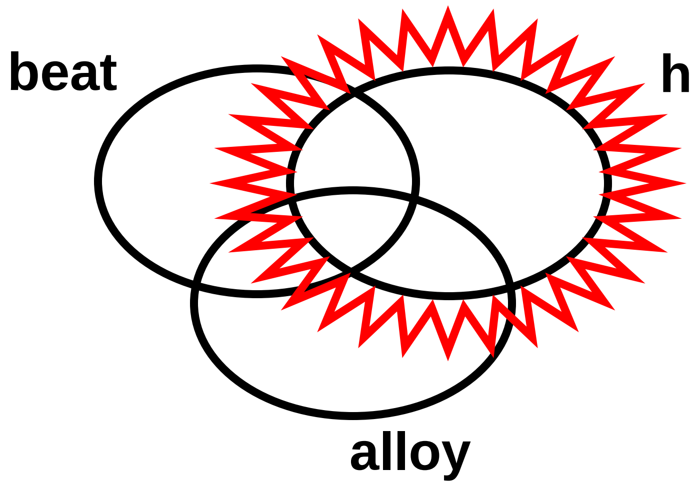
Physical Metallurgy

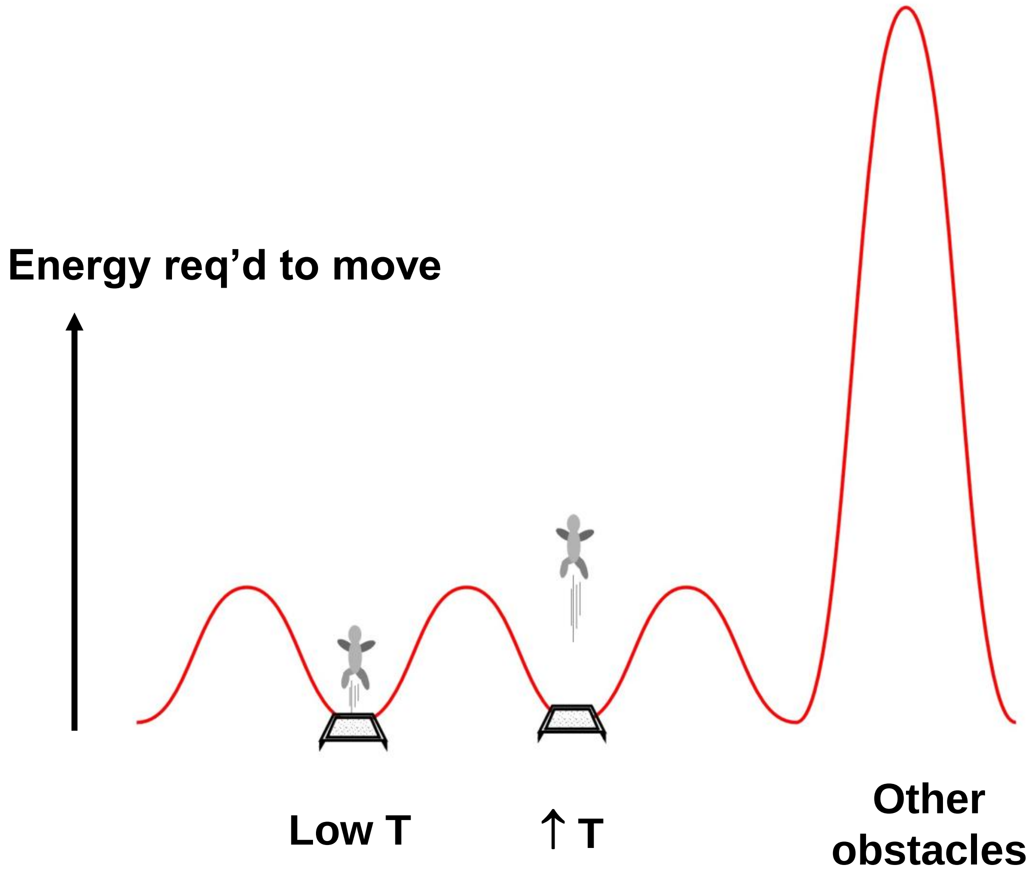
10/13-10/14 Lecture Review



Dept. of Mechanical Engineering, MIT

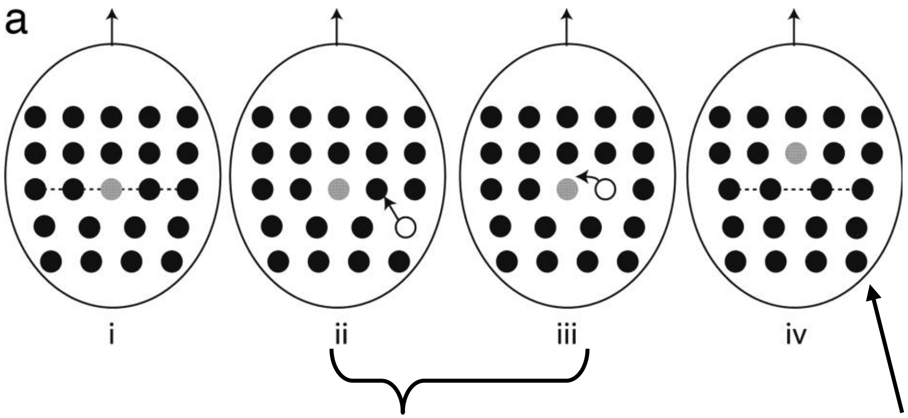
With increasing temperature

- Glide becomes easier
- Apparent activation barrier is lower



http://www.msm.cam.ac.uk/wjc/coursef/Lecture5.htm

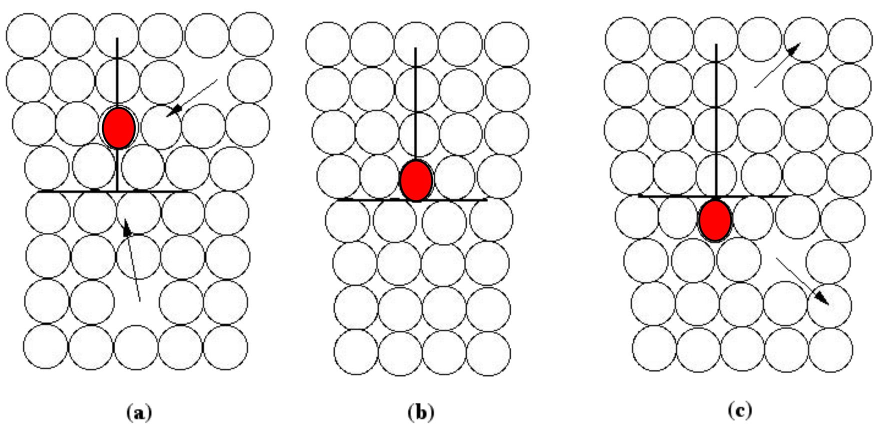
