Lecture 6:
Strengthening of Plain Carbon Steels

MMat 380

Contributions to strength in steels

- •Base material
- •Solid solution strengthening (i.e., %Mn)
- •Grain size (ferrite)
- •Precipitates (distance between ppts)
- •Cold work (dislocation density)

Steels - Fe-C-Mn alloys

- Mn added as ferromanganese
  - Helps to de-sulpherize steel MnS
    (Fe-S brittleness)
  - Powerful solid solution strengthener
  - Powerful effect on heat treating med. %C (0.3%C) and high %C steels which are usually Q&T

AISI-SAE No.	% C	% Mn
1006	0.08 max.	0.25–0.40
1010	0.08–0.13	0.30–0.60
1015	0.13–0.18	0.30–0.60
1020	0.18–0.23	0.30–0.60
1025	0.22–0.28	0.30–0.60
1030	0.28–0.34	0.60–0.90
1035	0.32–0.38	0.60–0.90
1040	0.37–0.44	0.60–0.90
1045	0.43–0.50	0.60–0.90
1050	0.48–0.55	0.60–0.90
1055	0.50–0.60	0.60–0.90
1065	0.60–0.70	0.60–0.90
1070	0.65–0.75	0.60–0.90
1075	0.70–0.80	0.40–0.70
1080	0.75–0.88	0.60–0.90
1085	0.80–0.93	0.70–1.00
1090	0.85–0.98	0.60–0.90
1095	0.90–1.03	0.30–0.50

P, 0.040 max; S, 0.05 max.

1xXX - %C in steel

Strengthening low C steels (0-0.3%C)

2 major ways:

- increase carbon content
  - sacrifice % elongation; toughness because of Fe_3C
- decrease grain size
  - increase strength but doesn't affect ductility
  - Hall-Petch Equation $\sigma_y = \sigma_o + kd^{-1/2}$ d = grain size (mm)

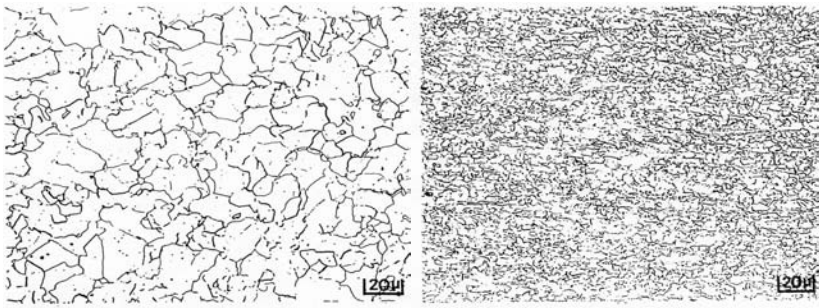
∴ better strength without sacrificing ductility and toughness

trend: use fine grained steels and lower C content

Examples

ASTM No	Grain	σ_y (MPa)
5	Coarse	250
8	Fine	300
12-13	Very fine	500

Grain size and strength



335 MPa   540 MPa

ASTM grain size

Grain boundaries act as barriers to dislocation motion

$$n = 2^{N-1}$$

n = # grains/in^2 @ 100x mag

N = ASTM grain size No

Note: Table 2.1 pg. 74 Smith

ASTM grain size

TABLE 2-1
Grain-size number as related to grain count

	Timken-ASTM No.	Grains per square inch of image at 100 × Maximum	Minimum	Mean	Grains per sq millimeter (mean actual)
	−3	0.088	0.044	0.06	1
	−2	0.176	0.088	0.125	2
	−1	0.35	0.176	0.25	4
	0	0.71	0.35	0.50	8
Usual range	1	1.41	0.71	1.0	16
Usual range	2	2.83	1.41	2.0	32
Usual range	3	5.66	2.83	4.0	64
Usual range	4	11.3	5.66	8.0	128
Usual range	5	22.6	11.3	16	256
Usual range	6	45.2	22.6	32	512
Usual range	7	90.5	45.2	64	1024
Usual range	8	181	90.5	128	2048
	9	362	181	256	4096
	10	724	362	512	8200
	11	1448	724	1024	16400
	12	2896	1448	2048	32800

