435              | 63  | 405            | 59  | 10                                   |
|       | H38    | 415              | 60  | 345            | 50  | 15                                   |
| 5456  | O      | 310              | 45  | 160            | 23  | 24                                   |
|       | H112   | 310              | 45  | 165            | 24  | 22                                   |
|       | H116   | 350              | 51  | 255            | 37  | 16                                   |
| 5182  | O      | 275              | 40  | 130            | 19  | 21                                   |

# Strengthening of heat treatable Al alloys



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- **Heat-treatable alloys**

- 2xxx series (Al-Cu & Al-Cu-Mg alloys)

- 6xxx series (Al-Mg-Si alloys)

- 7xxx series (Al-Zn-Mg and Al-Zn-Mg-Cu alloys)

- 8xxx series (Al-Li alloys)

- ❑ The highest strength levels are attained by the precipitation-hardenable alloys, which include 2xxx, 6xxx, 7xxx and 8xxx (Al-Li alloys)
- ❑ One rather disappointing property of high strength aluminum alloys is their fatigue performance.
- ❑ Increases in static tensile properties have not been accompanied by proportionate improvements in fatigue properties.

# Strengthening of heat treatable Al alloys

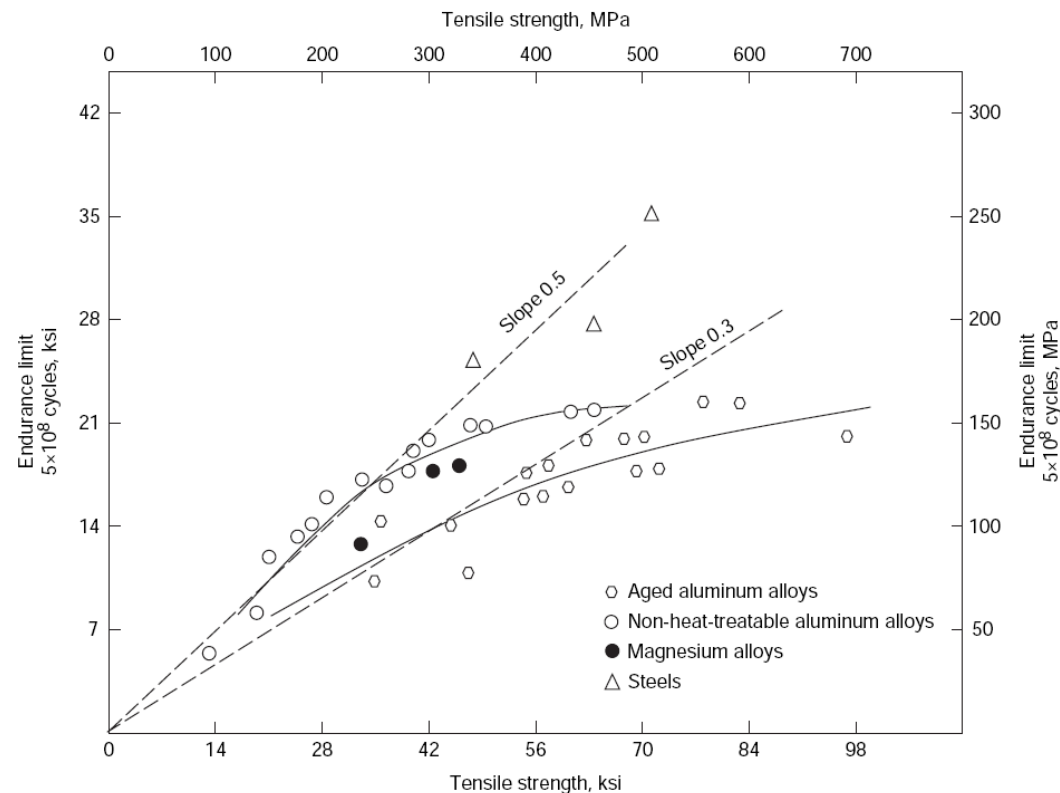


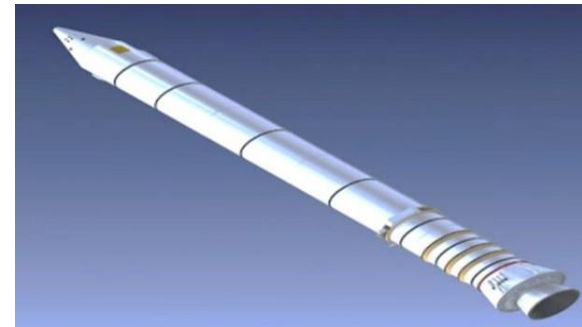
Fig. 26.1 Fatigue strength comparison for aluminum. Source: Ref 2

- ❑ The precipitation-hardened alloys exhibit only minimal fatigue improvement because of two factors:
- ❑ (1) cracks initiating at precipitate-free zones adjacent to grain boundaries, and (2) the re-solution of precipitate particles when they are cut by dislocations.

# 2xxx series – Al-Cu alloys

**2xxx: Al-Cu Alloys.** The major characteristics of the 2xxx series are:

- Heat treatable
- High strength at room and elevated temperatures
- Typical ultimate tensile strength range: 186–428 MPa (27–62 ksi)
- Usually joined mechanically, but some alloys are weldable
- Not as corrosion resistant as other alloys



# 2xxx series – Al-Cu alloys

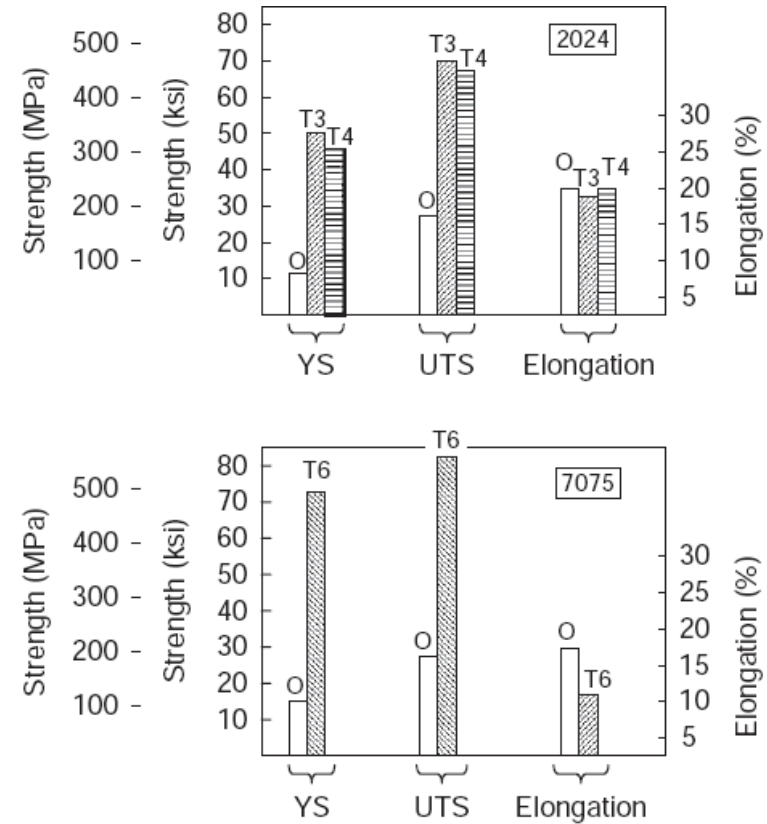
**Table 26.7** Compositions of select wrought heat treatable aluminum alloys

| Alloy   | Alloying element content, wt% |            |      |        |      |      |     |      |
|---------|-------------------------------|------------|------|--------|------|------|-----|------|
|         | Fe                            | Si         | Cu   | Mn     | Mg   | Cr   | Zn  | Zr   |
| 2008    | 0.40(a)                       | 0.65       | 0.9  | 0.3(a) | 0.4  | ...  | ... | ...  |
| 2219(b) | 0.30(a)                       | 0.20(a)    | 6.3  | 0.3    | ...  | ...  | ... | 0.18 |
| 2519(b) | 0.39(a)(c)                    | 0.30(a)(c) | 5.8  | 0.3    | 0.25 | ...  | ... | 0.18 |
| 2014    | 0.7(a)                        | 0.8        | 4.4  | 0.8    | 0.5  | ...  | ... | ...  |
| 2024    | 0.50(a)                       | 0.50(a)    | 4.4  | 0.6    | 1.5  | ...  | ... | ...  |
| 2124    | 0.30(a)                       | 0.20(a)    | 4.4  | 0.6    | 1.5  | ...  | ... | ...  |
| 2224    | 0.15(a)                       | 0.12(a)    | 4.4  | 0.6    | 1.5  | ...  | ... | ...  |
| 2324    | 0.12(a)                       | 0.10(a)    | 4.4  | 0.6    | 1.5  | ...  | ... | ...  |
| 2524    | 0.12(a)                       | 0.06(a)    | 4.25 | 0.6    | 1.4  | ...  | ... | ...  |
| 2036    | 0.50(a)                       | 0.50(a)    | 2.6  | 0.25   | 0.45 | ...  | ... | ...  |
| 6009    | 0.50(a)                       | 0.8        | 0.4  | 0.5    | 0.6  | ...  | ... | ...  |
| 6061    | 0.7(a)                        | 0.6        | 0.3  | ...    | 1.0  | 0.2  | ... | ...  |
| 6063    | 0.50(a)                       | 0.4        | ...  | ...    | 0.7  | ...  | ... | ...  |
| 6111    | 0.4(a)                        | 0.9        | 0.7  | 0.3    | 0.8  | ...  | ... | ...  |
| 7005    | 0.40(a)                       | 0.35(a)    | ...  | 0.45   | 1.4  | 0.13 | 4.5 | 0.14 |
| 7049    | 0.35(a)                       | 0.25(a)    | 1.6  | ...    | 2.4  | 0.16 | 7.7 | ...  |
| 7050    | 0.15(a)                       | 0.12(a)    | 2.3  | ...    | 2.2  | ...  | 6.2 | 0.12 |
| 7150    | 0.15(a)                       | 0.10(a)    | 2.2  | ...    | 2.4  | ...  | 5.4 | 0.12 |
| 7055    | 0.15(a)                       | 0.10(a)    | 2.3  | ...    | 2.1  | ...  | 8.0 | 0.12 |
| 7075    | 0.50(a)                       | 0.40(a)    | 1.6  | ...    | 2.5  | 0.25 | 5.6 | ...  |
| 7475    | 0.12(a)                       | 0.10(a)    | 1.6  | ...    | 2.2  | 0.20 | 5.7 | ...  |

(a) Maximum allowable amount.