Dislocation climb



Vacancy moves to core of dislocation

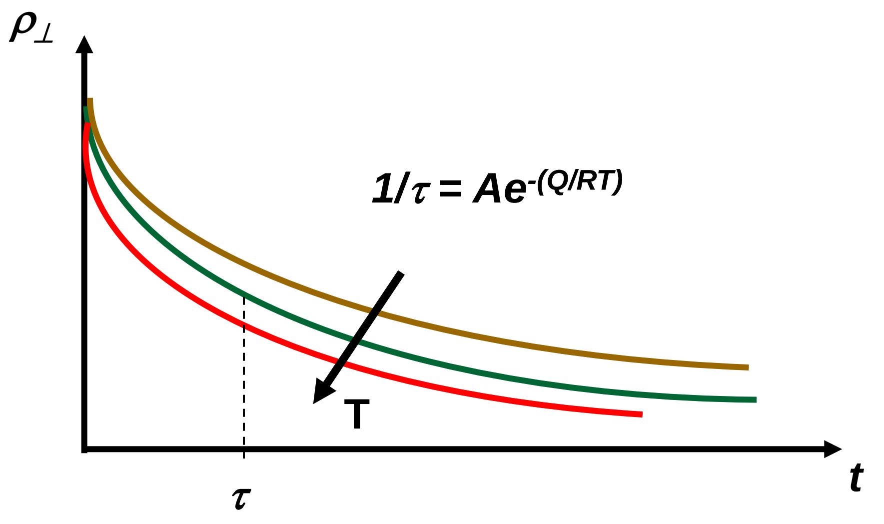
Dislocation shifts by one atomic distance

- Edge dislocations can leave their slip plane
- ⊥ climb can absorb or emit vacancies
- Increase T = increase vacancies



Vitelli V et al. PNAS 2006;103:12323-12328
http://neon.materials.cmu.edu/rohrer/defects_lab/polygoniz_bg.html

