Elastic energy induced microstructural refinement and self-organization

Martensitic microstructure in CuZnAl (M. Morin, INSA de Lyon)

Elastic Energy Abatement for Fully Coherent Precipitate

Fig. 3.48 For a coherent thin disc there is little misfit parallel to the plane of the disc. Maximum misfit is perpendicular to the disc.
Minimizing Elastic Energy for Fully Coherent Precipitate:

Transformation strain $\varepsilon = \begin{pmatrix} \delta & 0 & 0 \\ 0 & \delta & 0 \\ 0 & 0 & \delta \end{pmatrix}$

$\delta_{zz}$, $\delta_{zx}$, $\delta_{zy}$: geometrically “soft”

$\delta_{xx}$, $\delta_{yy}$, $\delta_{xy}$: geometrically “hard”

"Naively", $\Delta G_{\text{elastic}} \propto V^\beta \left( E_{xx} \delta^2 + E_{yy} \delta^2 + E_{zz} \delta^2 \right)$

orientationally softened

geometrically softened by disk shape

$(x/a)^2 + (y/a)^2 + (z/c)^2 = 1$
In cubic metals, \( E_{<100>} \) soft, \( E_{<111>} \) hard

\(<100>\)-parallel disks beat \(<111>\)-parallel disks

Competition between capillary energy and elastic energy in nanoscale, fully coherent precipitates in Al alloys (iso-structure, hydrostatically dilated)

capillary energy prefers blocky shape
elastic energy prefers disk shape
for fully coherent precipitates
Eshelby operation: stick an object into larger/smaller hole, and stitch up the interface.

Fig. 3.49  The origin of misfit strain for an incoherent inclusion (no lattice matching).
Coherent interface: **shear strong**

Semicohercient/incoherent interface: **shear weak**

For “greased” or shear-weak interface the relaxed elastic energy expression is quite different from that for coherent precipitate (even if isotropic elastic constants): it favors the **disk** shape even more.
elastic energy = $V^\beta \cdot 6\mu\delta^2E(c/a)$

F. R. N. Nabarro, “The strains produced by precipitation in alloys,”
Proc. R. Soc. Lond. A 175 (1940) 519.
Martensitic Transformation

Fig. 15. Optical micrograph showing the “thin-plate” morphology of martensite, observed in an Fe–31Ni–0.29C wt.% alloy transformed at −160°C.
octahedral site

weight % C
Signature of **displacive** transformation: surface relief

*Fig. 5. Surface relief micrograph of several martensite plates in Fe-25Pt showing opposite tilts of different habit plane variants, a roof-gable or "V" effect where impinged plates meet (A and B), displacement of pre-scribed fiducial scratches, and accommodation slip in the austenite (C and D).*
scratch marks (fiducial markers) indicate in-plane displacement as well as out-of-plane
Bain transformation

Figure 24.3: Lattice transformation and lattice correspondence in the f.c.c.→b.c.t. martensitic transformation. (a) Initial f.c.c. structure. (b) Final b.c.t. structure. Crosses denote interstitial sites partially occupied by C atoms in Fe–C solid solutions.

How to do $\gamma \rightarrow \alpha'$ while saving elastic energy?
Bain transformation

Note that $\mathbf{\varepsilon}_{v1} + \mathbf{\varepsilon}_{v2} + \mathbf{\varepsilon}_{v3} \approx 0$
This would never happen for hydrostatic transformation.
variant 1: \( w \)

variant 2: \( 1-w \)

\[
\gamma \rightarrow \alpha'_{v1} + \alpha'_{v2}
\]

\[
\overline{\varepsilon} = w\varepsilon_{v1} + (1 - w)\varepsilon_{v2}
\]

choose \( w, z' \) such that

\[
\overline{\varepsilon}_{x'x'} = \overline{\varepsilon}_{x'y'} = \overline{\varepsilon}_{y'y'} = 0
\]

1000-story high skyscraper
Elastic energy prediction of habit plane inclination (irrational) agrees with exp't to within 1°.