(b) 2219 and 2519 also contain 0.10% V and 0.06% Ti.

(c) 0.40% max Fe plus Si. Source: Ref 6



**Fig. 26.4** Effect of heat treatment on 2024 and 7075. YS, yield strength; UTS, ultimate tensile strength.

# 6xxx series – Al-Mg-Si alloys

**6xxx: Al-Mg-Si Alloys.** The major characteristics of the 6xxx series are:

- Heat treatable
- High corrosion resistance, excellent extrudability; moderate strength
- Typical ultimate tensile strength range: 124–400 MPa (18–58 ksi)
- Readily welded by gas metal arc welding and gas tungsten arc welding methods
- Outstanding extrudability



# 7xxx series – Al-Zn alloys

**7xxx: Al-Zn Alloys.** The major characteristics of the 7xxx series are:

- Heat treatable
- Very high strength; special high-toughness versions
- Typical ultimate tensile strength range: 221–607 MPa (32–88 ksi)
- Mechanically joined



## 8xxx series



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### **8xxx: Alloys** with Al/other elements

The major characteristics of the 8xxx series are:

- Heat treatable
- High conductivity, strength, hardness
- Typical ultimate tensile strength range: 117–414 MPa (17–60 ksi)
- Common alloying elements include Fe, Ni, and Li

# Designation of cast aluminium alloys



❑ Aluminum association of the United States has introduced a revised system which has some similarity to that adopted for wrought alloys.

- 1xx.x (pure Al- 99 % purity)
- 2xx.x (Al-Cu alloys)
- 3xx.x (Al-Si with Cu and/or Mg alloy)
- 4xx.x (Al-Si alloys)
- 5xx.x (Al-Mg alloys)
- 7xx.x (Al-Zn alloys)
- 8xx.x (Al-Sn alloys)
- 9xx.x (Al-other elements like Fe,Cr,Ti,Zr,Pb,Bi etc.,)
- 6xx.x (Unused series)

# Designation of cast aluminium alloys



AILEEN

- ❑ Aluminum association of the United States has introduced a revised system which has some similarity to that adopted for wrought alloys.
  - The **first digit** indicates the major alloying element
  - The **second and third digit** identifies the specific alloy
  - The **last digit after decimal point** indicates product form whether casting (designated by '0') or ingot (designated by '1' or '2')

Example: Alloy - A356.0 the capital A (Axxx.x) indicates a modification of alloy 356.0. The number 3 (A3xx.x) indicates that it is of the silicon plus copper and/or magnesium series. The 56 (Ax56.0) identifies the alloy within the 3xx.x series, and the .0 (Axxx.0) indicates that it is a final shape casting and not an ingot.

Example: For the 1xx.x series, the second two digits indicate purity. The last digit, which is separated from the others by a decimal point, indicates the product form, whether casting or ingot; the zero after a period identifies the alloy as a cast product. If the period is followed by the number 1, it indicates an ingot composition that would be supplied to a casting house.

# Heat treatable and non-heat treatable cast Al alloys



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## ■ **Non-heat-treatable alloys**

1xx.x series ----- (commercial pure aluminum)

4xx.x series ----- (Al-Si alloys)

5xx.x series ----- (Al-Mg alloys)

8xx.x series ----- (Al-Sn alloys)

9xx.x series ----- (Al-other elements like Fe,Cr,Ti,Zr,Pb,Bi etc.,)

## ■ **Heat-treatable alloys**

2xx.x series ----- (Al-Cu alloys)

3xx.x series ----- (Al-Si with Cu and/or Mg alloy)

7xx.x series ----- (Al-Zn alloys)

# Major characteristics of cast Al alloys



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## ■ 2xx.x series – Al-Cu alloys

- Heat treatable
- sand and permanent mould castings
- High strength at room and elevated temperatures
- high-toughness alloys
- Approximate ultimate tensile strength range: 131–448 MPa (19–65 ksi)

## ■ 3xx.x series - Al-Si with Cu or Mg Alloys

- Heat treatable
- sand, permanent mold, and die castings
- Excellent fluidity
- high-strength/some high-toughness alloys
- Approximate ultimate tensile strength range: 131–276 MPa (19–40 ksi)
- Readily welded

# Major characteristics of cast Al alloys



## ■ 4xx.x series – Al-Si alloys

- Non-heat-treatable
- sand, permanent mold, and die castings
- Excellent fluidity
- good for intricate castings
- Approximate ultimate tensile strength range: 117–172 MPa (17–25 ksi)

## ■ 5xx.x series - Al-Mg Alloys

- Non-heat-treatable
- sand, permanent mold, and die castings
- Tougher to cast
- Excellent corrosion resistance, machinability, surface finish
- Approximate ultimate tensile strength range: 117–172 MPa (17–25 ksi)

# Major characteristics of cast Al alloys



## ■ 7xx.x series – Al-Zn alloys

- Heat-treatable
- sand and permanent mold cast (harder to cast)
- Excellent machinability and appearance
- Approximate ultimate tensile strength range: 207–379 MPa (30–55 ksi)

## ■ 8xx.x series - Al-Sn Alloys

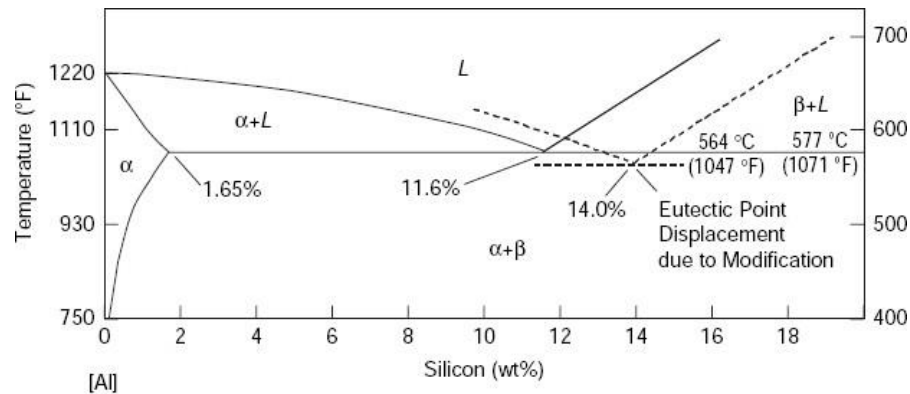
- Heat treatable
- sand, permanent mold, and die castings
- Tougher to cast
- Excellent corrosion resistance, machinability, surface finish
- Approximate ultimate tensile strength range: 117–172 MPa (17–25 ksi)

# Al-Si cast alloys

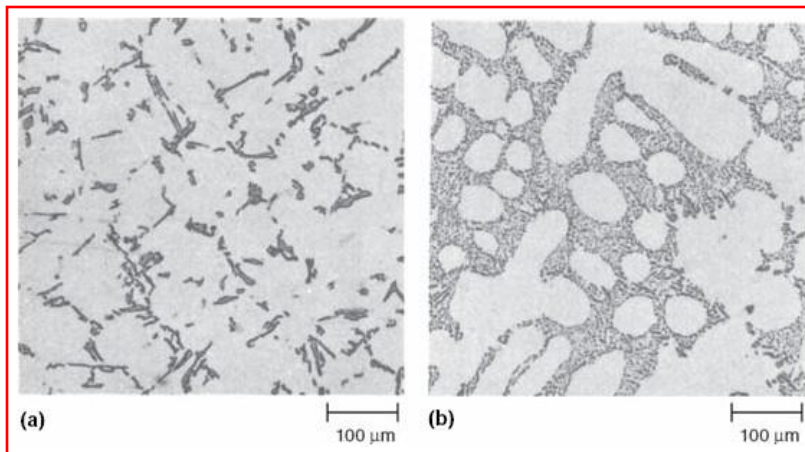


- ❑ Alloys of Al-Si series have good casting characteristics such as
  - small shrinkage
  - excellent fluidity
  - good gas impermeability
  - low tendency for crack after solidification.
  
- ❑ Addition of different elements like Cu, Mg, makes the Al-Si alloys heat treatable
  
- ❑ The ways for altering the microstructure of the Al-Si are
  - Chemical method
    - Addition of some elements like Sodium (Na), Strontium (Sr), Antimony (Sb) in trace levels to modify microstructure
  - Thermal method
    - involves rapid cooling of alloy for modification (transition from plate like to rod like form of Si)
  - Mechanical method
    - depends on force to break up large  $\alpha$ -Al dendrites and plate-like Si phases

# Al-Si cast alloys



Added sodium collects in the liquid at its interface with the newly formed silicon crystals, inhibiting and delaying their growth. Thus, undercooling occurs and new silicon nuclei are formed in large numbers, resulting in a relatively fine-grained eutectic structure.