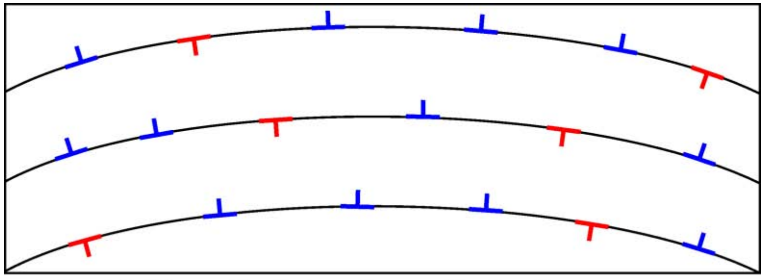
Recovery (Annealing)



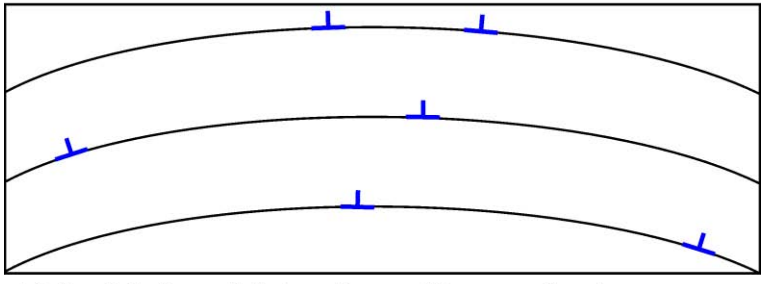
- Recovery of $\rho_\perp$, stored $\perp$ energy
- $T \geq 1/3\ T_{melt}$
- Heat + mobility = $\perp$ annihilation

Recovery: Polygonization

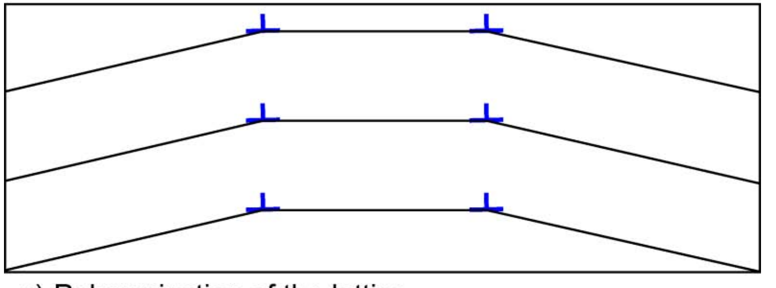
- ⊥ of like sign assemble into boundaries
- Subgrain formation of low-angle grain boundaries
- Localizes lattice curvature into polygonal regions



a) Bent lattice with dislocations of both sign



b) Annihilation of dislocations with opposite sign



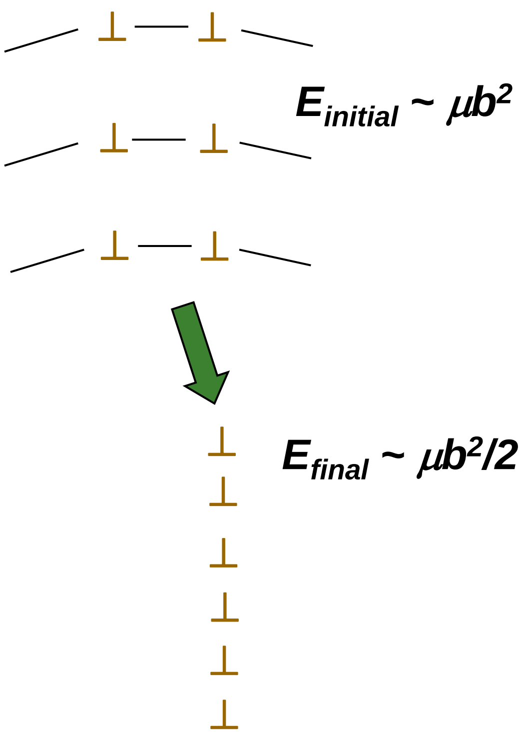
c) Polygonization of the lattice

Image removed due to copyright restrictions.
Please see Fig. 6.82 in Totten, George E.
Steel Heat Treatment Handbook: Metallurgy and Technologies. Vol. 1. Boca Raton, FL: Taylor & Francis, 2007.

Steel heat treatment: metallurgy and technologies, Totten (2006)
http://en.wikipedia.org/wiki/Recovery_%28metallurgy%29

Recovery: Coarsening

- Loss of boundary area to reduce interaction energy



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Please see Fig. 3 in Gutierrez-Urrutia, I., M. A. Muñoz-Morris, and D. G. Morris. "Recovery of deformation substructure and coarsening of particles on annealing severely plastically deformed Al-Mg-Si alloy and analysis of strengthening mechanisms." *Journal of Materials Research* 21 (February 2006): 329-342.

