Heat Treatment of Non-Ferrous Alloys

Introduction

Unlike steels, which rely heavily on phase transformations (austenite → ferrite/pearlite/martensite), many non-ferrous alloys are strengthened primarily by **precipitation (age) hardening**, solid solution strengthening, and grain refinement. Heat treatment is crucial to tailor strength, ductility, corrosion resistance, and high-temperature performance.

Aluminum Alloys

- **Two main groups:**
  - **Non-heat-treatable:** 1xxx (pure Al), 3xxx (Al–Mn), 5xxx (Al–Mg).
  - **Heat-treatable:** 2xxx (Al–Cu), 6xxx (Al–Mg–Si), 7xxx (Al–Zn–Mg), some 4xxx (Al–Si–Mg), 8xxx (Al–Li).
- **Heat treatment process:**
  - **Solution treatment:** Heat above solvus to dissolve alloying elements.
  - **Quenching:** Trap solutes in supersaturated solid solution.
  - **Aging (natural or artificial):** Controlled precipitation (e.g., θ′ Al_2Cu, β″ Mg_2Si, η′ $MgZn_2$).
- **Key properties:**
  - Excellent strength-to-weight ratio.
  - Precipitation hardening yields up to **10× strength increase** vs pure Al .
  - Limited high-temperature use (below ~175 °C due to precipitate coarsening).
- **Applications:** Aerospace frames (2024, 7075), automotive (6061), beverage cans (5xxx).

Magnesium Alloys

- **Non-heat-treatable:** Pure Mg, many Mg–Al solid solutions (limited strengthening).

- **Heat-treatable systems:** Mg–Al–Zn, Mg–Zn–Zr.
- **Heat treatment effect:**
  - Solution treat → quench → age to form precipitates like $MgZn_2$ or $Mg_{17}Al_{12}$.
  - Improves strength but creep/fatigue resistance still modest.
- **Applications:** Automotive wheels, aerospace parts, lightweight machinery.

Copper Alloys

- **Non-heat-treatable:** Brass (Cu–Zn), bronze (Cu–Sn, Cu–Al <9%). Strengthened by solid solution + cold work.
- **Heat-treatable:**
  - **Cu–Be (beryllium bronze):** Age hardening produces very high strength (~190 ksi).
  - **Cu–Cr, Cu–Ni–Si, Cu–Zr:** Precipitation of fine particles increases hardness.
  - **Cu–Al (≥9% Al):** Can form martensite-like phases and be tempered for toughness.
- **Applications:** Electrical contacts, springs, bearings, non-sparking tools.

Nickel and Cobalt Alloys (Superalloys)

- **Ni-based superalloys:**
  - Strengthened by γ′ precipitates (Ni_3Al, Ni_3Ti).
  - Carbide strengthening also used.
  - Excellent creep resistance and stability up to 1000 °C.
- **Co-based superalloys:**
  - High wear resistance at elevated temperatures.
  - Strengthened by carbides.
- **Applications:** Turbine blades, jet engines, heat exchangers.

Titanium Alloys

- **Allotropic transformation:** α (HCP) → β (BCC) at ~882 °C.
- **Heat treatment strategies:**
  - **α alloys:** Strengthened mainly by solution treatment.
  - **β alloys:** Solution treat + quench → metastable β → age → α precipitates.
  - **α+β alloys (e.g., Ti-6Al-4V):** Microstructure tailored by annealing, quenching, and aging.
- **Special case:** Titanium martensite (α′) can form on quenching; tempered to optimize strength/ductility.
- **Applications:** Aerospace, biomedical implants, chemical equipment.

General Comparison

Alloy system	Heat Treatable?	Strengthening Mechanism	Key Example	Applications
Al–Cu, Al–Mg–Si, Al–Zn–Mg	Yes	Precipitation hardening	2024, 6061, 7075	Aircraft, automotive
Mg–Al–Zn, Mg–Zn–Zr	Yes	Precipitation ($MgZn_2$, $Mg_{17}Al_{12}$)	AZ91	Automotive, aerospace
Cu–Be, Cu–Cr, Cu–Ni–Si	Yes	Precipitation hardening	Cu–2%Be	Springs, contacts
Ni-based alloys	Yes	γ′ (Ni_3Al, Ni_3Ti) + carbides	Inconel 713C	Turbine blades
Co-based alloys	Limited	Carbide strengthening	Stellite 6B	Cutting tools
Ti alloys (α+β, β)	Yes	α/β precipitation + martensite	Ti-6Al-4V	Implants, aerospace