Unmodified

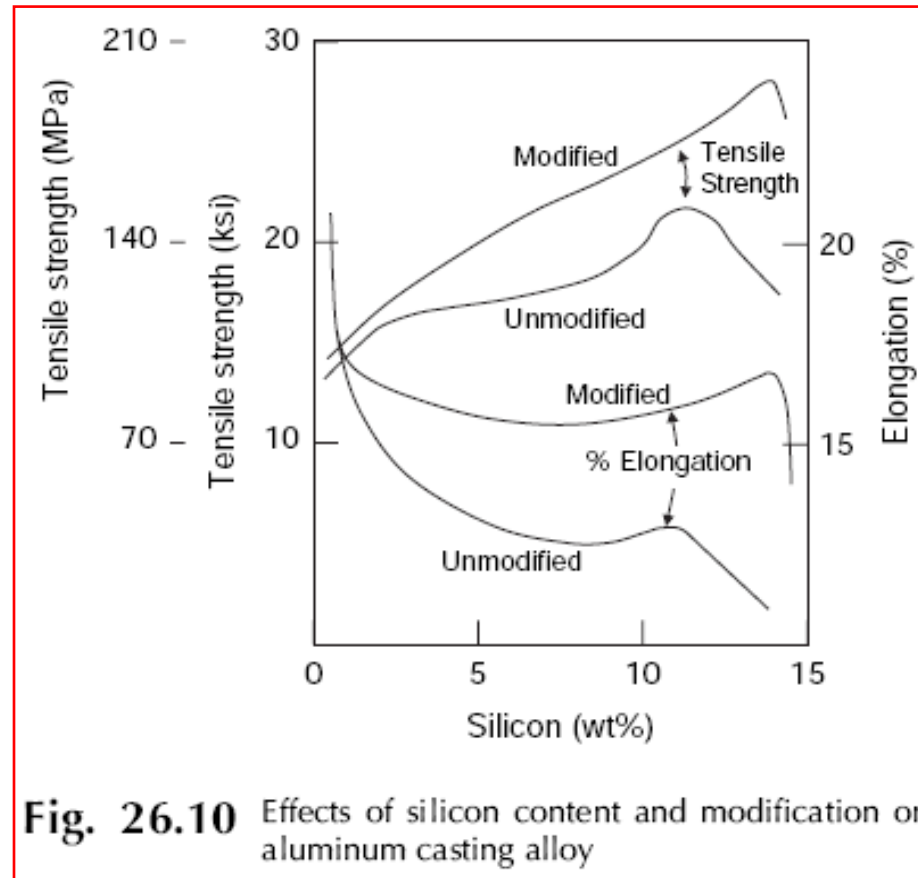
Modified

# Al-Si cast alloys



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- The relatively high ductility of this cast eutectic alloy is due to the solid-solution phase in the eutectic constituting nearly 90% of the total structure.
- Therefore, the solid-solution phase is continuous in the microstructure and acts as a cushion against much of the brittleness arising from the hard silicon phase.
- More recently, modifying with strontium is replacing sodium, because there is less loss during melting due to oxidation or evaporation; overmodification (too much addition) is not a problem because it forms the innocuous compound  $\text{SrAl}_3\text{Si}_3$ , and strontium suppresses the formation of **large primary silicon particles** in hypereutectic alloys.



# Al-Si cast alloys

- Addition of Na modifies the eutectic Si growth to an irregular fibrous form instead of the usual coarse flakes.

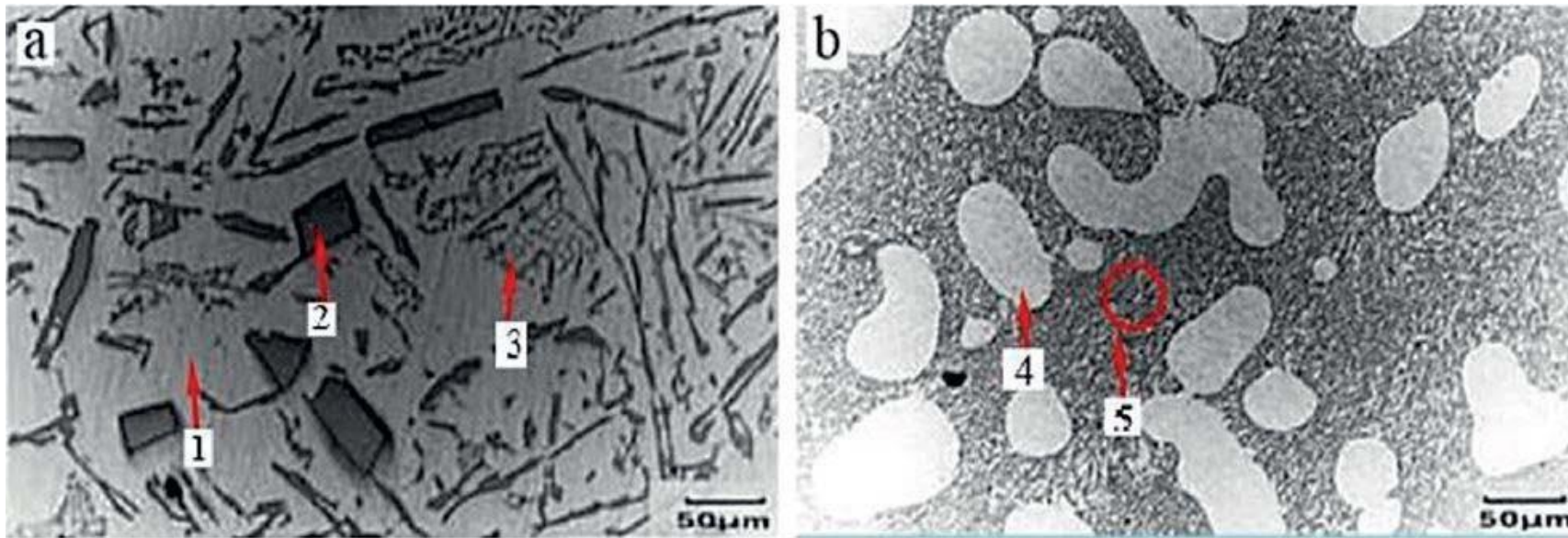


Figure: Micrograph of (a) Al-13%Si; (b) Al-13%Si-0.01%Na, where (1) $\alpha$ -Al dendrite; (2) primary Si; (3) *Eutectic* Si; (4)  $\alpha$ -Al; and (5) fibrous eutectic Si.

# Al-Si cast alloys

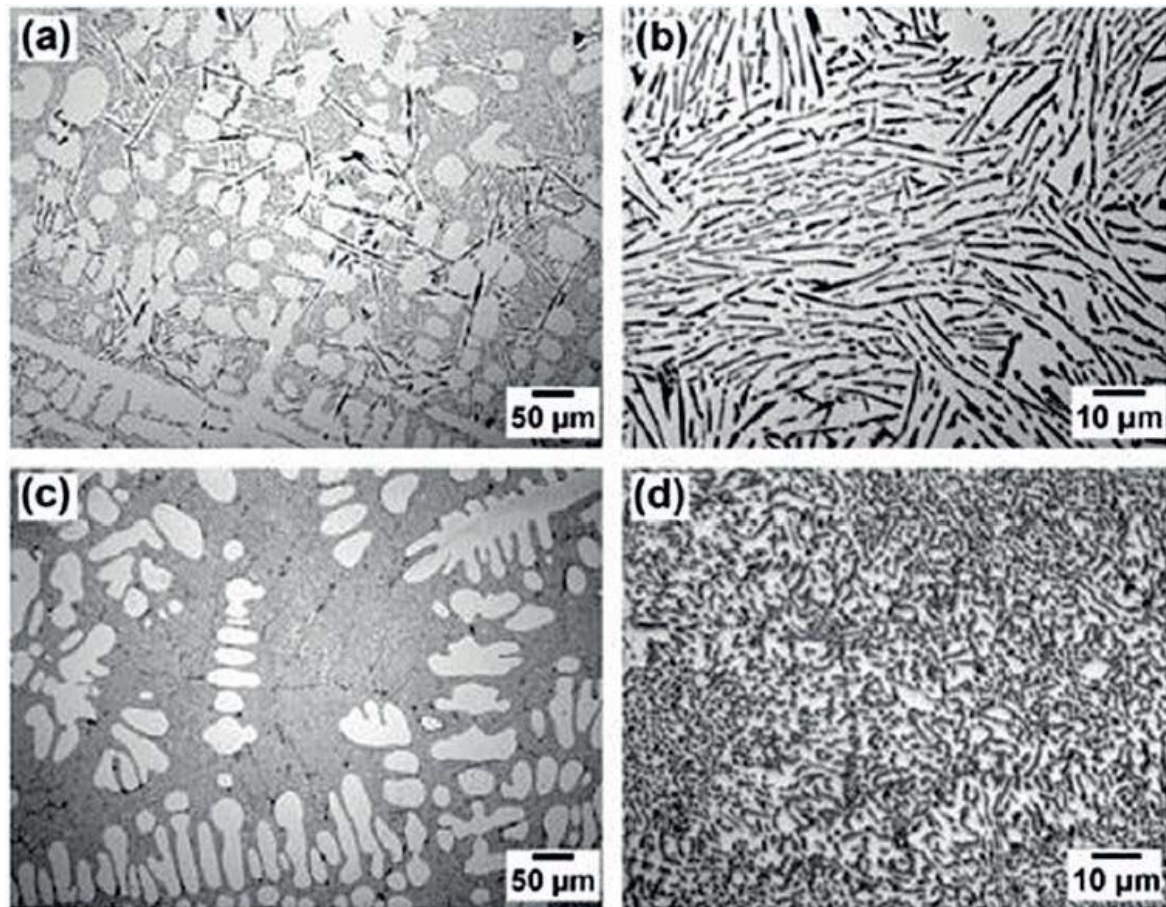


Figure: Optical micrographs of Al-10%Si-0.1Fe alloy: (a) and (b) unmodified alloy; (c) and (d) alloy modified by 200 ppm Sr