Gutierrez-Urrutia et al (2006) J. Materials Research

Recrystallization: ReX

- Nucleation of new, ⊥-free grains
- Heterogeneous process, complex kinetics
- Original microstructure <u>erased</u>

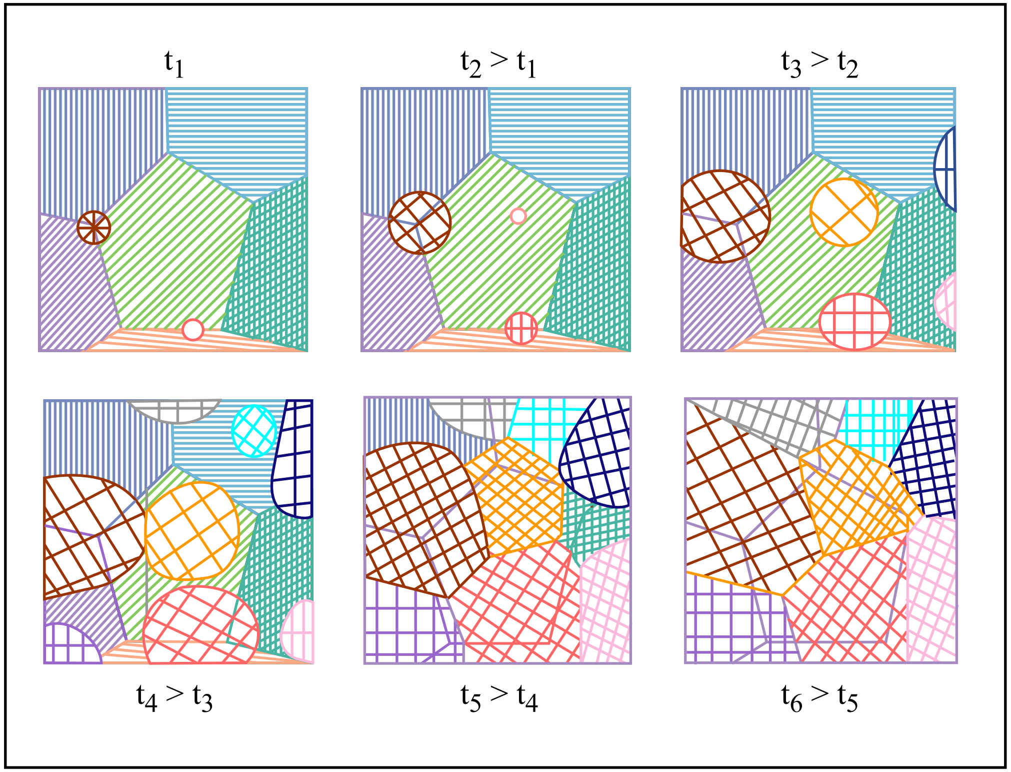


Figure by MIT OpenCourseWare. Adapted from Fig. 6.85 in Totten, George E. *Steel Heat Treatment Handbook: Metallurgy and Technologies*. Vol. 1. Boca Raton, FL: Taylor & Francis, 2007.

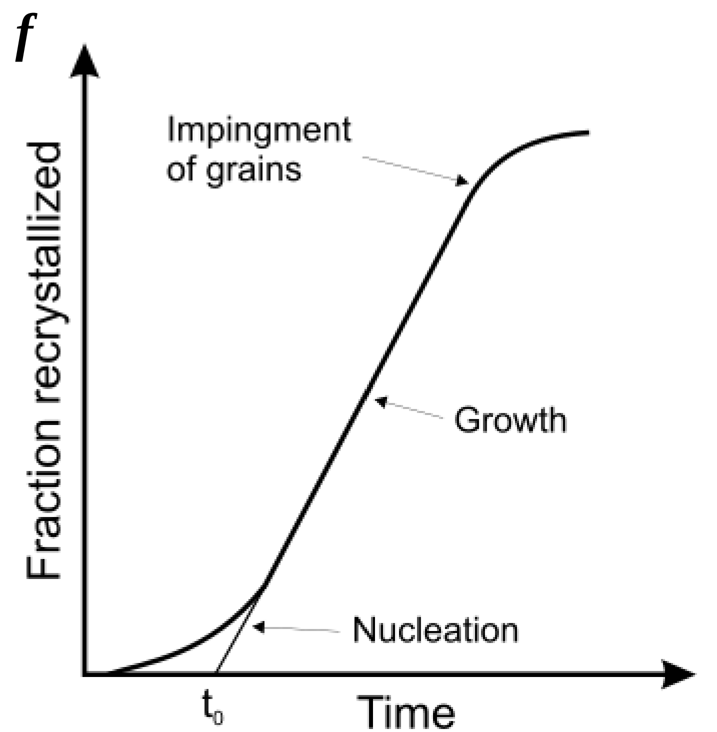
nucleation → growth → impingement

Steel heat treatment: metallurgy and technologies, Totten (2006)