Unit conversions

ASTM # 1

16 grains/mm^2 x $(25.4)^2$ = 10 323 gr/in^2

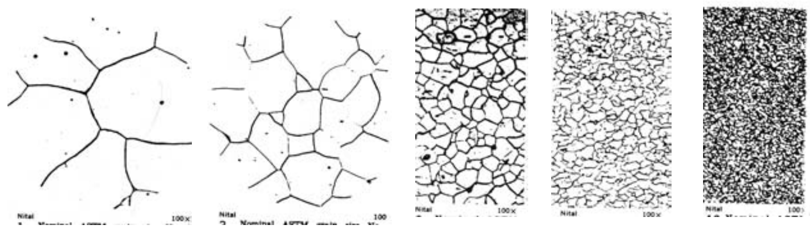
= 1.03 gr/in^2 @ 100x

ASTM # 8

2048 grains/mm^{2}x$(25.4)^2$ =1 321 287 gr/in^2

= 132 gr/in^2 @ 100x not 128

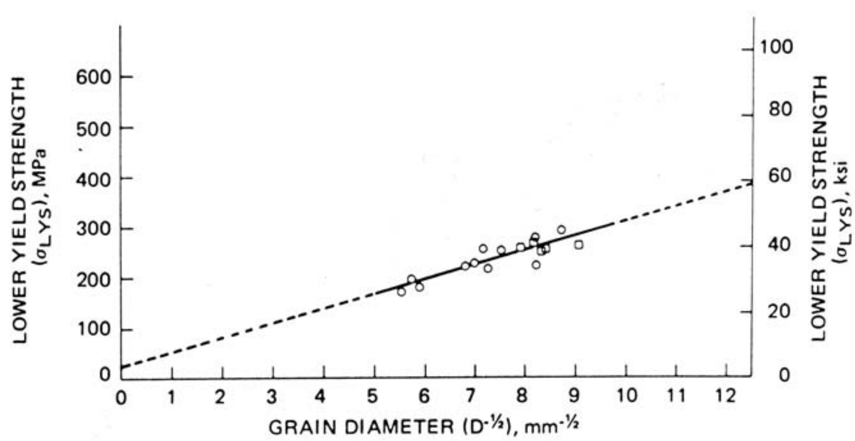
ASTM grain size



1 3 6 8 10

Same magnification

Effect of grain size on strength



Applications

Grade	%Mn	Product
1006	0.25-0.4	Sheet
1010-1025	0.3-0.6	Structural
1030	0.6-0.9	Heat treated

Low carbon steels (<0.25%C)

- Sheet Steels
- C <0.1%
  - Cold worked – quality surfaces (auto's, appliances)
  - Strain Aging
    - C, N producing inhomogeneous yielding
    - Need for temper rolling to obtain homogeneous yielding (for smooth surface forming)
- Very low carbon IF Steels (<0.05%C)
  - Paint bake strengthening (+70 MPa Y.S.)

Low carbon steels (<0.25%C)

- Structural Steels (<0.15-0.25%C)
- Equilibrium microstructures (25%α +75%P)
- Following hot rolling, use accelerated cooling to **decrease** $\gamma \rightarrow \alpha$+P transition temperature (below 721°C)

  ∴ produce fine α + increases amount of P
- Ferrite grain size ASTM # 5 (coarse) – ASTM # 8 (fine)
- Canadian Standards Association (CSA) – CSA G40.21 for quality structural steel

15

High Strength Low Alloy (HSLA) steels

Why low alloy if high alloy provides high strength?

- Traditionally for highest strength in a structural steel the C & Mn levels would be increased
  - i.e. 0.25-0.30%C 1.2-1.5%Mn
  - An increase of 1% Mn will increase YS by ~14%
- This led to **problems** with:
  - **Weldability** (problem with increased C and Mn)
  - **Brittle failure** (problem with increased C)
- New approach required: ↑ strength but ↓ C
- Now have steels with YS to 550 MPa but with excellent weldability and brittle fracture resistance

16

HSLA steels

- Solid solution hardening (Mn)
- Decrease ferrite grain size by
  - Controlled rolling
  - Controlled cooling
- Precipitation hardening
  - Nb (C,N)
  - VC

Typical x70 pipeline steel

%C = 0.06; %Mn = 1.50; %Nb and/or V ~0.04

Controlled rolling to produce very fine grain size

Strengthening HSLA steels

- Obtain fine grain size (ASTM 10-13) by:
  - Controlled rolling
  - Controlled cooling
- Can increase yield strength by 100-134 MPa (i.e. 300-440 MPa total)

Element	**σ_y increase of α per 1% addition**
Cr	6.7
Co	13.4
V	13.4
W	20
Mo	27
Al	40
Ti	67
Ni	80
Mn	94
Si	100
Be	600
P	670