# Applications of Al cast alloys



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**Table 7 Selected applications for aluminum casting alloys**

| Alloy  | Representative applications                                                                                                                                           | Alloy  | Representative applications                                                           |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|---------------------------------------------------------------------------------------|
| 100.0  | Electrical rotors larger than 152 mm (6 in.) in diameter                                                                                                              | 360.0  | Outboard motor parts; instrument cases; cover plates; marine and aircraft castings    |
| 201.0  | Structural members; cylinder heads and pistons; gear, pump, and aerospace housings                                                                                    | A360.0 | Cover plates; instrument cases; irrigation system parts; outboard motor parts; hinges |
| 208.0  | General-purpose castings; valve bodies, manifolds, and other pressure-tight parts                                                                                     | 380.0  | Housings for lawn mowers and radio transmitters; air brake castings; gear cases       |
| 222.0  | Bushings; meter parts; bearings; bearing caps; automotive pistons; cylinder heads                                                                                     | A380.0 | Applications requiring strength at elevated temperature                               |
| 238.0  | Sole plates for electric hand irons                                                                                                                                   | 384.0  | Pistons and other severe service applications; automatic transmissions                |
| 242.0  | Heavy-duty pistons; air-cooled cylinder heads; aircraft generator housings                                                                                            | 390.0  | Internal combustion engine pistons, blocks, manifolds, and cylinder heads             |
| A242.0 | Diesel and aircraft pistons; air-cooled cylinder heads; aircraft generator housings                                                                                   | 413.0  | Architectural, ornamental, marine, and food and dairy equipment applications          |
| B295.0 | Gear housings; aircraft fittings; compressor connecting rods; railway car seat frames                                                                                 | A413.0 | Outboard motor pistons; dental equipment; typewriter frames; street lamp housings     |
| 308.0  | General-purpose permanent mold castings; ornamental grilles and reflectors                                                                                            | 443.0  | Cookware; pipe fittings; marine fittings; tire molds; carburetor bodies               |
| 319.0  | Engine crankcases; gasoline and oil tanks; oil pans; typewriter frames; engine parts                                                                                  | 514.0  | Fittings for chemical and sewage use; dairy and food handling equipment; tire molds   |
| 332.0  | Automotive and heavy-duty pistons; pulleys, sheaves                                                                                                                   | A514.0 | Permanent mold casting of architectural fittings and ornamental hardware              |
| 333.0  | Gas meter and regulator parts; gear blocks; pistons; general automotive castings                                                                                      | 518.0  | Architectural and ornamental castings; conveyor parts; aircraft and marine castings   |
| 354.0  | Premium-strength castings for the aerospace industry                                                                                                                  | 520.0  | Aircraft fittings; railway passenger car frames; truck and bus frame sections         |
| 355.0  | Sand: air compressor pistons; printing press bedplates; water jackets; crankcases. Permanent: impellers; aircraft fittings; timing gears; jet engine compressor cases | 535.0  | Instrument parts and other applications where dimensional stability is important      |
| 356.0  | Sand: flywheel castings; automotive transmission cases; oil pans; pump bodies. Permanent: machine tool parts; aircraft wheels; airframe castings; bridge railings     | A712.0 | General-purpose castings that require subsequent brazing                              |
| A356.0 | Structural parts requiring high strength; machine parts; truck chassis parts                                                                                          | 713.0  | Automotive parts; pumps; trailer parts; mining equipment                              |
| 357.0  | Corrosion-resistant and pressure-tight applications                                                                                                                   | 850.0  | Bushings and journal bearings for railroads                                           |
| 359.0  | High-strength castings for the aerospace industry                                                                                                                     | A850.0 | Rolling mill bearings and similar applications                                        |

# Role of alloying elements in Al



## **Silicon, Si (up to 17%)**

- Improves castability of aluminium alloys due to a better fluidity and lower shrinkage of molten aluminium-silicon alloys.
- Increases strength of the alloys.
- Improves resistance to abrasive wear.
- Silicon in a combination with magnesium allows to strengthen the alloys by precipitation hardening heat treatment (Wrought aluminium-magnesium-silicon alloys (6xxx), Cast aluminium alloy 356.0)
- Si reduces ductility and machinability

# Role of alloying elements in Al



## **Copper, Cu (up to 6.5%)**

- Increases tensile strength, fatigue strength and hardness of the alloys due to the effect of solid solution hardening.
- Allows to strengthen the alloys by precipitation hardening heat treatment (Wrought aluminum-copper alloys (2xxx), Cast aluminum alloy 201.0).
- Improves machinability and thermal conductivity
- Decreases the ductility of the alloys.
- Decreases castability and corrosion resistance.

# Role of alloying elements in Al



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## **Magnesium, Mg (up to 10%)**

- Strengthens and hardens the alloys by solid solution hardening mechanism without considerable decrease of ductility (Wrought aluminium-magnesium alloys (5xxx), Cast aluminium alloy 518.0).
- In a combination with silicon or zinc allows to strengthen the alloys by precipitation hardening heat treatment (Wrought aluminium-magnesium-silicon alloys (6xxx), Wrought aluminium-zinc-magnesium alloys (7xxx), Cast aluminium alloy 356.0, Cast aluminium alloy 713.0).
- Improves weldability and makes alloy heat treatable
- Prone to oxidation

# Role of alloying elements in Al



## **Manganese, Mn (up to 1.5%)**

- Strengthens and hardens the alloys (Wrought aluminum- manganese alloys (3xxx)) by solid solution hardening and dispersion hardening mechanisms.
- Improves low cycle fatigue resistance.
- Increases corrosion resistance.
- Controls the intermetallic form of Iron
- Improves ductility of aluminum alloys containing iron and silicon due to modification of  $\text{Al}_5\text{FeSi}$  intermetallic inclusions from platelet to cubic form  $\text{Al}_{15}(\text{MnFe})_3\text{Si}_2$ .

# Role of alloying elements in Al



AILEEN

## **Zinc, Zn (up to 8%)**

- In a combination with magnesium or magnesium-copper allows to strengthen the alloys by precipitation hardening heat treatment (Wrought aluminum-zinc-magnesium alloys (7xxx), Cast aluminum alloy 713.0).
- Increases susceptibility of the alloys to Stress corrosion cracking.
- Increase the problem of internal shrinkage porosity

# Role of alloying elements in Al



## Chromium, Cr (up to 0.3%)

- Suppresses the grain growth at elevated temperatures (e.g. during heat treatment).
- Control grain growth in Al-Mg alloys
- Improves ductility and toughness of aluminum alloys containing iron and silicon due to modification of  $\text{Al}_5\text{FeSi}$  intermetallic inclusions from platelet to cubic form (similar to the effect of manganese).
- Reduces susceptibility of the alloys to Stress corrosion cracking.

# Role of alloying elements in Al



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## **Nickel, Ni (up to 2%)**

- Increases hardness and strength of aluminum-copper (Wrought aluminum-copper alloys (2xxx) and aluminum-silicon (Wrought aluminum-silicon alloy 4032) at elevated temperatures.
- Ni improves creep resistance
- Reduces the Coefficient of Thermal Expansion.

## **Lithium, Li (up to 2.6%)**

- Increases strength by the precipitation treatment.
- Increases Modulus of Elasticity.
- Reduces density.

# Role of alloying elements in Al



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## **Titanium, Ti (up to 0.35%)**

- Refines primary aluminum grains (grains formed during the Solidification) due to formation of fine nuclei  $\text{Al}_3\text{Ti}$ . Titanium is commonly added to aluminum alloys together with boron due to their synergistic grain refining effect. Acts as grain refiner, added in the form  $\text{TiB}_2$

## **Boron, B (up to 0.03%)**

- Boron in a combination with titanium refines primary aluminum grains (grains formed during the Solidification) due to formation of fine nuclei  $\text{TiB}_2$ .

# Role of alloying elements in Al



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## **Zirconium, Zr (up to 0.3%); Vanadium, V (up to 0.2%)**

- Inhibit recovery and recrystallization
- Increase the recrystallization temperature.

## **Iron, Fe (up to 1.1%)**

- Increases strength due to formation of Al-Fe intermetallics.
- Decreases ductility. In most aluminum alloys Iron is undesirable impurity.

# Role of alloying elements in Al



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**Sodium, Na (up to 0.015%); Antimony, Sb (up to 0.5%); Calcium, Ca (up to 0.015%), Strontium, Sr (up to 0.05%)**

- Increase ductility of hypoeutectic and eutectic aluminum-silicon alloys (Wrought aluminium-silicon alloys (4xxx), Cast aluminum alloy 443.0) by a modification of the silicon phase from coarse platelet like particles to fine fibrous structure.

**Tin, Sn (up to 40%)**

- Reduces coefficient of friction of aluminum alloys (Aluminum based bearing materials).
- Increases compatibility of the aluminum bearing alloy.

# Precipitation and age hardening



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- PRECIPITATION HARDENING is used extensively to strengthen Al alloys, Mg alloys, Ni-base superalloys, Be-Cu alloys, precipitation-hardening stainless steels.
- It should be noted that sometimes the term age hardening is used to denote alloys that harden on aging at RT, while the term precipitation hardening is used to denote alloys that must be heated above room temperature for hardening to occur at an appreciable rate.
- In precipitation hardening, an alloy is heated to a high enough temperature to take a significant amount of an alloying element into solid solution.
- It is then rapidly cooled (quenched) to room temperature, trapping the alloying elements in solution.
- On reheating to an intermediate temperature, the host metal rejects the alloying element in the form of fine precipitates that create matrix strains in the lattice.
- These fine precipitate particles act as barriers to the motion of dislocations and provide resistance to slip, thereby increasing the strength and hardness.

# Conditions required for Age Hardening



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1. The main basic requirement of a precipitation-hardening alloy system is that the **solid solubility limit should decrease with the decrease in temperature**

2. The **precipitates of the second phase should be coherent in nature**. As the precipitate size increases, partial and later complete loss of coherency at the interface occurs, when finally the equilibrium-precipitate  $\theta$  forms, but by then over ageing had already begun. Alloy systems Al-Mn, Al-Mg, Mg-Pb show decrease of solid solubility with decrease of temperature, but coherent-precipitates are not formed. Alloys of such systems cannot be age-hardened.

3. On reheating to an intermediate temperature, the host metal rejects the alloying element in the form of fine precipitates that **create matrix strains** in the lattice.