*The 1000-story skyscraper is a self-organized nanocomposite*
Transformer Blocks™
Dislocation plasticity can join the fun:

\[ \gamma \rightarrow \alpha'_{v1} + \alpha'_{v2} + \alpha'_{v1\text{plastic}} + \alpha'_{v2\text{plastic}} \]

**Figure 8-1.** Some photomicrographs of martensite plates in steel. (a) Initial plates in a 7.97 Cr–1.17 C steel. 200 X. (Courtesy of C. M. Wayman.) (b) Specimen largely transformed to martensite. Note how successively smaller plates form in the austenite remaining between the initial plates. (Fe–Ni alloy. 500 X.) (Courtesy of W. A. Leslie, U.S. Steel Company.)
Importance of Martensitic Transformation to Human Civilization:

Hardening due to:

(a) Supersaturation of carbon in bct
(b) Proliferation of twin boundaries

Fig. 19.20 The hardness of martensitic steels as a function of their carbon concentration. The cross-hatched area shows the effect of retained austenite. The hardness of steels with pearlite (plus ferrite) and spheroidized cementite structures are also shown. (From Krauss, G., Principles of Heat Treatment of Metals, American Society for Metals, Metals Park, Ohio, 1980.)
Figure 1. (a)–(c) Schematic illustration of the mechanism of the shape-memory effect and superelasticity, in which solid lines represent the shape-memory path and dotted lines represent the superelasticity path. (d) A series of photographs showing the shape-memory effect: (1) the Ti-Ni wire is straight in the parent phase; (2) the wire is deformed in the martensitic state; (3)–(5) the wire reverts to its original shape upon heating to a temperature above $A_t$ (the temperature at which the reverse transformation finishes). (graph, inset) Stress–strain curve showing superelasticity in a Cu-Al-Ni single crystal at a temperature above $A_t$. Label $\beta$ indicates an ordered phase; $\beta'$ indicates a martensitic phase. See text for more detailed explanations.
Figure 2. The SmartGuide™ is a deflectable, multipurpose 2.0-mm-diameter needle produced by Daum. It can be deflected at a 90° angle by advancing a curved Nitinol tube from stiffer, straight tubing. Such redirection applications become a commonplace use of superelasticity due to the abruptness with which the redirection can be affected.

Figure 3. This grasper (cut from 0.3-mm-diameter Nitinol tubing) is designed to percutaneously retrieve embolized occlusion coils from the neurovascular system. Reaching the arterial system of the brain from the groin requires a shaft that is exceedingly small, flexible, and kink-resistant.

Figure 4. Application of SMAs to an active endoscope. (a) The unit segment of the active stem of endoscope. (b) The total system of the test-produced active endoscope. (c) The test-produced active endoscope in test motion. (Courtesy of Prof. K. Buda.)

Figure 5. A Nitinol SMART® stent is shown as it is released, expanding from <2 mm to 8 mm in diameter. This particular stent is intended for use in the biliary tract, but is commonly used “off-label” in a variety of other ducts. Several other Nitinol-based stents and stent grafts are in common use in hospitals throughout the world.


Large reversible shape change
Classification of Phase Transformations and Plasticity

Civilian transformation

Military transformation
Military versus civilian growth kinetics

Growth speed $\nu$ (velocity of $\alpha\beta$ interface)

- Collective shear
  - "athermal"

- Higher $T$

- Short-range / long-range diffusion:
  - linear response kinetics

Driving force vs. threshold
TTT diagram for AISI 1080 steel (0.79%C, 0.76%Mn) austenitised at 900°C.
SEM micrograph of etched pearlite (Wikipedia)

\[ \gamma \rightarrow \alpha + \text{Fe}_3\text{C} \]

Pearlite (2-phase lamellar composite)
Classification of Phase Transformations and Plasticity

Civilian transformation

Military transformation
Table 3.5  Classification of Nucleation and Growth Transformations


<table>
<thead>
<tr>
<th>Type</th>
<th>Military</th>
<th>Civilian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of temperature</td>
<td>Athermal</td>
<td>Thermally activated</td>
</tr>
<tr>
<td>Interface type</td>
<td>Glissile (coherent or semicoherent)</td>
<td>Non-glissile (coherent, semicoherent, incoherent, solid/liquid or solid/vapor)</td>
</tr>
<tr>
<td>Composition of parent and product phases</td>
<td>same</td>
<td>different</td>
</tr>
<tr>
<td>Nature of diffusion processes</td>
<td>No diffusion</td>
<td>Short-range diffusion (across interface)</td>
</tr>
<tr>
<td>Interface, diffusion, or mixed control?</td>
<td>Interface control</td>
<td>Mainly interface control</td>
</tr>
<tr>
<td>Martensitic Deformation Twinning</td>
<td>Massive Ordering Polymorphic Recrystallization Grain growth Condensation Evaporation</td>
<td>Precipitation Dissolution Bainite Condensation Evaporation</td>
</tr>
</tbody>
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