Recrystallization: JMAK analysis

Johnson-Mehl-Avrami-Kolmogorov Theory

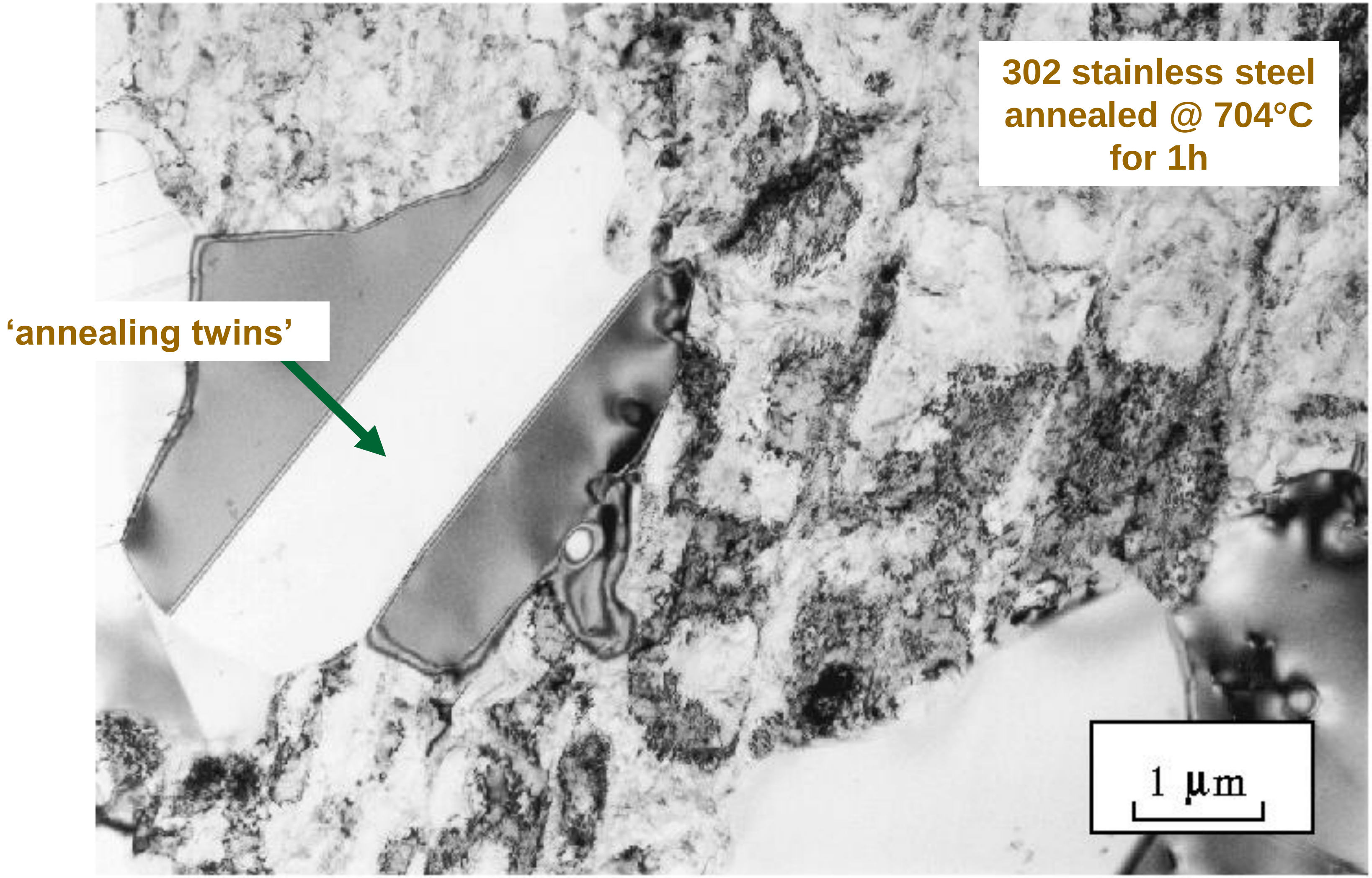
- Nucleation
  - N = nucleation rate
- Growth
  - G = constant growth rate
- Impingement
  - $df = df_{ex}\,(1-f)$



Spherical grains	$f = 1 - \exp\left(-\frac{\pi}{3}\dot{N}G^3t^4\right)$
General form **(n = d + 1)**	$f = 1 - \exp(-K\,t^n)$

http://en.wikipedia.org/wiki/Recrystallization_%28metallurgy%29

Recrystallization: ReX



http://www.doitpoms.ac.uk/miclib/full_record.php?id=772

Courtesy of H. K. D. H. Bhadeshia and DoITPoMS, University of Cambridge.