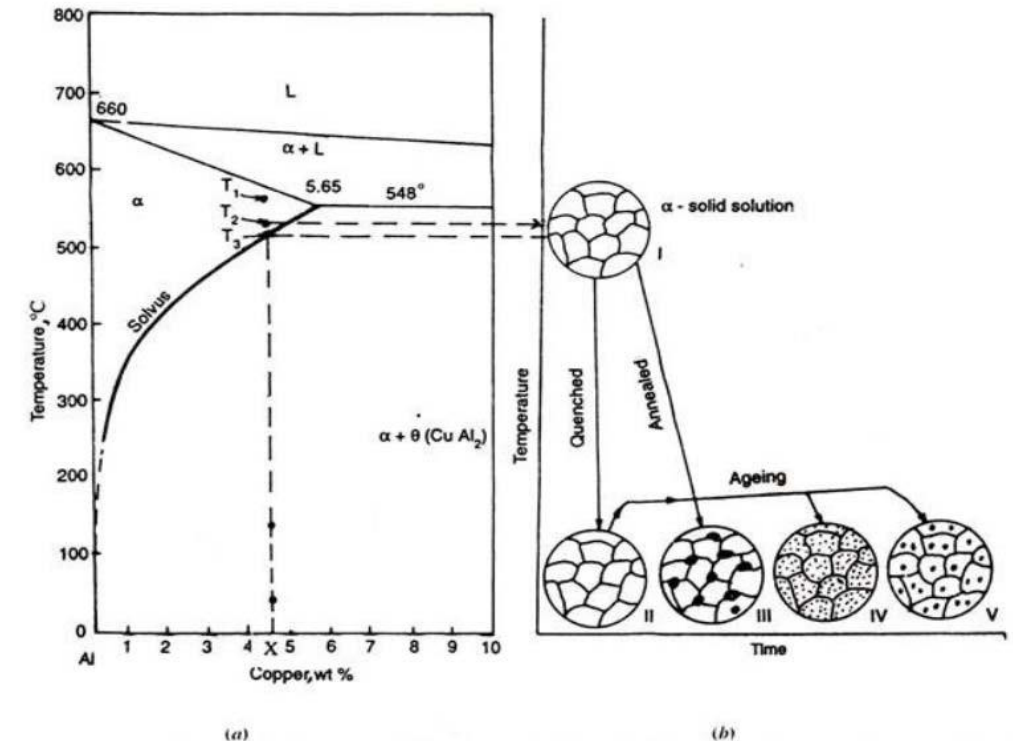
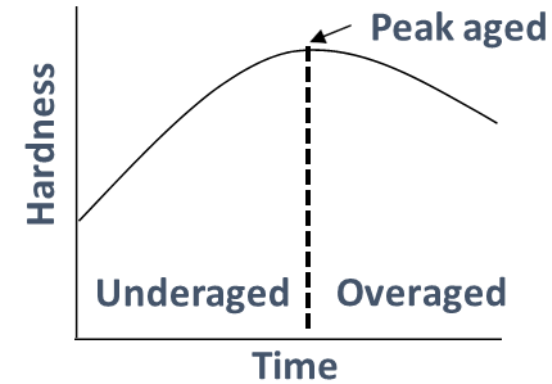
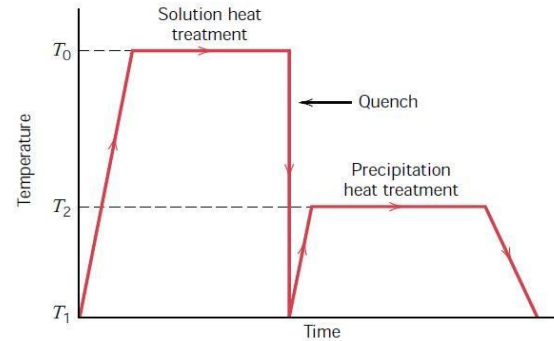
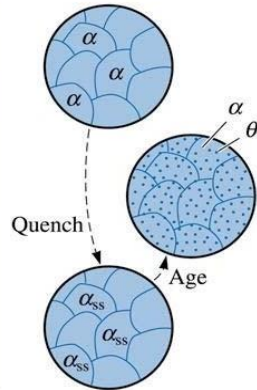
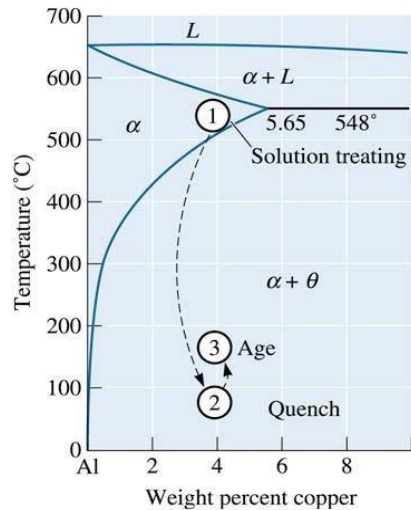


Fig. 13.1. Age-hardening: (a) Typical case of Al-Cu diagram. (b) Schematic illustrations of various treatments: (I) Solid solution,  $\alpha$  at temperature  $T_3$ . (II) Quenched, solid solution retained. It is supersaturated solid solution, (III) Annealing causes coarse grain boundary precipitation of  $\theta$ . (IV) Age-hardened, submicroscopic precipitates. (V) Overaging. Coarsening of precipitate occurs.

# Steps in Age Hardening



Typical aging curve

## 1. Solution treatment and 2. Rapid quenching

- Heat to dissolve all the coarse second phase particles
- Rapidly cool to achieve supersaturation

## 3. Aging treatment

- Heat and soak to form precipitates with desired morphology

# Steps in Age Hardening



AILEEN

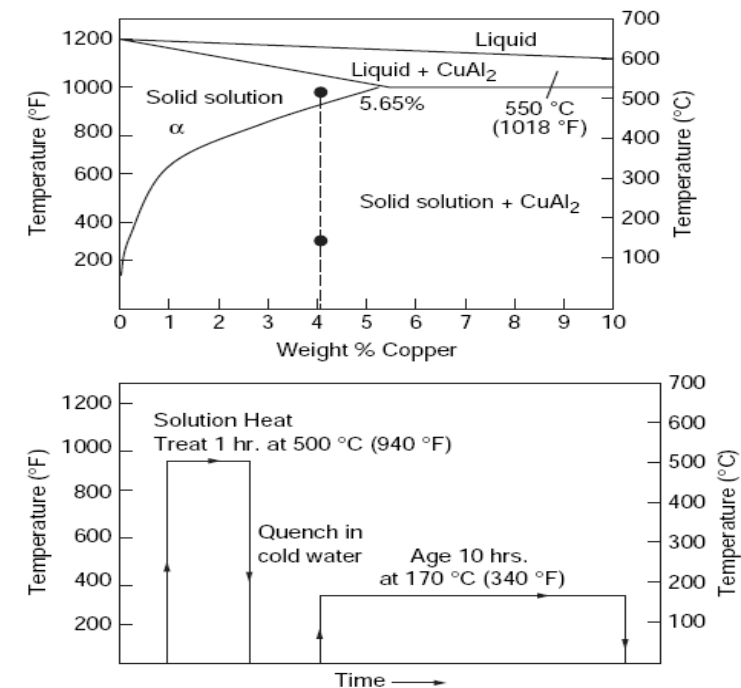
- In **solution heat treating**, the alloy is heated to a temperature that is high enough to put the soluble alloying elements in solution.
- After holding at the solution-treating temperature long enough for diffusion of solute atoms into the solvent matrix to occur, it is **quenched** to a lower temperature (e.g., room temperature) to keep the alloying elements trapped as **supersaturated solid solution**.
- During aging, the alloying elements trapped in solution precipitate to form a uniform distribution of very fine particles.
- Some aluminium alloys will harden after a few days at room temperature, a process called **natural aging**, while others are artificially aged by heating to an intermediate temperature.

# Steps in Age Hardening Al-Cu System



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- If an alloy of aluminium containing 4% Cu is heated to 500°C and held for 1 h, the copper will go into solution in the aluminium.
- After solution heat treating, the alloy is quenched in cold water to room temperature to keep the copper in solution.
- The alloy is then artificially aged at 170 °C for 10 h. During the aging process, very fine particles of aluminium-copper are precipitated, and the strength and hardness increase dramatically.
- Precipitation heat treatments generally are low-temperature, long-term processes. Aging temperatures for aluminium range from 115 to 190 °C, with times between 5 and 48 h.



**Fig. 9.6** Precipitation hardening of an aluminum-copper alloy

# Steps in Age Hardening Al-Cu System



AILEEN

- On quenching, the copper is trapped as a supersaturated solution in the matrix. There is a strong driving force to precipitate the copper as the equilibrium precipitate,  $\theta$  ( $\text{CuAl}_2$ ).
- However, in aluminum alloys, precipitation occurs by one or more metastable transition precipitates appearing before the appearance of the final equilibrium phase, with each successive stage lowering the free energy of the system.
- The transition precipitates are often crystallographically similar to the matrix, allowing the formation of a low-energy coherent interface during the nucleation process.
- Often, the precipitation sequence begins with the nucleation of small, **fully coherent phases known as Guinier-Preston (GP) zones**. The GP zones are ordered, solute-rich clusters resulting from phase separation that nucleate and grow.



