Appendix: Overview over (some) hardening mechanisms

1. Imperfections in crystals

Crystals are seldom perfect; typical imperfections are these:

Vacancies (a) and (b) foreign (solute) atoms (b) are point-defects (0-D).
Dislocations (c) are 1-D (delimiting line of an extra half-plane of atoms).
Grain boundaries (d) are 2-D.

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2. Dislocations

Dislocations are defined by their Burgers vector \( \mathbf{b} \), which describes the closing error of the Burgers circuit:
- if the Burgers vector is normal to the dislocation line: edge dislocation;
- if the Burgers vector is parallel to the dislocation line: screw dislocation.

In general, dislocations are of mixed character (curved).
3. Movement of dislocations

Dislocations are the predominant carriers of plastic deformation. This is because the movement of a dislocation requires the breaking of atomic bonds only along one single line (at a given time) instead of along an entire plane! Therefore plastic slip can operate at stresses far below the theoretical strength of the material!

Plastic slip operates by shear.
4. Obstacles to dislocation motion

Hardening of a metallic material is typically achieved by blocking the movement of dislocations, i.e. by introducing obstacles that will slow down or impede the movement of dislocations.

- Solute atoms (foreign atoms that provide solution hardening);
- Hard particles (introduced by dispersion or — more often — by precipitation);
- Other dislocations (introduced by cold work);
- And others (such as grain boundaries).

Example: Cu alloys
5. Precipitation hardening

A quite elegant way to introduce particles acting as obstacles to dislocation motion inside a metallic material is via precipitation (otherwise it is quite difficult to achieve a fine and homogeneous distribution of small particles). The method necessitates a good solubility of alloy elements within the base metal at elevated temperature, and a significant decrease of solubility towards lower temperature (cf. precipitation of air humidity in the form of dew or frost during a cold night). In alloys, a fine precipitation is achieved by quenching the alloy from elevated temperature (which leaves the solute atoms in supersaturated solution within the alloy), and by tempering at some intermediate temperature (where the diffusivity is high enough such that atoms diffuse and form precipitates). Also required is, of course, a good mechanical resistance of these precipitates.
6. Some references