Annealing of stainless steel bellows

Please see MazzolaTermomacchine.
"Stainless Steel Bellows End Annealing." March 12, 2009.
YouTube. Accessed May 5, 2010. http://www.youtube.com/watch?v=VJNY-68ulGk

http://www.youtube.com/watch?v=VJNY-68ulGk

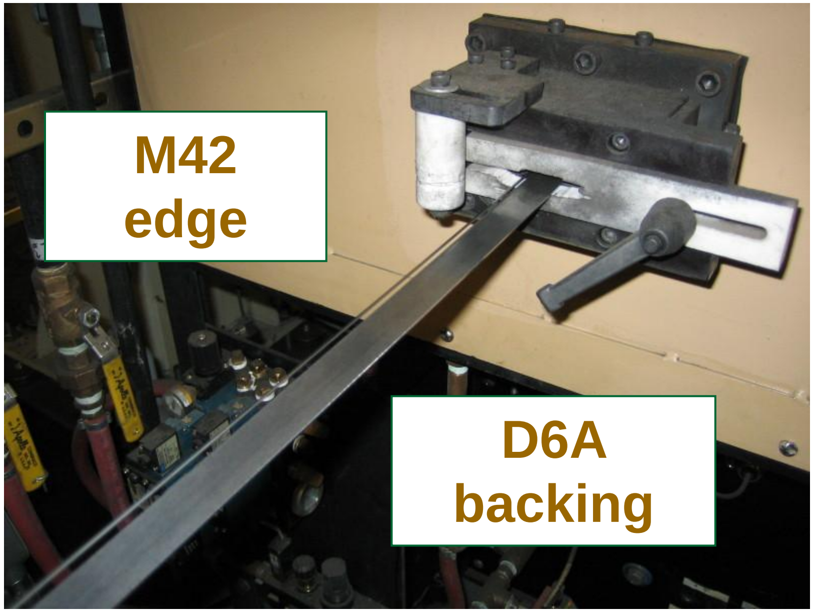
Recrystallization! (copper(II) sulfate)

Please see mikishima. "Recrystallization of Copper Vitriol." April 4, 2007. YouTube. Accessed May 5, 2010. http://www.youtube.com/watch?v=erjXD1iUXKo

