### Table 10.1: Some Precipitation-Hardening Systems

<table>
<thead>
<tr>
<th>Base Metal</th>
<th>Alloy</th>
<th>Sequence of Precipitates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Al–Ag</td>
<td>Zones (spheres) —— γ’ (plates) —— γ(Ag,Al)</td>
</tr>
<tr>
<td></td>
<td>Al–Cu</td>
<td>Zones (disks) —— θ’ (disks) —— θ’ —— θ (CuAl₂)</td>
</tr>
<tr>
<td></td>
<td>Al–Zn–Mg</td>
<td>Zones (spheres) —— M’ (plates) —— (MgZn₂)</td>
</tr>
<tr>
<td></td>
<td>Al–Mg–Si</td>
<td>Zones (rods) —— β’ —— (Mg₂Si)</td>
</tr>
<tr>
<td></td>
<td>Al–Mg–Cu</td>
<td>Zones (rods or spheres) —— S’ —— S(Al₂CuMg)</td>
</tr>
<tr>
<td></td>
<td>Al–Li–Cu</td>
<td>Zones —— θ” ——&gt; θ’ ——&gt; θ (CuAl₂)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>δ’ ——&gt; δ (AlLi)</td>
</tr>
<tr>
<td>Cu</td>
<td>Cu–Be</td>
<td>Zones (disks) —— γ’ —— γ (CuBe)</td>
</tr>
<tr>
<td></td>
<td>Cu–Co</td>
<td>Zones (spheres) —— β</td>
</tr>
<tr>
<td>Fe</td>
<td>Fe–C</td>
<td>ε-Carbide (disks) —— Fe₃C(“laths”)</td>
</tr>
<tr>
<td>Fe</td>
<td>Fe–N</td>
<td>α” (disks) —— Fe₄N</td>
</tr>
<tr>
<td>Ni</td>
<td>Ni–Cr–Ti–Al</td>
<td>γ’ (cubes) —— γ(Ni₂Ti)</td>
</tr>
</tbody>
</table>
The International Alloy Designation System is the most widely accepted naming scheme for wrought alloys. Each alloy is given a four-digit number, where the first digit indicates the major alloying elements.

- **1XXX series:** pure Al, work hardening, non-heat treatable alloys
- **2XXX series:** Al- Cu, precipitation hardening (Al-Cu), heat treatable alloys
- **3XXX series:** Al- Mn, work hardening (0.62%Mn), non-heat treatable alloys
- **4XXX series:** Al- Si (1.5%Si), non-heat treatable alloys
- **5XXX series:** Al- Mg (17.1%Mg), non-heat treatable alloys
- **6XXX series:** Al- Mg- Si, precipitation hardening (Al-Mg-Si), heat treatable alloys
- **7XXX series:** Al- Zn-Mg, precipitation hardening (Al-Zn-Mg), heat treatable alloys
- **8XXX series:** Miscellaneous alloys eg. Al-Li alloys
C2: Upper yield points caused by Solutes

Low carbon steel

Low-carbon steel in a temper-rolled condition and annealed for one hour between 100 °C and 34.3 °C
Upper yield points caused by Solutes: Mechanism

- Solute atoms will preferentially segregate to the distorted regions near the dislocations such that the total elastic strain can be minimized (i.e., solutes will move to locations that minimize the distortion of the lattice caused by their presence).

- This segregation of solutes results in the formation of solute atmospheres wherein solute atoms will tend to accumulate in the stress field of the dislocation.

Cottrell-Bilby Model
Upper yield points caused by Solutes: Mechanism

• At elevated temperatures, diffusion processes increase mobility for the solute atoms. Solute atmospheres can move along with the dislocation line in order to maintain a minimum energy state.

• Diffusion of solutes, within a specific temperature-strain rate range, restricts dislocation motion because the dislocations must “drag” the solute atmospheres along with them.

• Dislocation motion will be restricted until the applied stress is large enough to “break the dislocations free” from the solute atmospheres.
C3 Strain Localization of Lueders Band

After the upper yield point, there follows a plateau region called as the lower yield point where dislocations are free of the solute atmospheres.

Nonhomogeneous deformation, such as Lueders bands appears and propagates through the sample. This is known as Lueders band along the stress-concentrated zones, i.e., along 45 degrees to the tensile direction.

Figure 12.18. Lüder's bands on a low carbon steel tensile specimen. From S. Kalpakjian, Mechanical Processing of Materials, Van Nostrand, 1967, p. 194. Courtesy of J. F. Butler, Jones and Laughlin Steel Corp.
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Nonhomogeneous deformation, such as Lueders bands appears and propagates through the sample. This is known as Lueders band along the stress-concentrated zones, i.e., along 45 degrees to the tensile direction.
Phenomenon II: Strain Localization of Lueders Band

To reduce the formation of Lueders band:
1. Adding Al, V, Ti and Nb or B to steel
2. Prestraining the sheet to a strain larger than the yield point
Strain ageing is a phenomenon in which the metal increase in strength while losing ductility after being heated at relatively low temperature or cold-working.