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# Steps in Age Hardening Al-Cu System

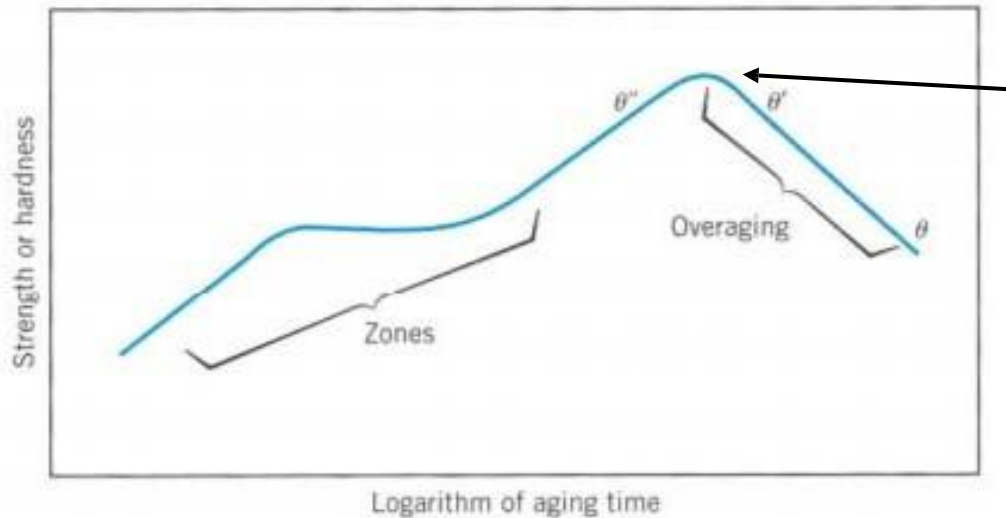
- The general sequence of precipitation in Al-Cu alloys can be represented by

Supersaturated solid solution (SSS)  $\rightarrow$  GP1 zones  $\rightarrow$  GP2 zones ( $\theta''$ )  $\rightarrow$   $\theta'$   $\rightarrow$   $\theta$  ( $\text{CuAl}_2$ )

- Guinier-Preston (GP) zones – Segregation of Cu atoms into clusters or platelets. These are only one atom thick and around 5 nm to 10 nm in diameter, but still part of the parent lattice (few atoms thick (4–6 Å) and about 80–100 Å in diameter). GP zone formation occurs by Cu diffusion, aided by quench-in vacancies over relatively short distances.
- The GP zones are the first to nucleate, because of their small size and coherency with the matrix. The interfacial energy term is extremely low, providing a low barrier to nucleation
- Since a Cu atom is about 11% smaller than an Al atom in diameter and the GP zones are richer in Cu than the solid solution, the crystal lattice is strained around the GP zones. The strain fields associated with the GP zones allow them to be detected in the electron microscope.
- In the next step above around 100°C, Cu atoms diffuse to the GP1 zone to form a larger one called GP(2) zones, sometimes known as  $\theta''$  phase. These lie parallel to {001} plane, and are a few atoms thick and up to 15 nm in diameter (10–40 Å thickness and 100 to 1000 Å in dia).
- The  $\theta''$  precipitate has tetragonal structure which fits perfectly with the Al unit cell in 2 directions but not in 3<sup>rd</sup>. For the precipitate and matrix to maintain coherency the Al planes have to be distorted and thus gives rise to coherency strains

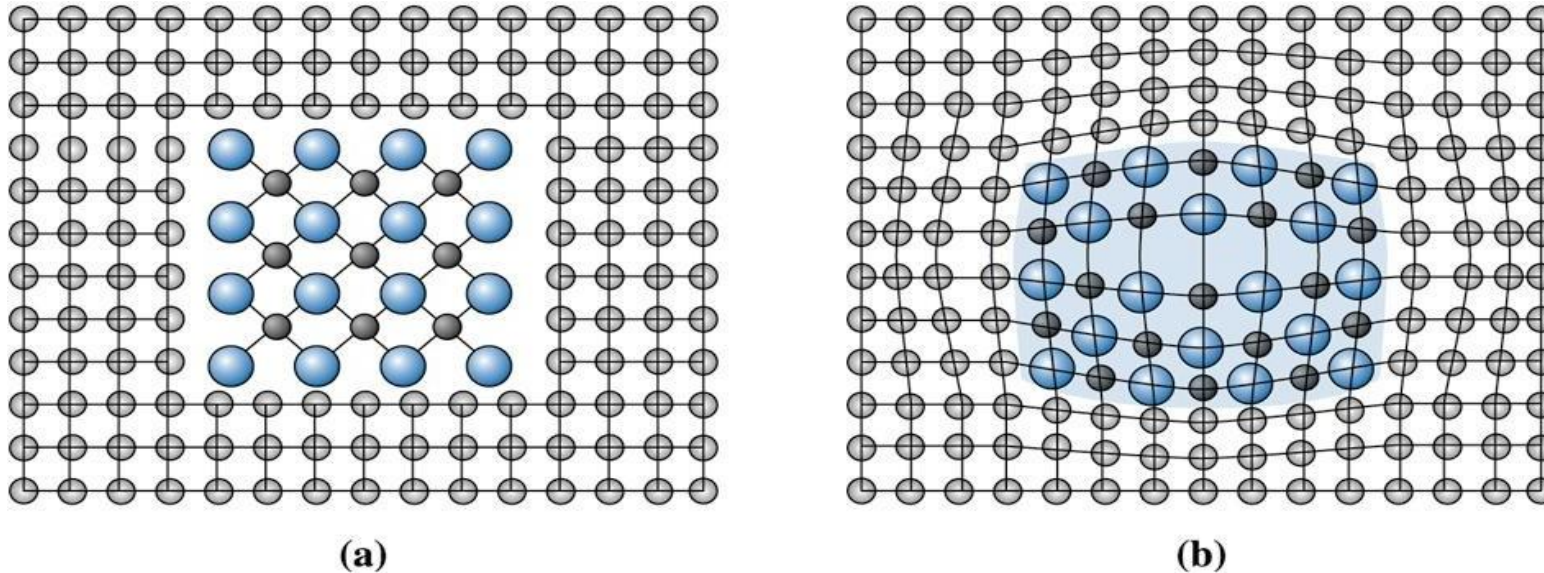
# Steps in Age Hardening Al-Cu System

- The combination of fine particle size and the localized strain fields is an effective barrier to dislocation movement
- Further growth of the GP(2) zones leads to the formation of the  $\theta'$  phase, which is not fully coherent with the lattice (size ranges from 100 to 150 Å in thickness and 100 to 6000 Å or more in diameter depending on the time and temperature of aging).
- Over-aging develops the equilibrium tetragonal phase ( $\text{Al}_2\text{Cu}$ ), which is fully incoherent and does not have a strong strengthening effect.



Peak strength: both particle cutting and particle bowing (looping) of dislocations contribute to the alloy strength

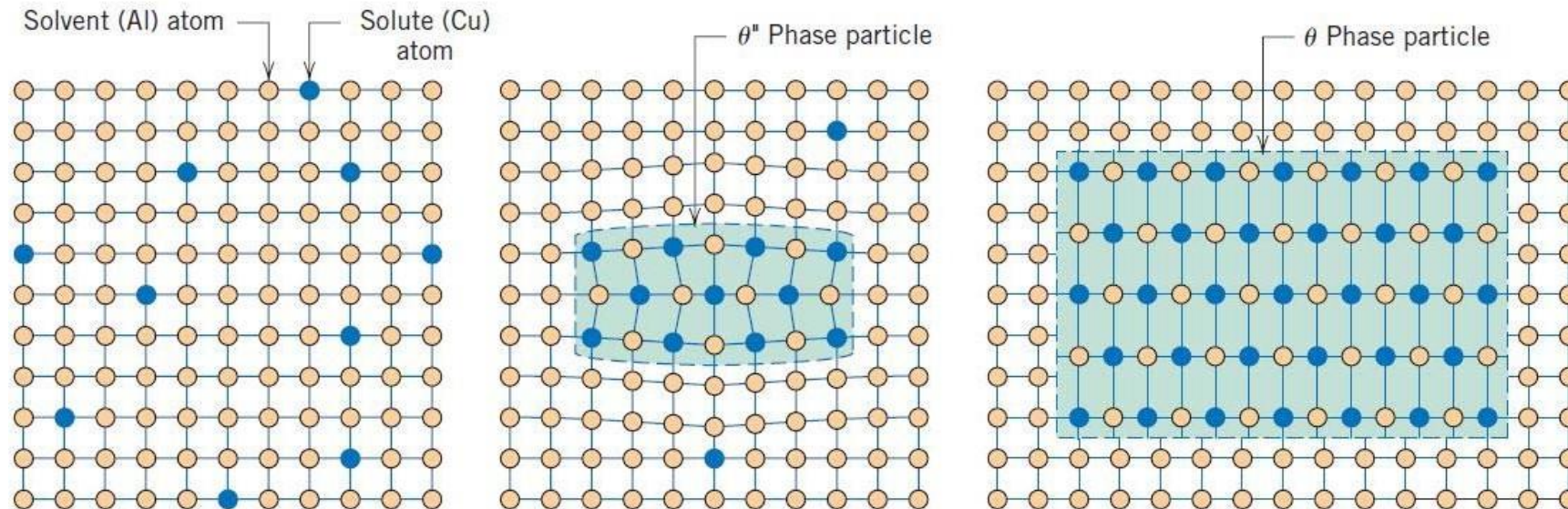
# Steps in Age Hardening Al-Cu System



**Figure 11.8 (a) A noncoherent precipitate has no relationship with the crystal structure of the surrounding matrix. (b) A coherent precipitate forms so that there is a definite relationship between the precipitate's and the matrix's crystal structure.**

- The lattice distortion produced by a coherent precipitate, which impedes the dislocation motion
- The equilibrium phase no longer imposes a strain field on the matrix and is not effective in blocking dislocation motion, strength properties decrease.