Heat Treatment

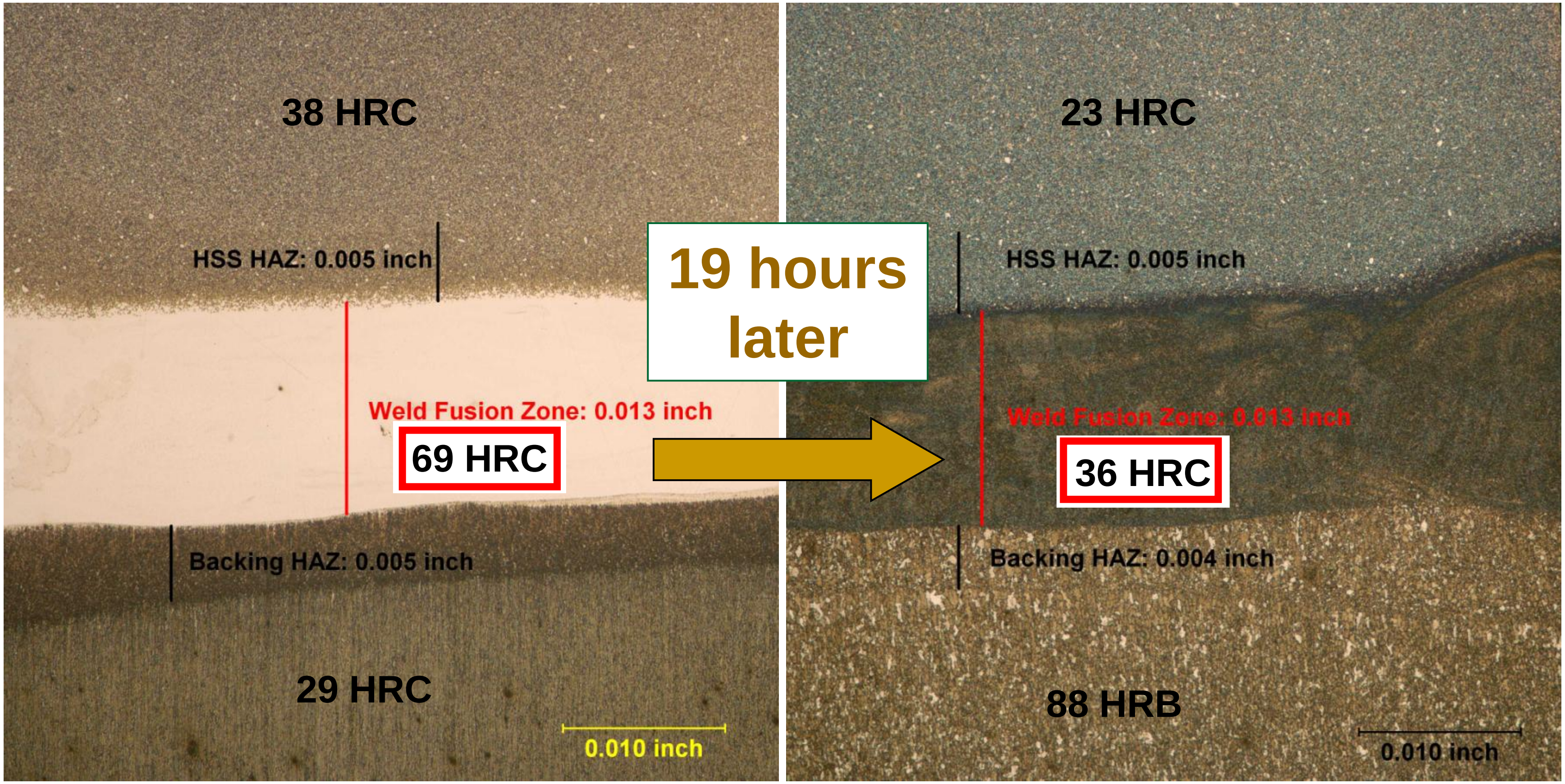
Please see dziadunio. "Heat Treatment." February 29, 2008.
YouTube. Accessed May 5, 2010. http://www.youtube.com/watch?v=rAm2Y0wGRF4