- Reloading at X and straining to Y does not produce yield point.
- After this point if the specimen is reloading after ageing (RT or ageing temp) the yield point will reappear at a higher value.
- This reappearance of the yield point is due to the diffusion of C and N atoms to anchor the dislocations.
- N has more strain ageing effect in iron than C due to a higher solubility and diffusion coefficient.
C5 Phenomenon IV: Dynamic Strain Aging

- Strain ageing is also associated with serrated stress-strain curves or repeated yielding, due to high speed of diffusion of solute atoms to catch and lock dislocations.

- This dynamic strain ageing is also called Portevin-LeChatelier effect.
Phenomenon IV: Dynamic Strain Aging

- Serrated stress-strain curves are observed and serrated yielding is also known as the Portevin-LeChatelier (PLC) effect.
- PLC occurs when the solutes are mobile enough to continuously diffuse to and pin dislocations during deformation.
- Each serration represents repeated pinning and breakaway of dislocations from solute atmospheres.
Phenomenon IV: Dynamic Strain Aging

Table 12.1. Temperature range for dynamic strain aging in several metals

<table>
<thead>
<tr>
<th>Metal</th>
<th>Temperature range for $d\sigma/dT &gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta</td>
<td>$(\varepsilon = 0.01, \dot{\varepsilon} = 0.001/s)$</td>
</tr>
<tr>
<td>V</td>
<td>$(\varepsilon = 0.01, \dot{\varepsilon} = 0.001/s)$</td>
</tr>
<tr>
<td>DH 36 steel</td>
<td>$(\varepsilon = 0.01, \dot{\varepsilon} = 0.001/s)$</td>
</tr>
<tr>
<td>Ti</td>
<td>$(\dot{\varepsilon} = 0.0003/s)$</td>
</tr>
<tr>
<td>Al 2024</td>
<td></td>
</tr>
</tbody>
</table>
C6: Bake-hardened (BH) steel

Bake-hardening process:

Cold forming (auto-body) → Painting →

Heat-treating (at 170 °C for 20 min) → Increasing of Y.S. due to aging effect (~ 40-50 MPa)

Figure 1 Schematic Illustration Showing Strain Hardening and Bake Hardening Index and the Increase in Yield Strength that Occurs During The Bake Cycle.
Schematic of Bake-hardened (BH) steel

Steel producer

Steel sheet

Carbon solute

before press-forming

Car manufacture

Press-process

after press-forming

Work-hardening

Baking process

after baking

Baking-hardening
C7 High Strength Low Alloy Steel (HSLA)

• Addition of micro-alloy (carbide, nitride or carbo-nitride forming elements) such as Nb, V, Ti in structural steel and strip steel grades, the materials are known as “High Strength Low Alloy (HSLA) steel”

• At slab soaking temperature ~ 1200 °C

- undissolved particles (such as TiN, NbC and AlN) restricts the size of austenite grain (affect to inhibit recrystallization during hot rolling → produces fine austenite grain size → induces fine ferrite grain size)

- a proportion of micro-alloys are dissolved to solid solution (affect to precipitate in later process in form of fine carbide/ carbonitride/ nitride at austenite-ferrite interface on cooling to room temperature)
<table>
<thead>
<tr>
<th>Element(s)</th>
<th>Main Precipitates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niobium</td>
<td>Nb(C,N), Nb$_4$C$_3$</td>
</tr>
<tr>
<td>Vanadium</td>
<td>V (C,N), V$_4$C$_3$</td>
</tr>
<tr>
<td>Niobium + molybdenum</td>
<td>(Nb,Mo)C</td>
</tr>
<tr>
<td>Vanadium + nitrogen</td>
<td>VN</td>
</tr>
<tr>
<td>Copper + niobium</td>
<td>Cu,Nb(C,N)</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti(C,N), TiC</td>
</tr>
<tr>
<td>Aluminum + nitrogen</td>
<td>AlN</td>
</tr>
</tbody>
</table>
Hardening mechanism of high Strength Low Alloy Steel (HSLA)

Yield stress: annealed steel

Solid Solution: Mn, Si, Mo

Fine grain : Nb, Ti

Precipitation: Ni, Ti

Cold working : TM

Yield stress: annealed steel
C8 Hot-Rolled Strip

Continuous furnace

Roughing Stand

Finishing Mill

Cooling

Coiler

Austenitize

Austenite grain growth

Dissolution of precipitates

Precipitation

Work hardening

Re-crystallization recovery

Transformation
C8 Heat Treatment of Steel

Austenitize + Quenching

Hardening

Tempering
Fe-C Diagram