# Steps in Age Hardening Al-Cu System



**Figure 3.4 Schematic depiction of several stages in the formation of the equilibrium precipitate ( $\theta$ ) phase. (a) A supersaturated  $\alpha$  solid solution. (b) A transition,  $\theta''$ , precipitate phase. (c) The equilibrium  $\theta$  phase, within the  $\alpha$ -matrix phase. Actual phase particle sizes are much larger than shown here [2].**

# Steps in Age Hardening Al-Cu System



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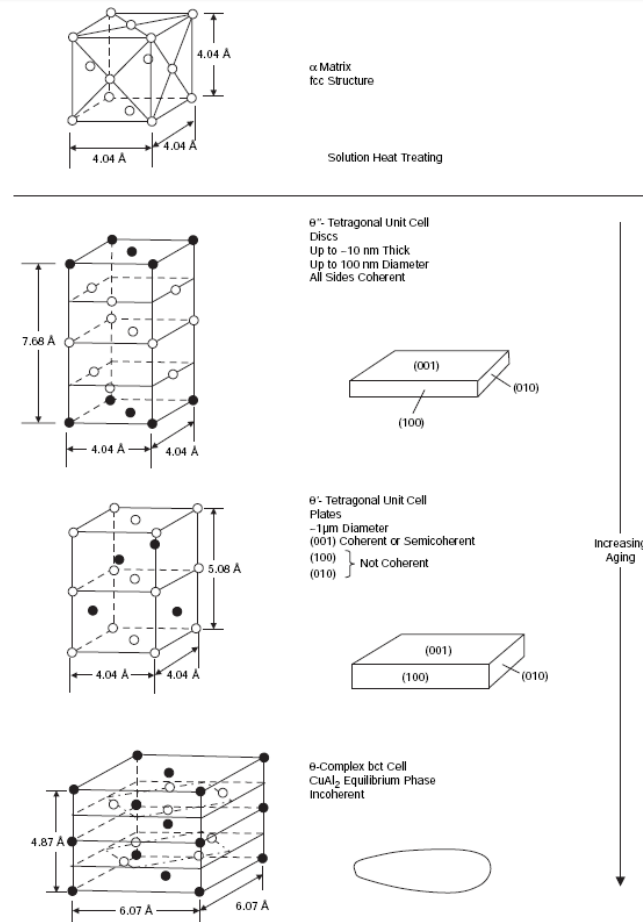
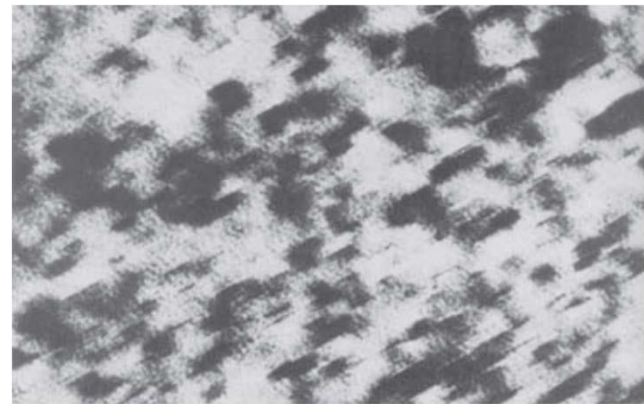


Fig. 9.7 Aluminum-copper precipitation sequence. fcc, face-centered cubic; bct, body-centered tetragonal. Source: Ref 4

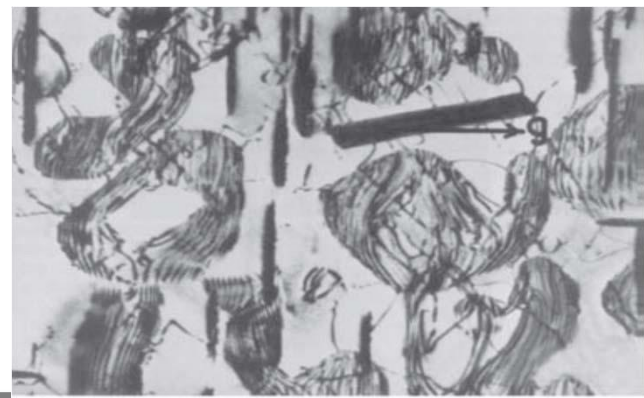
## TEM of Al-Cu age-hardened alloy



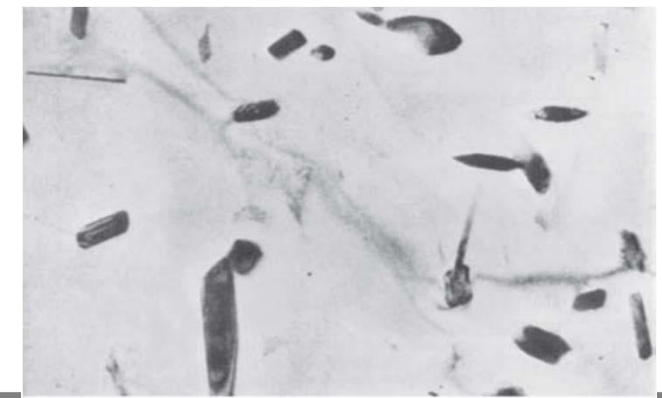
GP zones (720000 x) 0.01  $\mu$ m



$\theta''$  (63000 x) 0.25  $\mu$ m



$\theta'$  (18000 x) 0.5  $\mu$ m



$\theta$  (8000 x) 1  $\mu$ m

# Steps in Age Hardening Al-Cu System



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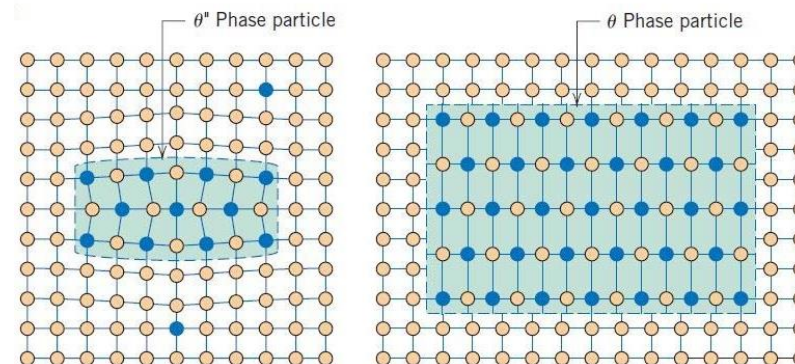
| Alloy    | Precipitates formed                                                                                                                                                       |
|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Al-Cu    | GP zones as thin plates, $\theta''$ , $\theta'$ (tetragonal), $\theta$ (body centered)                                                                                    |
| Al-Mg    | Spherical GP zones, $\beta'$ hexagonal, $\beta$ FCC ( $\text{Mg}_2\text{Al}_3$ )                                                                                          |
| Al-Si    | Silicon diamond cubic                                                                                                                                                     |
| Al-Cu-Mg | Disordered clusters of Cu & Mg atoms, GP (Cu,Mg) zones as rods, $S'$ orthorhombic $\text{Al}_2\text{CuMg}$ , $S$ orthorhombic $\text{Al}_2\text{CuMg}$ .                  |
| Al-Mg-Si | Clusters & co-clusters of Mg & Si atoms, GP zones, $\beta'$ monoclinic (MgSi), $\beta'$ hexagonal ( $\text{Mg}_{1.7}\text{Si}$ ), $\beta'$ FCC ( $\text{Mg}_2\text{Si}$ ) |
| Al-Li-Mg | $\delta'$ cubic ( $\text{Al}_3\text{Li}$ ), $\text{Al}_2\text{LiMg}$ cubic                                                                                                |
| Al-Zn-Mg | GP zones, $\eta'$ hexagonal (MgZn), $\eta$ hexagonal ( $\text{MgZn}_2$ ), $T'$ hexagonal ( $\text{Mg}_{32}(\text{Al}, \text{Zn})_{49}$ )                                  |

# Dispersion strengthening



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- The strength and hardness in some metal alloys may be enhanced by the presence of extremely small and uniformly dispersed particles within the original phase matrix.
- Whether introduced as insoluble particles in powder compaction (**dispersion strengthening**), or as precipitates in a solid state reaction (precipitation or age hardening), second phase particles are generally the most potent strengthening agent in practical high strength engineering materials.
- Iron-base, aluminium, nickel, titanium alloys all employ second phases to achieve high strength
- The size, shape, and amount of second phase particles controls the mechanical properties of the alloy.
- Second phase particles in the form of very small uniformly distributed particles are added to the matrix.
- These will block dislocation motion extremely well, and strengthen the material. This is the basis for all high strength alloys

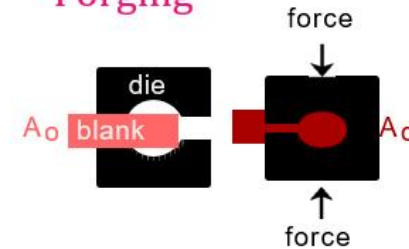


# Strain – Hardening



- Strain hardening is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed.
- Some times it can also be called as work hardening or cold working. Generally, the metals which cannot be heat treated can be cold worked. Most metals strain harden at room temperature.
- The reason for strain hardening is the increase of dislocation density with plastic deformation.
- As a metal is plastically deformed, new dislocations are created, so that the dislocation density becomes higher and higher.
- In addition to multiplying, the dislocations become entangled and impede each others' motion. The result is increasing resistance to plastic deformation with increasing dislocation density.
- This resistance increases strength but decreases ductility
- Non-heat treatable Al alloys goes through strain hardening

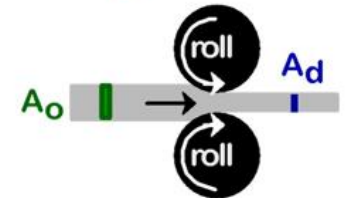
-Forging



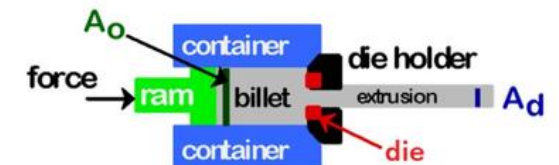
-Drawing



-Rolling



-Extrusion



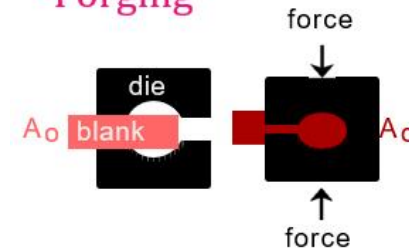
# Annealing



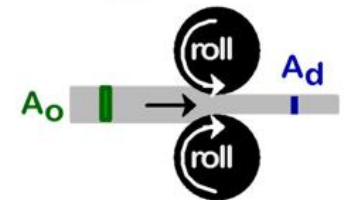
AILEEN

- Since the work hardened condition increases the stored energy in the metal and is thermodynamically unstable, the deformed metal will try to return to a state of lower energy.
- This generally cannot be accomplished at room temperature. Elevated temperatures, in the range of  $1/2$  to  $3/4$  of the absolute melting point, are necessary to allow mechanisms, such as diffusion, to restore the lower-energy state.
- The process of heating a work-hardened metal to restore its original strength and ductility is called annealing.