Bandsaw blade manufacturing



Vacuum pit furnace

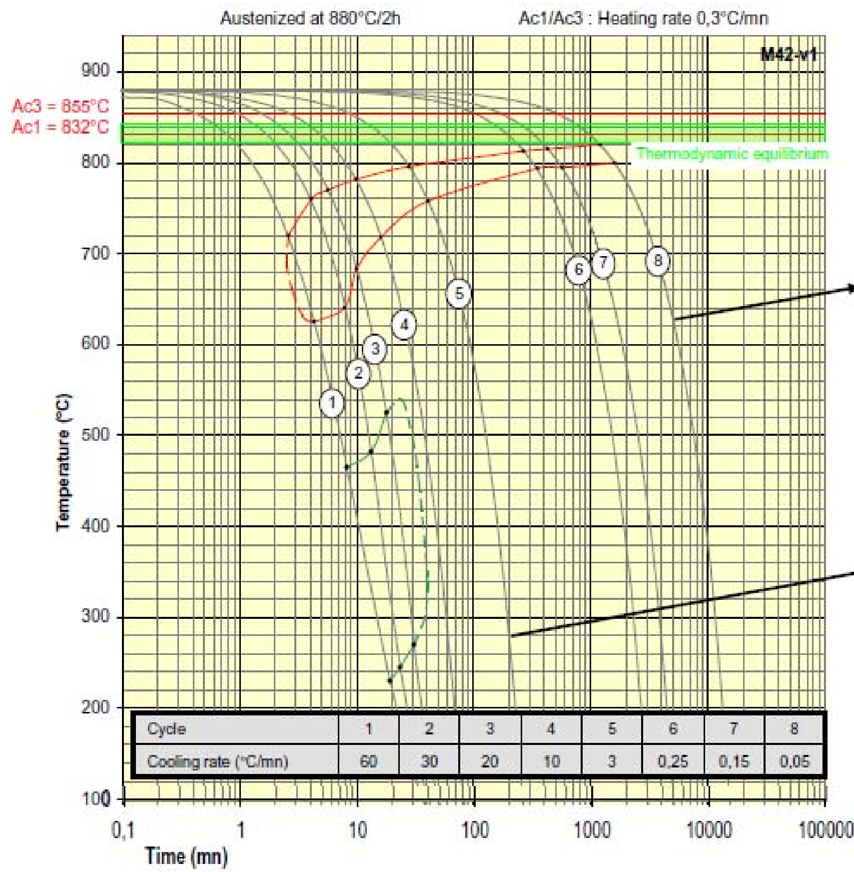
Bandsaw blade annealing



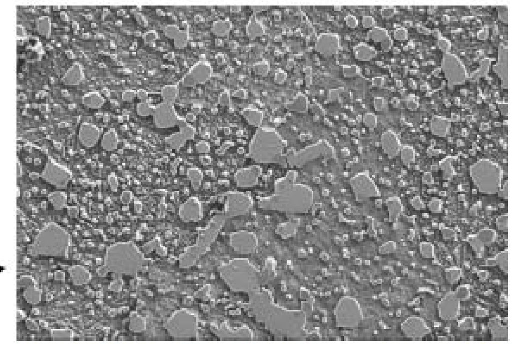
Before Anneal **After Anneal**

Recovery time vs. hardness

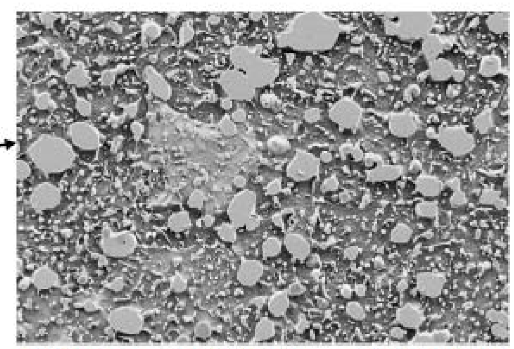
ER projects on annealing



Cycle	1	2	3	4	5	6	7	8
Cooling rate (°C/mn)	60	30	20	10	3	0,25	0,15	0,05

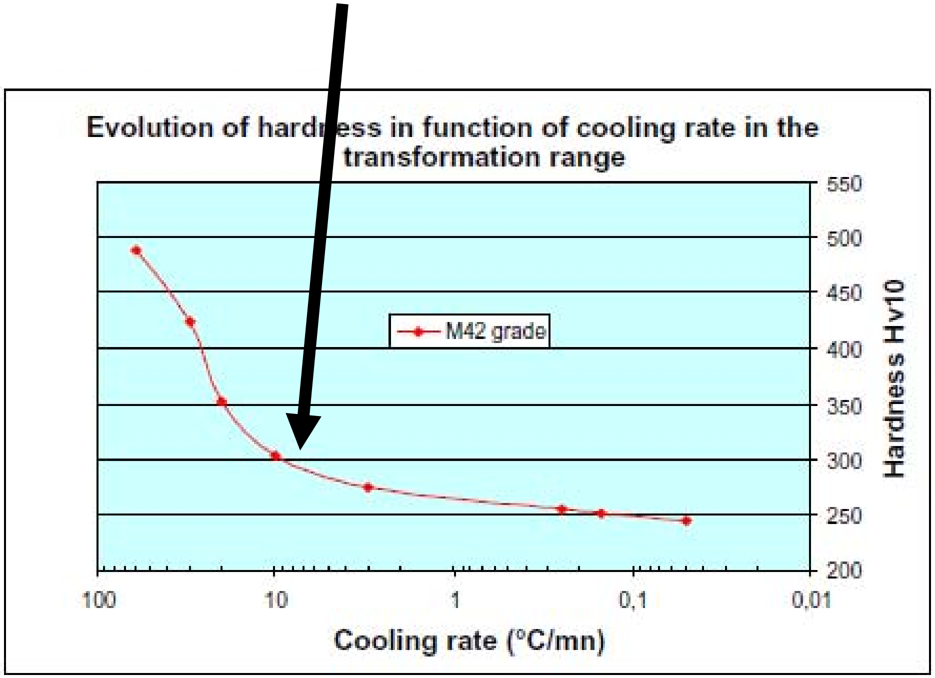


0.05°C/mn = 3°C/h → 244 Hv10



3°C/mn = 180°C/h → 275 Hv10

Familiar looking curve?



Cooling rate	Hardness
°C/mn	Hv10
0,05	244
0,15	251
0,25	255
3	275
10	304
20	352
30	424
60	489

softwares	Temperature	M_2C	M_6C	MC	$M_{23}C_6$	M_7C_3	Ferrite	Austenite
THERMO-CALC	750°C	6.36	7.02	0.91	-	5.31	80.41	-
	880°C	6.73	6.27	0.81	-	1.5	-	84.70
MAT-CALC	750°C	10.94	0.16	1.70	3.29	-	83.92	-
	880°C	7.78	2.92	2.21	-	-	-	87.08

Have a good day!