Controlled rolling

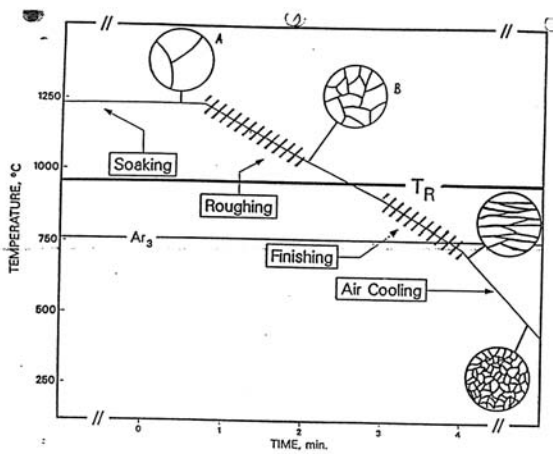
- **Normal** finish T in hot rolling: 900-1000°C
- Finish at temperatures: **750-800°C**
  - Lower temperature
  - R_x & grain growth after hot rolling takes longer
  - end up with smaller g grain size\ smaller α grain size

Controlled rolling

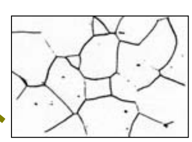
- transformation of **deformed** γ gives finest grain size

$\therefore$ want to ↑ T of R_x and make R_x more difficult
  - Nb in small amounts does this (~0.04%Nb added)
  - Need massive roll force to give required deformation
- Controlled rolled plate typically < 1” in thickness
- Thick plate usually has larger α grain size because
  - it is finished at a higher T and $\therefore$ has a larger γ grain size

Controlled rolling schematic

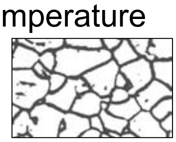


Controlled cooling and grain size



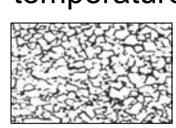
Slow cooling

Higher transformation temperature



Fast cooling

Lower transformation temperature

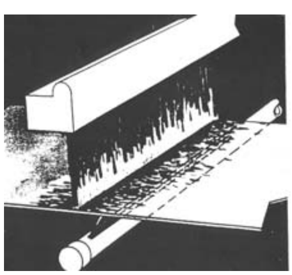


Controlled cooling

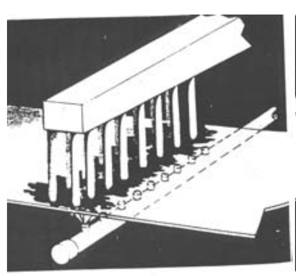
- Now consider cooling rate after rolling
- On increased cooling rate (i.e. H_20 jets)
  - T_{transf} is decreased
  - Higher nucleation rate and low grain growth rate
- When external cooling is the same, a thick plate will cool slower

$\therefore$ larger α grain size

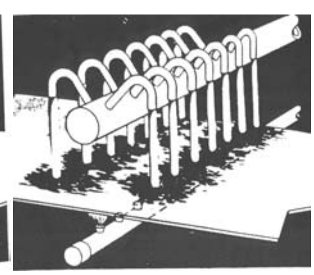
Means of controlled cooling



Water-wall strip cooling concept



Dual-jet laminar flow header



Early form of laminar jet flow system – 2 rows of U-tubes from 1 header

Thick sections

Why do "thick" sections have lower yield stress?

- When finish rolling at higher T (larger γ grain size) thick sections **cool slower**
- raises T_{transf} $\gamma \rightarrow \alpha$
- fewer α nuclei grow to larger α grain size $\therefore$ lower σ_y

Precipitation hardening

Microalloying – Nb, V, Ti

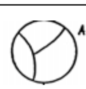
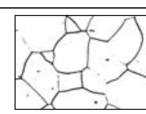
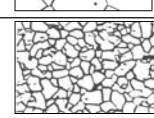
- Nb (C,N) precipitate **during** hot rolling in γ
  - restricts γ grain growth
  - refines α grain size
  - retards R_x & raises T_{transf}
- Pancake grains
  - nuclei closer together therefore finer R_x grain size
- V – VC precipitate on cooling **after** rolling

Strength in HSLA steels

+ Standard C-Mn Steel	200-300 MPa
+ Decrease grain size	100-134 MPa
+ Increase Mn	67 MPa
+ Increase Nb, V, Ti ppt hardening	67-100 MPa
Total:	**434-600 MPa**

- Can now afford to lower the C content and still have 470-500 MPa steel
- Can have any strength level wanted by varying the degree of strengthening components

Effect of austenite grain size

Austenite grains		TRANSFORM TO	Ferrite grains
Large		→	
Small		→	
Deformed		→