-Forging



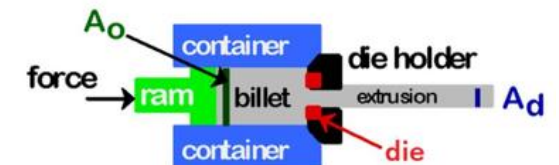
-Rolling



-Drawing



-Extrusion



# Welding of Al alloys



AILEEN

## – Reasons to weld...

- Aluminium alloys are vital in transport applications because they provide engineering materials with good strength-to-weight ratios at reasonable cost.
- Further applications make use of the corrosion resistance and conductivity (both thermal and electrical) of some alloys.
- Although normally low strength, some of the more complex alloys can have mechanical properties equivalent to steels.
- Owing to the many benefits of aluminium alloys offered to industry, there is a need to identify best practices for joining them.

# Welding of Al alloys



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## – Issues in welding...

- **High thermal conductivity:** This results in excessive dissipation of heat, which can make welding difficult and/or result in unwanted distortion of the parts, owing to a larger heat input being required.
- **Hydrogen solubility:** Hydrogen is very soluble in molten aluminium, resulting in the weld pool absorbing hydrogen during processing. Once the molten material solidifies, the hydrogen bubbles become entrapped, creating porosity.
- **Oxide layer:** Aluminium have an oxide layer (aluminium oxide), which has a much higher melting point (2060 C°) than the parent aluminium alloy (660 C°). When welding, this can result in the oxide layer being included in the weld region, potentially causing lack of fusion defects and reducing the strength of the weld. Consequently, the workpieces should be cleaned with a wire brush or chemical etching prior to welding to prevent oxide inclusion.

# Welding of Al alloys



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## – Processes...

- Numerous processes are applicable.
- Arc welding
- Laser welding
- Electron beam welding
- Friction welding

# Welding of Al alloys



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## – Arc welding process...

- Arc welding is commonly used for joining aluminium alloys. Most of the wrought grades in the 1xxx, 3xxx, 5xxx, 6xxx and medium strength 7xxx (e.g. 7020) series can be fusion welded with arc-based processes. The 5xxx series alloys, in particular, have excellent weldability.
- High strength alloys (e.g. 7010 and 7050) and most of the 2xxx series are not recommended for fusion welding because they are prone to liquation and solidification cracking.

# Welding of Al alloys



## – Arc welding process...

- MIG > The process is best suited for thinner gauges of material, such as aluminium sheet, because the amount of heat required is less when compared to thicker plates. Pure Argon is the preferred shielding gas for this process.
- TIG > Owing to the high thermal conductivity of bulk aluminium (quick heat dissipation), the TIG process enables sufficient generation of heat to keep the weld region hot enough to create a weld pool. TIG welding can be used to join thick and thin sections. Similarly to MIG welding, pure argon is the preferred shielding gas.
- The welding wire/rod used should be compositionally similar to the parts being welded in both MIG and TIG processes.

# Welding of Al alloys



## – Laser welding process...

- It's a faster process and creates small weld pools.
- Laser beams can be used to weld many series of aluminium alloys.
- Laser beam welding can be used with crack sensitive materials, such as the 6000 series of aluminum alloys when combined with an appropriate filler material such as 4032 or 4047 aluminum alloys.
- Shielding gases used are selected dependent on the aluminium grade to be joined.

# Welding of Al alloys



- Electron beam welding process...
  - Produces fast welds with small weld pools.
  - Better at producing welds in very thick sections of aluminium.
  - No shielding gas required, mostly carried out in vacuum > creating pure welds
  - Proper filler wire should be selected

# Welding of Al alloys



## – Friction welding process...

- Friction welding is capable of joining all series of aluminium alloys, including 2xxx and 7xxx, which are difficult with fusion-based processes
- No shielding gas as it is a solid state welding process > Pure welds
- Superior mechanical performance of the weld region is obtained when compared to fusion welding processes
- Compatible with various friction welding variants...
- FSW > The process is typically used for joining aluminium sheet/plate material
- FSSW > Creates spot welds replacing rivets in aluminium sheets
- LFW > Used for joining bulk aluminium parts using pressed linear oscillations
- RFW > Used for joining cylindrical bulk aluminium parts using rotatory oscillations

# Welding of Al alloys



## – Fillers...

- Proper filler metal selection (filler wire or filler rod) is essential in order to minimise the risk of hot cracking in aluminium alloys when using fusion welding processes like arc, electron beam and laser welding.
- Filler metal composition is determined by:
  - weldability of the parent metal
  - minimum mechanical properties of the weld metal
  - corrosion resistance
- Nominally matching filler metals are often employed for non-heat-treatable alloys. However, for heat-treatable alloys, non-matching fillers are used to prevent solidification cracking.
- The choice of filler metal composition for the various weldable alloys is specified in BS EN 1011 Pt 4:2000 for TIG and MIG welding

# Welding of Al alloys



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## – Fillers...

Recommended filler metal compositions for the more commonly used alloys

| Alloy Designation | Chemical Designation | Classification | Filler            | Application                 |
|-------------------|----------------------|----------------|-------------------|-----------------------------|
| EN AW-1080A       | EN AW-Al 99.8(A)     | NHT            | R-1080A           | Chemical plant              |
| EN AW-3103        | EN AW-Al Mn1         | NHT            | R-3103            | Buildings, heat exchangers  |
| EN AW-4043A       | EN AW-Al Si5(A)      | -              | -                 | Filler wire/rod             |
| EN AW-5083        | EN AW-Al Mg4.5Mn0.7  | NHT            | R-5556A           | Ships, rail wagons, bridges |
| EN AW-5251        | EN AW-Al Mg2Mn0.3    | NHT            | R-5356            | Road vehicles, marine       |
| EN AW-5356        | EN AW-Al Mg5Cr(A)    | -              | -                 | Filler wire/rod             |
| EN AW-5556A       | EN AW-Al Mg5Mn       | -              | -                 | Filer wire/rod              |
| EN AW-6061        | EN AW-Al Mg1SiCu     | HT             | R-4043A<br>R-5356 | Structural, pipes           |
| EN AW-7020        | EN AW-Al Zn4.5Mg1    | HT             | R-5556A           | Structural, transport       |

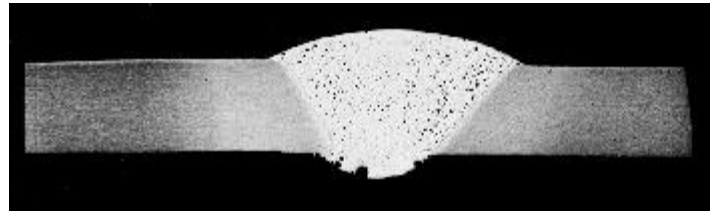
HT = Heat treatable, NHT = Non Heat treatable

# Welding of Al alloys



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## – Welding issues...

- The most likely imperfections in Al fusion welds are:
    - Porosity, cracking and poor weld bead profile
- 
- Porosity: Common in MIG and TIG welds. Main cause is hydrogen absorption. Its sources are hydrocarbons, water vapour in the atmosphere or moisture on parent material / filler wire surfaces
    - To minimize the risk: Three cleaning techniques are suitable; mechanical cleaning, solvent degreasing and chemical etch cleaning.
    - Mechanical: Wire brushing, scraping or filing surface to remove surface oxides
    - Solvents: Dipping, spraying or wiping with organic solvents can be used to remove grease, oil, dirt and loose particles.
    - A solution of 5% sodium hydroxide can be used for batch cleaning but this should be followed by rinsing in  $\text{HNO}_3$  and water to remove reaction products on the surface.

# Welding of Al alloys

## – Welding issues...

- Cracks: Solidification cracking
- Solid cracking occurs in aluminium alloys because of high stresses generated across the weld due to the high thermal expansion (twice that of steel) and the substantial contraction on solidification
- Solidification cracks form in the centre of the weld, usually extending along the centreline during solidification.
- The main causes of solidification cracks are:
  - incorrect filler wire/parent metal combination
  - incorrect weld geometry
  - welding under high restraint conditions



# Welding of Al alloys



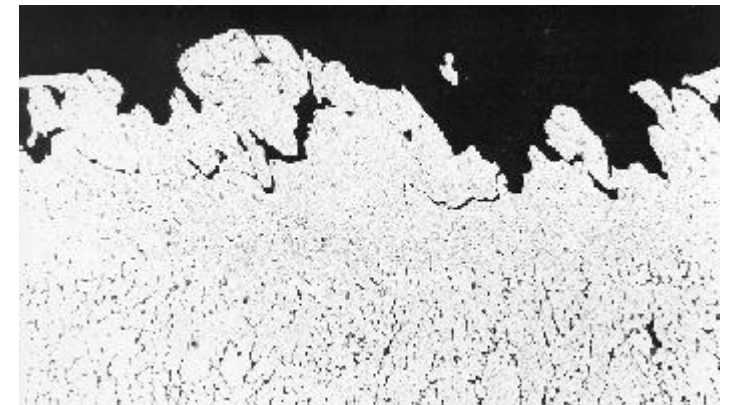
## – Welding issues...

- Cracks: Solidification cracking
- The cracking risk can be reduced by using a non-matching, crack-resistant filler (usually from the 4xxx and 5xxx series alloys). The disadvantage is that the resulting weld metal may have a lower strength than the parent metal and not respond to a subsequent heat treatment. The weld bead should be thick enough to withstand contraction stresses.

# Welding of Al alloys

## – Welding issues...

- Cracks: Liquation cracking
- Liquation cracking occurs in the HAZ, when low melting point films are formed at the grain boundaries. These cannot withstand the contraction stresses generated when the weld metal solidifies and cools. Heat treatable alloys, particularly 6xxx and 7xxx series alloys, are more susceptible to this type of cracking.
- The risk can be reduced by using a filler metal with a lower melting temperature than the parent metal, for example the 6xxx series alloys are welded with a 4xxx filler metal.



# Welding of Al alloys



## – Welding issues...

- Poor weld bead profile (irregularities in the weld seam)
- Incorrect welding parameter settings or poor welder technique can introduce weld profile imperfections such as lack of fusion, lack of penetration and undercut.
- The high thermal conductivity of aluminium and the rapidly solidifying weld pool make these alloys particularly susceptible to profile imperfections.



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